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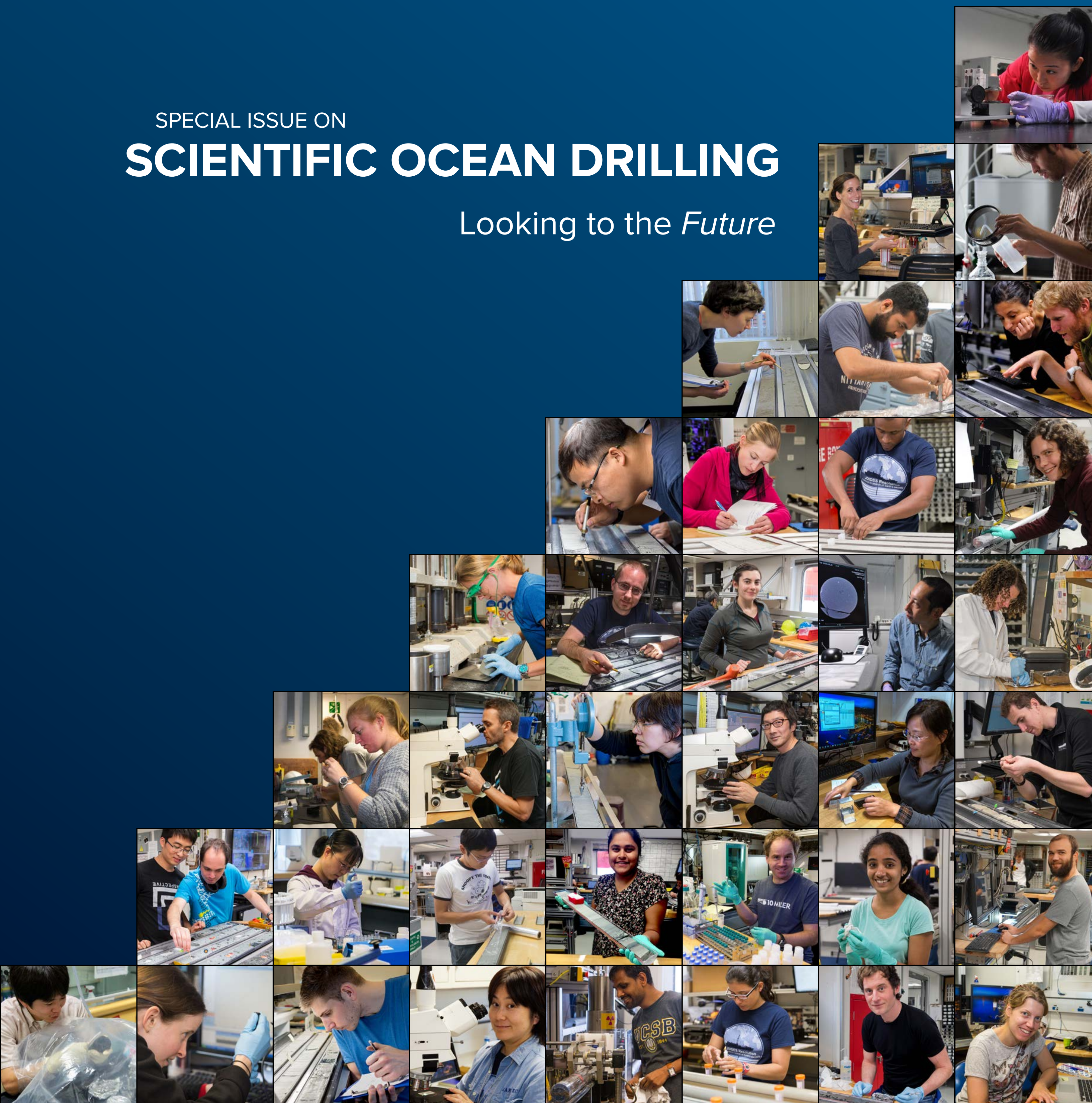
Oceanography

VOL.32, NO.1, MARCH 2019

SPECIAL ISSUE ON

SCIENTIFIC OCEAN DRILLING

Looking to the *Future*



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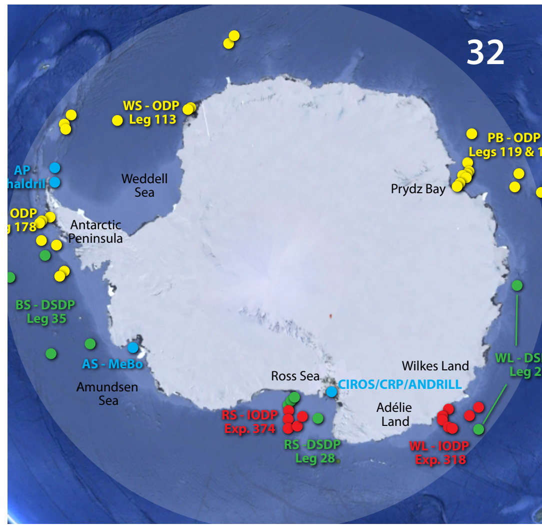

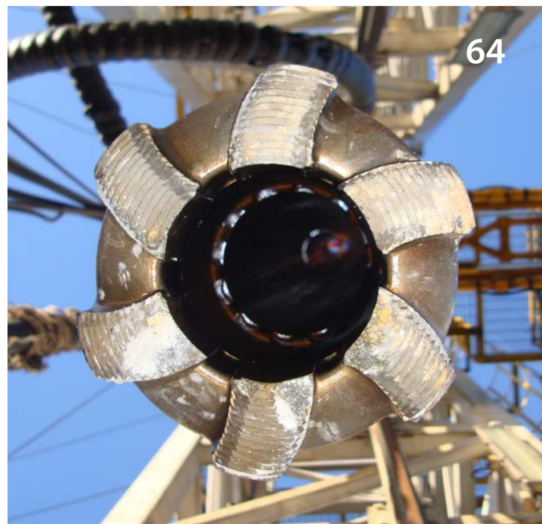

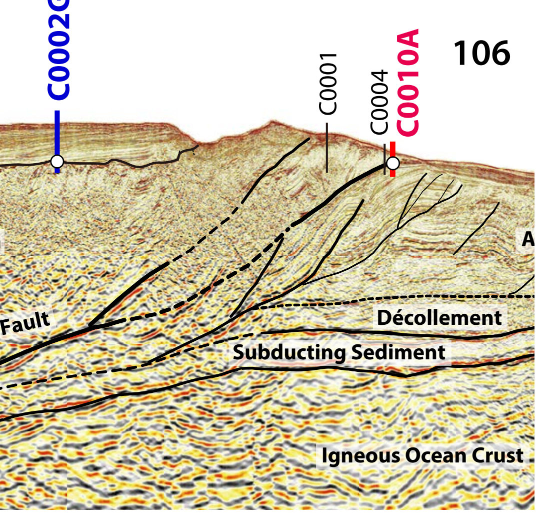

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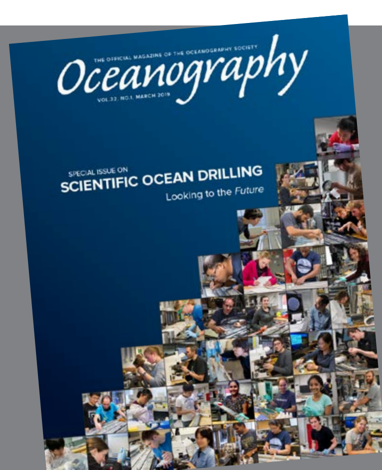

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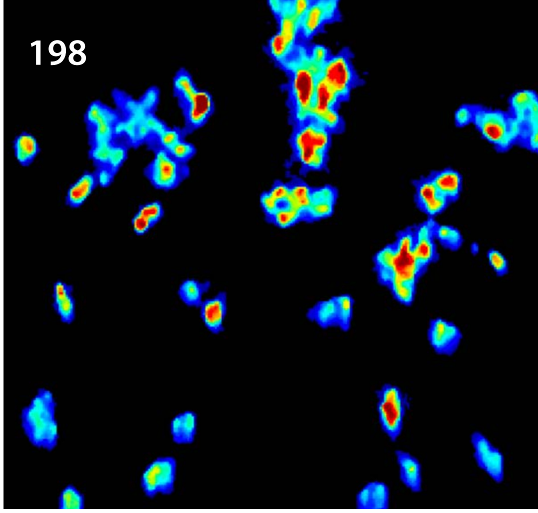

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The Oceanography Society was founded in 1988 to advance oceanographic research, technology, and education, and to disseminate knowledge of oceanography and its application through research and education. TOS promotes the broad understanding of oceanography, facilitates consensus building across all the disciplines of the field, and informs the public about ocean research, innovative technology, and educational opportunities throughout the spectrum of oceanographic inquiry.

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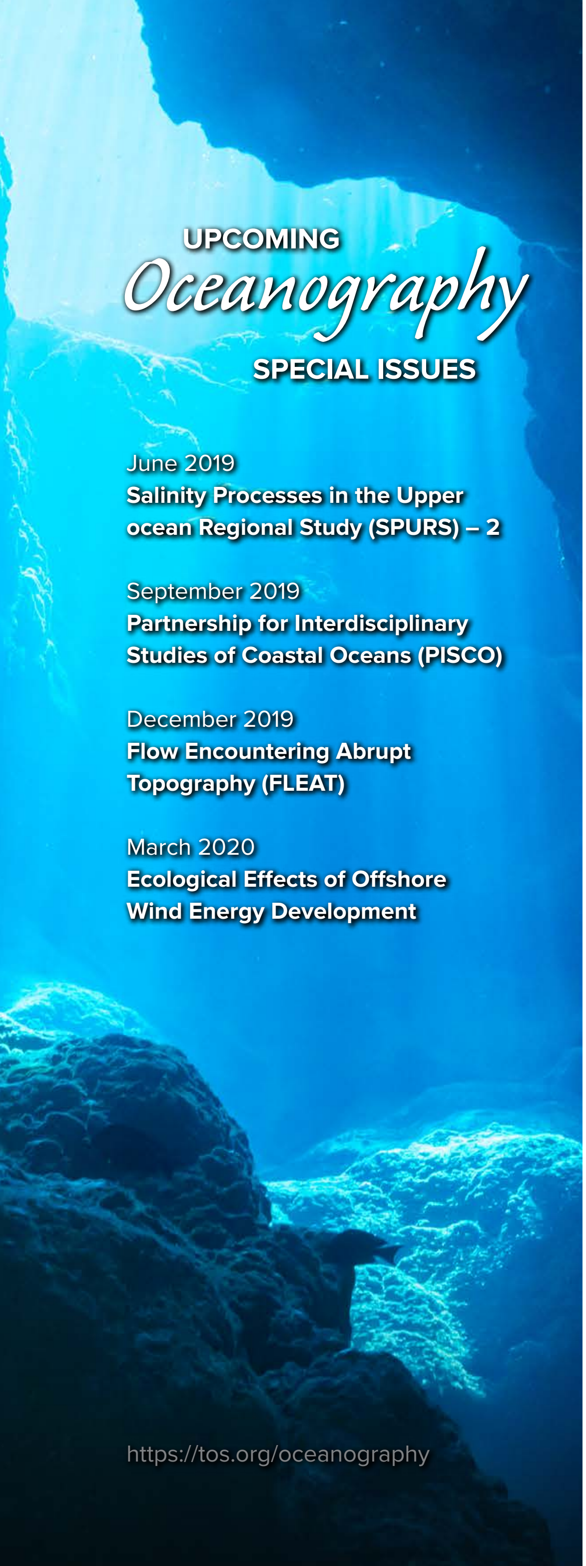

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June 2019
Salinity Processes in the Upper ocean Regional Study (SPURS) – 2

September 2019
Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO)

December 2019
Flow Encountering Abrupt Topography (FLEAT)

March 2020
Ecological Effects of Offshore Wind Energy Development

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CALL FOR IDEAS!

Do you have an idea for a special issue of Oceanography? Please send your suggestions to Editor Ellen Kappel at ekappel@geo-prose.com.

We Are Family

We are family
Got my drilling partners with me
We are family
Time to drill down under the sea…[1]

Over the past two decades, it's been a joy watching my family grow, thrive, and accomplish so much. While I haven't been a constant presence, I've been invited to assist at critical junctures, helping to make sure that they continue to achieve great things and break new ground globally, as well as nurture the newest family members. At other times, I keep up with their activities by reading and occasionally chatting with old friends. Busy with current projects, I kvell[2] from afar.

Of course, I'm talking about my scientific ocean drilling family. Although it's been more than two decades since I was a program manager for the Ocean Drilling Program (ODP) at Joint Oceanographic Institutions (JOI), I still consider myself a devoted member of this community.

When I arrived at JOI as a young PhD, the senior program managers at both JOI and the National Science Foundation—Tom Pyle and Bruce Malfait (both sadly no longer with us)[3], as well as Paul Dauphin—took me under their wings, welcomed me to the family. They were generous with their time and taught me the ropes. I learned how dedicated, thoughtful, and sometimes creative management could help the community achieve its goals. These awesome people remain an inspiration.

So too does the scientific community involved in ODP. As a result of attending numerous ODP and US Science Support Program meetings and other activities, I was surrounded by outstanding and generous mentors, too many to name here. They shared their passion for the program and the science, and also their ideas about new technologies that could transform data collection in boreholes. Some of those dreams led to breakthroughs highlighted in this special issue of *Oceanography*. Through their actions and words, this community demonstrated how true scientific collaboration can create a whole that is much, much more than the sum of its parts.

I should add that employment at JOI was also the beginning of a lifelong friendship and working relationship with two very special people who make The Oceanography Society tick. Jenny Ramarui, the TOS Executive Director, and Johanna Adams, the *Oceanography* designer and TOS webmaster, were part of the JOI ODP team way back when. I thank them for making each workday fun and for their continued outstanding service and dedication to the ocean sciences community.

It is said that first jobs can have an impact that lasts a whole lifetime. No doubt, scientific ocean drilling has done that for me—and I'm certain for tens or even hundreds of others. It's been an honor serving and being a part of this large, wonderful family.

Ellen S Kappel

Ellen S. Kappel, Editor

1 With apologies to Sister Sledge.
2 From the Yiddish kveln, meaning "to be delighted," which, in turn, comes from the Middle High German word quellen, meaning "to well, gush, or swell."
3 Read tributes to Tom and Bruce at https://doi.org/10.5670/oceanog.2011.82 and https://doi.org/10.5670/oceanog.2014.97


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The Oceanography Society in 2030 – What is Our Joint Ambition?

After two years serving as TOS president-elect, I am now looking forward to working with TOS membership to grow and advance our society. Under the leadership of Alan Mix, we have made excellent progress in a number of areas, including the Society's budget and have approved the urgently needed TOS policies concerning professional integrity, ethics, and conduct. My goal as president is to articulate a vision for the Society for the coming decade. How should TOS adapt to the changes in ocean science? How can TOS provide value for our members? And how can we strengthen the profile and impact of TOS? Not only is scientific ocean drilling "Looking to the Future," we should be, too.

One area that has seen increased engagement, awareness, and possibly urgency is that of Integrated Ocean Research or Ocean Systems Science. Over the last decade, the (non-scientific) world has discovered and recognized the critical role that the ocean plays in Earth's life-support system, and as such, its importance for societies and their economies. First, a growing population, its affluence, and industrialization have increased pressures on the ocean system. Ocean science has documented the effects of over-exploitation of natural resources such as fish and minerals; of increasing levels of pollution from nutrients, carbon dioxide, toxins, and plastic; and of climate change and coastal habitat destruction. Second, questions arise about the resilience of coastal communities. Ocean science and engineering are expected to provide insights about how to manage change and stress on our coasts and how to promote diversity in our natural defense systems. Finally, societies around the world are interested in figuring out how the ocean domain can provide lasting prosperity for their people. What are our options for safeguarding the ocean, husbanding its resources for human good, and preserving and benefiting from its cultural and ecological services? Answering these complex questions will require ingenuity and innovation in order to combine knowledge and insights from a wide range of sources. This approach is often referred to as "integrated science" or "system science." Does our society provide good answers? Do we promote this kind of ocean research?

The next decade provides a unique opportunity for TOS to engage in the development of the recently established UN Decade of Ocean Science for Sustainable Development (2021–2039). The program for the Ocean Science Decade is currently under debate and will very likely encourage actions toward a more integrated and sustainable ocean observing system to facilitate discovery, understanding of ocean systems, and environmental monitoring. Advances in robotics and the combination of remote and in situ ocean observations offer new opportunities, and free and open data sharing and multi-stakeholder contributions by governments (rich and poor), the private sector, and citizens are opening exciting new dimensions. International efforts, such as the Global Ocean Observing System, the Blue Planet initiative of the Group on Earth Observations, and the community developed Framework for Ocean Observing provide a basis and an opportunity for growth and evolution. The upcoming decadal conference on ocean observations, OceanObs'19 (Hawaii, September 16–20, 2019), will provide an excellent opportunity to advance our ocean observing ambitions. TOS is a proud sponsor of that conference.

The Ocean Science Decade will also highlight opportunities for integrated research informing human-ocean development options, will promote initiatives for global capacity building, and should improve current ocean governance systems. All this is actively discussed in the Executive Planning Group for the Decade. I am a member of this group, and I thank TOS for the nomination and support.

Our organization has the flexibility to explore new approaches and programs. However, it is not the president's job to define the future of TOS. I will work with President-Elect Andone Lavery and the TOS Council to establish a consultative process to develop an exciting and engaging strategy as we look ahead to creating a plan for The Oceanography Society in 2030: Looking to the Future.

Martin Visbeck, TOS President

Wallace S. Broecker

1931–2019

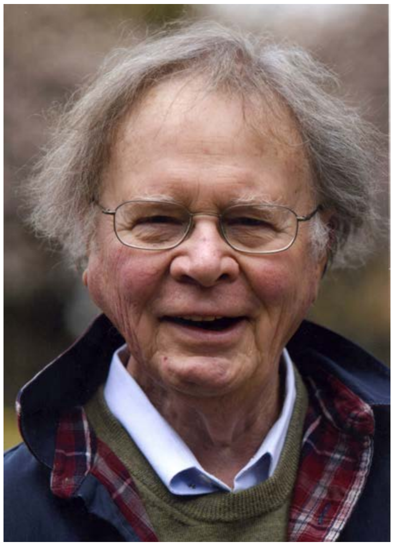

Photo credit: Lamont-Doherty Earth Observatory

It is with great sadness and even greater respect that we mourn the passing of Wallace S. Broecker. To say that Wally's work led to significant advancements in ocean sciences and climate change is a gross understatement. It is hard to imagine oceanography without Wally as a source of ideas beyond count, a voice to bring understanding of the ocean and the carbon cycle to the forefront of public policy, and a spirited antagonist who goaded the rest of us to work both more creatively and more rigorously.

Wally's career started in the 1950s—the early days of isotope geochemistry—with key contributions in radiocarbon and uranium series dating. He provided early chronological evidence in favor of the astronomical theory of glaciation, a theory then out of favor but now broadly accepted as one of the cornerstones of paleoclimatology, and a key to understanding the high sensitivity of global climate to radiative forcing.

Wally's kinetic model of ocean chemistry, which nearly 50 years ago defined the ocean as a dynamic chemical system defined by inputs and outputs and response times rather than one at equilibrium, transcends his own work, and it changed how we think about the world.

With this dynamical framework in hand, Wally took on the task of understanding the mechanisms of natural CO_2 variations, and especially the marine carbon cycle. He promoted the idea that the role of CO_2 in natural climate oscillations preserved in the geologic record would yield insights into future consequences of polluting our atmosphere with greenhouse gases. Wally's inference of multiple stable states of the ocean-atmosphere system suggested the possibility of "unpleasant surprises" in global greenhouse warming should the system shift toward a new mode of operation. These concepts continue to provide a stark warning to policymakers regarding what may be irreversible consequences of humanity's propensity to pollute.

Many wonder how Wally accomplished so much. He revealed his secret during a public talk on ocean chemistry and carbon dioxide when he started with, "This morning in the shower I had an idea…." After the laughter died down, he said, "Well, what do YOU think about in the shower?" Clearly, the rest of us can learn to be more efficient with our time. Wally inspired generations of students and fellow scientists to think harder, faster, and better. Few of us in the field have escaped a battle with Wally at one time or another. He was often right, but again revealing his greatness, he was the first to admit publicly when he was wrong.

All ocean scientists have been influenced by Wally's ideas, and now we mourn the end of an era.

Alan C. Mix

Alan C. Mix, Past President, TOS

A New Wave SCIENCE AND ART MEET IN THE SEA

BY CHERYL LYN DYBAS

Stay along the coast, offers the ad. Enjoy views of bald eagles, great blue herons, and ospreys. But this is no vacation condo promotion. It's a flyer for a University of Mississippi Field Station course, Biology & Art. Students learn scientific illustration techniques and conduct research on the Gulf of Mexico ecosystem.

It's part of a global effort known as transforming STEM to STEAM: science, technology, engineering, the arts, and mathematics.

BRANCHES OF THE SAME TREE: FROM STEM TO STEAM

A recent US National Academies of Sciences, Engineering, and Medicine (NAS) report, *The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher Education: Branches from the Same Tree,* emphasizes that all disciplines and forms of inquiry are, as Einstein stated, "branches from the same tree."

Faculty and administrators, notes the 2018 report, "are advocating an approach to education that moves beyond the general education requirements found at almost all institutions, to an approach that melds knowledge in the arts, humanities, physical and life sciences, social sciences, engineering, technology, mathematics, and the biomedical disciplines."

The report refers to this new direction as integration. "Advocates of integration see all human knowledge as connected, a network of branches arising from a trunk made up of human curiosity, passion, and drive, but also generative, as new branches split off and grow from old ones, extending into new spaces and coming into contact with other branches in new ways."

Take the idea of in-course integration. That can range from a class that includes a component of another discipline, such as a neuroscience lecture series with an assignment to write a haiku poem about synapses, or an entire course such as design engineering. In such "left brain meets right brain" efforts, integration works well.

In one undergraduate neuroscience course, students who were required to make a three-to-five minute film outperformed those who learned concepts solely through conventional approaches, according to the NAS report. And a course in biochemistry that featured sculpture-building based on how proteins fold allowed students to develop a new understanding of the complex concepts of protein structure.

DRAWING WITH LIVING LIGHT: BIOLUMINESCENT BACTERIA

In the marine sciences, STEM has morphed into STEAM in an unusual way in the artwork of Hunter Cole. A geneticist at Loyola University New Orleans, Cole produces paintings that are inspired by science but literally live as art through the otherworldly glow of the bioluminescent bacterium *Photobacterium phosphoreum.*

Photobacterium phosphoreum lives in Pacific rockfish, where it emits bluish light. The rockfish, also called Pacific Ocean perch (*Sebastes alutus*), are widely distributed in the North Pacific from southern California to northern Honshu, Japan, including the Bering Sea. Pacific Ocean perch are abundant in British Columbia, the Gulf of Alaska, and the Aleutian Islands.

Cole cultures *Photobacterium phosphoreum*, then, using a paintbrush, draws the bacteria, which she refers to as her collaborators, into different shapes in a Petri dish. The biologist-artist then photographs the luminescent petri dishes to create what she calls modern works of provocative symbolism.

Bioluminescent bacteria become art. Pictured: A work titled "Insecta." *Image: Hunter Cole*

With a paintbrush, a geneticist–artist draws bioluminescent bacteria into different shapes, then photographs them. Pictured: Series titled "Her Own DNA." In the second and third images, the bioluminescence has begun to dim. *Images: Hunter Cole*

Her subjects include lilies, insects, and other flora and fauna, all seen by the light of bioluminescent bacteria. She often photographs people illuminated by her paintings—onlookers as the bacteria's living light shines then slowly disappears.

"Art and science have always been mutually inclusive for me," says Cole. "Biology serves as a vehicle for expressing my creativity and artistry. Art serves as a motivation to interpret our living world."

In January 2018, a multimedia display at Chicago's ARC Gallery—Living Light: Photographs by the Light of Bioluminescent Bacteria—featured Cole's creations. The exhibit showcased her bioluminescent artworks developed between 2005 and 2017. In addition to looking at bioluminescent photos, visitors watched a time-lapse video of luminous bacteria growing and dying, accompanied by a musical score based on protein sequences in the bacteria.

A SPARK OF AN IDEA

How did Cole come up with the concept of painting with living light? "In 2003, I was an adjunct professor at the University of Wisconsin-Milwaukee, and that's when I started using bioluminescent bacteria in art," she says.

A member of her lab, she recalls, drew a heart in bioluminescent bacteria. "That was such a meaningful symbol," says Cole. "One of the functions of bioluminescence is to attract a mate. Bioluminescence is also important in communication and is integral to many marine predator-prey relationships."

The symbolism and surreal nature of using light created by an organism that lives for a brief time, she says, attracted her to this medium.

Drawing with bioluminescent bacteria is a tricky endeavor, Cole found. "First I make a culture of the bacteria, dipping a paintbrush or Q-tip in liquid and painting on agar in a Petri dish. But it's like painting with invisible ink. You need to wait until the next day to see it glowing—and what you've created." She photographs the paintings as the luminescent bacteria grow and die over a period of days.

Cole's paintings are some of the more unusual examples of ocean art. Among her most stunning works is what might be called a triptych of her own DNA. As the bacteria's bioluminescence begins to fade, each painting grows dimmer. "It's a metaphor for life," she muses.

Cole has now developed a Loyola course: Biology Through Art. The class offers students an opportunity to create their own bioluminescent drawings while working in a biology laboratory. "It's amazing how much the arena of art and science has expanded, especially related to the ocean," says Cole. "There are so many more practitioners now than there were just a few years ago."

It's a symbiotic relationship, say Cole and others. Collaboration with artists has altered scientists' designs and methods, according to Aaron Ellison of the University of Massachusetts Amherst. In a recent paper in the *Bulletin of the Ecological Society of America,* Ellison writes that partnering with scientists "has helped artists delve deeper into issues, gain insight into processes, and tackle more complicated concepts in their artistic practice. These partnerships may change and enrich the way we do both science and art."

ABOUT THE AUTHOR

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Foreword

By Arthur E. Maxwell and Margaret Leinen

One of us (Art Maxwell) played a pioneering role in proposing the first scientific ocean drilling program during the 1960s. The other (Margaret Leinen) was a graduate student at the time whose research interest in the history of the ocean depended on the core samples collected via this new program. Together, we have watched scientific ocean drilling evolve in many ways. The focus of drilling expanded from an effort to recover samples that could resolve hypotheses about Earth's crust (the nature of the Moho, plate tectonics, and global volcanism) to one that addresses hypotheses about the history of the ocean itself, about the interactions between the ocean, ice sheets, mountain building, and climate, and now to one that studies the coevolution of the ocean, oceanic crust, and life.

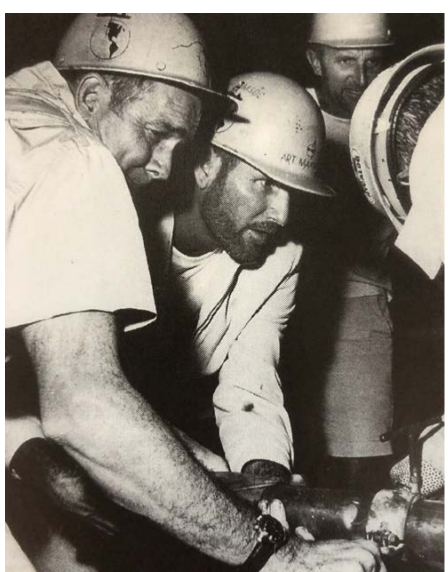
Along the way, technology innovations in scientific ocean drilling and sampling developed by both the program and scientists involved in the program led to vastly improved recovery of sediments and rock, the ability to collect pristine samples of fluids and microbiota associated with the samples, and capabilities for performing a range of experiments within the boreholes.

The scope of the program has expanded dramatically in 50 years. Several years ago, an internal analysis by the US National Science Foundation found that nearly a quarter of all US geoscientists in the country had some association with ocean drilling, through participation in expeditions or site surveys, through the use of samples and data made available by the program, or through participation in planning or scientific workshops focused on scientific ocean drilling.

The program originally depended on a single drilling ship funded by the United States. It now encompasses mission-specific platforms contributed by a European-led consortium and a unique riser vessel funded by Japan that is capable of deep drilling into tectonically active ocean margins.

During these 50 years, ocean drilling has pulled together the global geology, oceanography—and now also the geomicrobiology—communities. Many of our individual research relationships began in the core labs of the drilling vessels *Glomar Challenger*, *JOIDES Resolution*, *Chikyu*, and other platforms, or on ships conducting site surveys in preparation for and in support of the expeditions. The luxury of time spent together in labs at sea, or over meals during those cruises, spawned new ideas and directions for geology, geophysics, oceanography, and the life sciences that are independent of nationality or academic institution affiliation. Furthermore, the well-preserved core samples are available for continuing use by the global community. These core repositories represent an important data archive that will be used by scientists ad infinitum.

In this way, the drilling programs have supercharged scientific discovery. For example, paleoceanography was a word barely used before scientific ocean drilling provided the samples on which this very field depends so heavily.



One of the features of the program that excites us is its capacity for nurturing new ideas and creating opportunities to follow new scientific directions. While early drilling focused on resolving questions of interest to scientists, the themes of recent and proposed expeditions focus on issues critical to the future of humankind that depend on answers to basic science questions about climate, natural hazards, Earth dynamics, and the limits and sensitivity of life. This capacity for meaningful evolution is a key feature of the scientific ocean drilling program and one that makes us confident that it will continue to be an essential element of Earth, ocean, and life sciences studies in the future.

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ABOVE. Co-Chief Scientists David Rea and Margaret Leinen on the bridge of D/V *Glomar Challenger* during DSDP Leg 92 in 1983. *Photo credit: Victor Sotelo*

LEFT. Art Maxwell (center), along with Jim Dean and Dick Von Herzen, removing a core aboard *Glomar Challenger* on DSDP Leg 3 in 1968. *Photo credit: DSDP*

INTRODUCTION TO THE SPECIAL ISSUE ON

Scientific Ocean Drilling

Looking to the *Future*

By Anthony A.P. Koppers, Carlota Escutia, Fumio Inagaki, Heiko Pälike, Demian M. Saffer, and Debbie Thomas

This special issue of *Oceanography* on Scientific Ocean Drilling: Looking to the Future celebrates the more than 50 years of investigating the subseafloor of the world's ocean and seas that began in the summer of 1968 with Leg 1 of the Deep Sea Drilling Project (DSDP, 1968–1983). Since those early years, scientific ocean drilling has evolved from a US-only program to a fully fledged international one, now including more than 26 countries. It transformed from a focus on exploration during DSDP to more targeted, hypothesis-driven science aimed at understanding fundamental processes during the Ocean Drilling Program (ODP, 1985–2003), the Integrated Ocean Drilling Program (IODP, 2003–2013), and the current International Ocean Discovery Program (IODP, 2013–2023). Together, these programs have recovered more than 490 km of core and engaged more than 5,000 scientific participants from around the globe. The drilling vessels *Glomar Challenger* (1968–1983; see Spotlight 1) and *JOIDES Resolution* (since 1985; see Spotlight 4) have been the workhorses, carrying out 90% of the science missions, whereas the *Chikyu* (since 2007; see Spotlight 7) provides specialized capabilities to reach very deep targets, and mission-specific platforms (since 2004; see Spotlight 11) allow individual expeditions in locations where drilling is challenging, for example, in ice-covered seas or in waters that are too shallow for *JOIDES Resolution*. Analysis of cores and geophysical data collected by scientific ocean drilling have yielded insight into first-order questions about how our planet works, and have resulted in more than 11,000 peer-reviewed publications (see Spotlight 9), with more than 500 appearing in the leading *Nature* and *Science* journals.

Scientific ocean drilling can count many significant discoveries in the Earth, ocean, and life sciences. This long list includes, among others:

- Key validation of the seafloor spreading hypothesis
- Discovery and characterization of subseafloor microbial life and the deep biosphere
- Sampling and measuring the energy budget of a mega-earthquake
- Uncovering numerous details concerning the evolution of Earth's climate over the past 150 million years
- Documentation of the evolution and stability of the polar ice sheets and their roles in past oceanographic conditions and sea level changes
- Assembling a multimillion-year record that defines the biogeochemical and magmatic fluxes between deep mantle reservoirs and the lithosphere that together make up Earth's interconnected system

Along with these groundbreaking results, new questions have emerged, often based on previous scientific ocean drilling expeditions and the detailed analysis of cores and logging data carried out by the shipboard scientific party as well as other researchers who have obtained samples and data from the programs. For most of these studies, drilling provides the only way to access materials from the below the seafloor, collect a wide variety of measurements, and develop a long-term presence in the subsurface that is needed to improve our understanding of Earth's climate history, structure, dynamics, and deep biosphere.

The overall goal of this special issue is to celebrate 50 years of scientific ocean drilling and to reflect on the wide-ranging accomplishments made possible through DSDP, ODP, and the two recent IODP programs—and also, importantly, to document the need for continuation of scientific ocean drilling into the future. As the articles in this volume attest, scientific ocean drilling is an invaluable tool through which an extraordinarily interdisciplinary, vibrant, and diverse community in the Earth, ocean, and life sciences addresses fundamental and acutely societally relevant questions. Scientific ocean drilling fosters strong collaborations between scientists from different

(a) *Chikyu*, *credit: JAMSTEC*. (b) Expedition 381 Science Party in the IODP Bremen Core Repository, *credit: V. Diekamp, ECORD-IODP*. (c) *JOIDES Resolution* docked in Colombo, Sri Lanka, for Expedition 360, *credit: Benoît Ildefonse, IODP JRSO*. (d) Scientists aboard *JOIDES Resolution* carry the last Expedition 362 core, *credit: Tim Fulton, IODP JRSO*. (e) Expedition 302 mission-specific platform operations, credit: *M. Jakobsson, ECORD-IODP*

disciplines, institutions, and countries. The drillships are ideal platforms for graduate students and postdocs to gain valuable seagoing experience and network with scientists from around the globe. The chapters in this special issue show that there remain many outstanding scientific problems that can only be solved by analysis of new core samples and other types of data collected through scientific ocean drilling. With drilling, coring, logging, and borehole observatory technologies rapidly improving, and with anticipated future enhancements to the scientific ocean drilling facilities, this international science program will serve the needs of the ever-broadening community for years to come.

This special issue is organized into four themes that transcend DSDP, ODP, and IODP. The driving questions within the **Climate and Ocean Change** theme capture the urgent need to explore past changes in climate at higher spatial and temporal resolutions. Articles highlight significant recent advances toward addressing two of these questions based on reconstructions of ice sheet and sea level variations in the context of climate change and by gaining a deeper understanding of the processes that impact monsoon variations. Articles in the **Probing the Dynamic Earth and Assessing Geohazards** theme show how, through scientific ocean drilling, researchers are characterizing the various processes that generate earthquakes, tsunamis, and explosive volcanism. In this special issue we focus on key IODP contributions that significantly enhanced our understanding of Earth's largest tsunami-genic earthquakes and the particular importance of slow earthquakes. The third theme investigates the **Window into Earth's Crust and Mantle**, where we look at the initiation of subduction and its influence on global-scale plate tectonics, the architecture of the ocean floor created at slow and fast spreading centers and where large igneous provinces have formed, and the history of the mobility of deep mantle plumes. In the final theme, **Microbial Life Deep Beneath the Seafloor**, we review advances in our knowledge of the makeup of subseafloor life, the deepest expanses of Earth's biosphere, and the limits of life in extreme environments, all enabled by scientific ocean drilling.

For the last five decades, scientific ocean drilling has been a foundational tool that provides the Earth, ocean, and life sciences communities access to the subseafloor not achievable in any other way. The programs' interdisciplinary approaches to addressing difficult scientific problems, to advancing and maintaining the technical capabilities of the drilling vessels and onboard laboratories, and to nurturing productive and enduring international collaborations have resulted in numerous significant scientific achievements. Many stellar scientific careers have been launched through involvement in scientific ocean drilling programs. A vibrant new generation is ready to take the helm and apply scientific ocean drilling to test the newest hypotheses on the frontier of the Earth, ocean, and life sciences.

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SPOTLIGHT 1. *Glomar Challenger*

The purpose-built Deep Sea Drilling Project (DSDP) research vessel *Glomar Challenger* operated from 1968 through 1983. Its objective was fundamental exploration of the ocean basins. The ship was owned, designed, and built by Global Marine Inc., while Scripps Institution of Oceanography was responsible for the management and operations of the program.

Over its 15-year history, 96 expeditions recovered more than 97 km of core (see table below). Despite primarily using spot coring rather than continuous coring early in the program, the impact of scientific ocean drilling with *Glomar Challenger* was immediate: among other early accomplishments, Leg 3 provided crucial data that validated the seafloor spreading hypothesis. The scientific results from DSDP Legs 1 to 96 were published in the *Initial Reports of the Deep Sea Drilling Project* (http://deepseadrilling.org/i_reports.htm). These reports describe the core and scientific data obtained at sea and include scientific papers based on post-cruise data obtained by individual investigators working in shore-based laboratories. DSDP data are available online from NOAA's National Centers for Environmental Information (http://www.ngdc.noaa.gov/mgg/geology/dsdp/start.htm).

Many of the techniques and tools that are now considered routine in scientific drilling were initially designed, tested, and refined on *Glomar Challenger*. For example, Leg 15 in 1970 marked the first use of reentry systems that provide the capability to replace worn-out bits mid-expedition in order to allow deeper penetration. The initial rotary coring system used by DSDP was augmented in 1979 with deployment of the Hydraulic Piston Corer, an early version of the current Advanced Piston Corer, revolutionizing scientific ocean drilling by recovering undisturbed sequences of unlithified sediment. This technology advancement was followed by deployment of the Extended Core Barrel on Leg 90 in 1982, which brought improved recovery in moderately lithified sediments that are not well recovered by either piston or rotary coring.

– Mitch Malone and Brad Clement

***GLOMAR CHALLENGER* STATISTICS**

Deep Sea Drilling Project (1968–1983)

Expeditions	96
Distance Traveled (nmi)	375,632
Number of Sites	624
Number of Holes	1,053
Number of Cores	19,119
Core Recovery (m)	97,056
Deepest Water (m)	7,044
Deepest Hole (m)	1,741

50 Years of Scientific Ocean Drilling

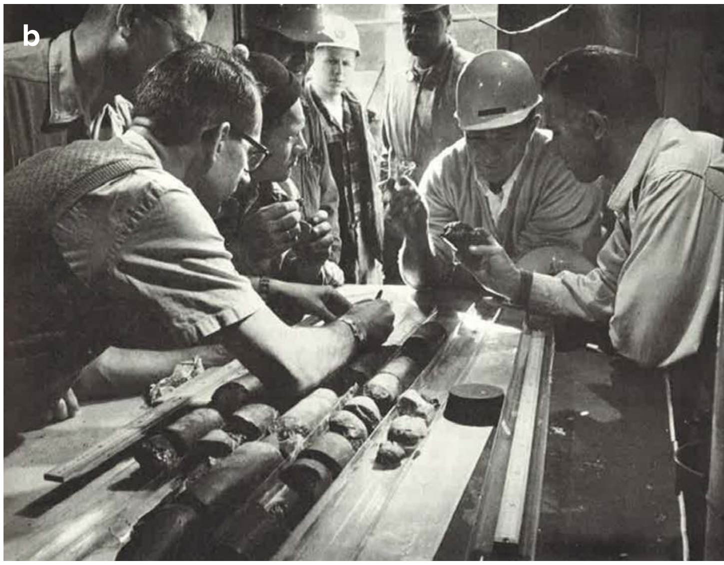
By Keir Becker, James A. Austin Jr., Neville Exon, Susan Humphris, Miriam Kastner, Judith A. McKenzie, Kenneth G. Miller, Kiyoshi Suyehiro, and Asahiko Taira

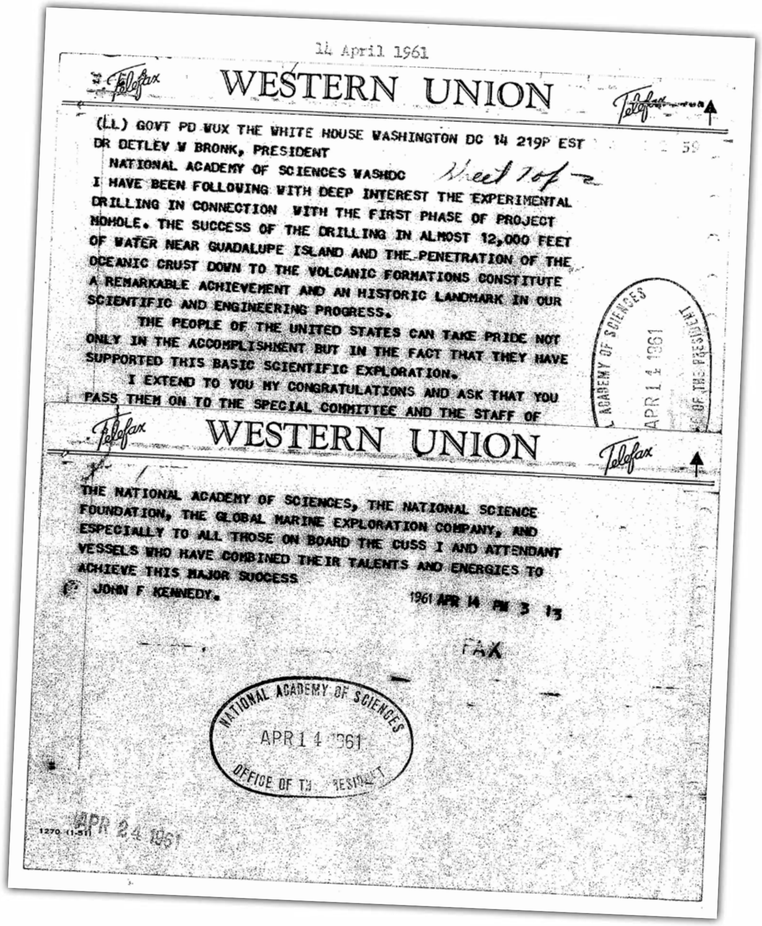
ABSTRACT. Nearly a century after the first systematic study of the global ocean and seafloor by HMS *Challenger* (1871–1876), US scientists began to drill beneath the seafloor to unlock the secrets of the ~70% of Earth's surface covered by the seas. Fifty years of scientific ocean drilling by teams of international partners has provided unparalleled advancements in Earth sciences. Here, we briefly review the history, impacts, and scientific achievements of five decades of coordinated scientific ocean drilling.

PROJECT MOHOLE (1958–1964)

The origins of scientific ocean drilling date back more than 60 years to Project Mohole. Originally suggested in 1957 by Walter Munk and Harry Hess, it was then proposed to the National Science Foundation (NSF) by the famously named, partly self-organized American Miscellaneous Society (AMSOC). At that time, plate tectonics was yet to be formally hypothesized, but it was already known from seafloor seismic refraction studies (e.g., Raitt, 1956) that the Mohorovičić seismic discontinuity between crust and mantle (Moho) was much shallower beneath the ocean floor than the continents. NSF supported phase I of Mohole drilling in 1961 using the Global Marine drilling barge *CUSS I* (Figure 1a), to which four large outboard motors had been added so it could operate as the first dynamically positioned drilling vessel in the world (Bascom, 1961). In a successful demonstration, phase I cored 170 m of sediments and 13 m of underlying basalt at a deepwater site offshore Baja California (Figure 1b). Huge public interest developed, thanks to a prominent article by the famous novelist John Steinbeck in *Life* magazine (Steinbeck, 1961). Recovering subseafloor basalt was a major scientific accomplishment at the time, so much so that it inspired a congratulatory telegram from US President John F. Kennedy

FIGURE 1. (a) The drilling vessel *CUSS I* as used during phase 1 of Project Mohole. (b) A first examination of cores onboard ship during Project Mohole. *Photographs from National Research Council (1961)*

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WESTERN UNION

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DR DETLEV W BRONK, PRESIDENT
NATIONAL ACADEMY OF SCIENCES WASHDC
Sheet 1 of 2

I HAVE BEEN FOLLOWING WITH DEEP INTEREST THE EXPERIMENTAL DRILLING IN CONNECTION WITH THE FIRST PHASE OF PROJECT MOHOLE. THE SUCCESS OF THE DRILLING IN ALMOST 12,000 FEET OF WATER NEAR GUADALUPE ISLAND AND THE PENETRATION OF THE OCEANIC CRUST DOWN TO THE VOLCANIC FORMATIONS CONSTITUTE A REMARKABLE ACHIEVEMENT AND AN HISTORIC LANDMARK IN OUR SCIENTIFIC AND ENGINEERING PROGRESS.

THE PEOPLE OF THE UNITED STATES CAN TAKE PRIDE NOT ONLY IN THE ACCOMPLISHMENT BUT IN THE FACT THAT THEY HAVE SUPPORTED THIS BASIC SCIENTIFIC EXPLORATION.

I EXTEND TO YOU MY CONGRATULATIONS AND ASK THAT YOU PASS THEM ON TO THE SPECIAL COMMITTEE AND THE STAFF OF

WESTERN UNION

THE NATIONAL ACADEMY OF SCIENCES, THE NATIONAL SCIENCE FOUNDATION, THE GLOBAL MARINE EXPLORATION COMPANY, AND ESPECIALLY TO ALL THOSE ON BOARD THE CUSS I AND ATTENDANT VESSELS WHO HAVE COMBINED THEIR TALENTS AND ENERGIES TO ACHIEVE THIS MAJOR SUCCESS

JOHN F KENNEDY.

1961 APR 14 PM 3 13

FAX

NATIONAL ACADEMY OF SCIENCES APR 14 1961 OFFICE OF THE PRESIDENT

APR 24 1961

FIGURE 2. The congratulatory telegram from US President John F. Kennedy at the successful conclusion of phase 1 of Project Mohole.

(Figure 2). However, the effort to continue drilling to the Mohole was derailed by politics when Congress was evaluating various expensive proposals to build an appropriate, custom drilling vessel. As a result, Project Mohole had faded away by 1965. (See Munk, 1980; Maxwell, 1993; and Winterer, 2000, for many fascinating details of the Mohole story.)

JOIDES AND THE DEEP SEA DRILLING PROJECT (1968–1983)

Meanwhile, the directors of four major US oceanographic institutions (Lamont Geological Observatory, Institute for Marine Sciences at the University of Miami, Scripps Institution of Oceanography, and Woods Hole Oceanographic Institution) recognized the value of a concerted program to core the sedimentary record throughout the ocean. In 1964, they signed a memorandum establishing the Joint Oceanographic Institutions Deep Earth Sampling (JOIDES) program. Their vision was to propose to NSF separate scientific drilling "projects" operated by individual oceanographic institutions. The first JOIDES project was a 1965 transect of holes across the Blake Plateau, managed by Lamont and drilled by the chartered vessel *Caldrill*. The Deep Sea Drilling Project (DSDP) was the second JOIDES project, managed by Scripps starting in 1966, including construction of the drilling vessel *Glomar Challenger* (see Spotlight 1). In the summer of 1968, the University of Washington joined JOIDES, and DSDP scientific drilling began with Leg 1 sediment coring in the Gulf of Mexico, in the western Atlantic offshore Bahamas, and on the Bermuda Rise. Originally proposed as an 18-month project, DSDP was so successful that it was extended through 1983. DSDP remained an NSF-funded American effort through 1974 as the National Ocean Sediment Coring (NOSC) program. Between 1973 and 1975, more US institutions and the first international partners (Spotlight 2) joined JOIDES and DSDP for the 1975–1983 International Phase of Ocean Drilling (IPOD), which added an emphasis on penetrating the basaltic basement beneath ocean sediments. In 1975, the first JOIDES Office was established (at Lamont-Doherty Geological Observatory) to coordinate scientific planning for the program, with a subtle change in its title to "Joint Oceanographic Institutions *for* Deep Earth Sampling" (though the acronym remained the same). Scientific ocean drilling has been international ever since (Spotlight 2), and has always been held up as a prime example of successful international scientific collaboration (e.g., Smith et al., 2010).

Revelle (1981) provided an early summary of the scientific impact of DSDP. The most famous DSDP result may well have been direct verification of seafloor spreading by Leg 3 in 1968. That expedition cored and dated the basal sediments immediately above oceanic basement in a transect across the South Atlantic, confirming that crustal age increased nearly linearly with distance from the Mid-Atlantic Ridge spreading center.

DSDP was inherently exploratory and global-ranging, and in that mode made many key scientific contributions—see the section below on Selected Achievements of Scientific Ocean Drilling (1968–2018). DSDP also made important technological contributions, including development of deepwater reentry capabilities (1970) and the hydraulic piston corer (1979) for soft to semi-lithified sediments that continues to be the workhorse of the science of paleoceanography (see Moore and Backman, 2019, in this issue).

OCEAN DRILLING PROGRAM (1983–2003)

In 1983, DSDP was formally concluded, and Texas A&M University was named as the science operator for the Ocean Drilling Program (ODP). Texas A&M

leased a newer and more capable commercial drilling vessel rechristened *JOIDES Resolution* that also included a number of state-of-the-art laboratories for initial analyses (Spotlight 4). Whereas DSDP had been exploratory, ODP was designed as a more thematically driven program, with drilling expeditions based on proposals submitted to the JOIDES advisory structure by the scientific community in response to multi-year science plans (Spotlight 3) developed in periodic international workshops (see section below on Scientific Ocean Drilling and its Advisory Structure). In this planning mode, ODP was very successful across a broad range of scientific themes and gave the community 18 years of continued scientific ocean drilling from 1985 to 2003. NSF provided the majority (about two-thirds) of the financial support throughout ODP, but there were also substantial financial contributions from international partner countries and consortia (Spotlight 2).

INTEGRATED OCEAN DRILLING PROGRAM (2003–2013) AND INTERNATIONAL OCEAN DISCOVERY PROGRAM (2013–2023)

Starting in the mid-1990s, momentum began to develop for a multi-platform continuation of scientific ocean drilling beyond ODP. A new program was envisioned to involve increased international co-funding to make three types of drilling capabilities available to the worldwide scientific community: a riser drilling vessel (Yamada et al., 2019, in this issue) supplied by Japan that was later named *Chikyu* (Japanese for "Earth"; Spotlight 7); continued riserless drilling provided by the United States using a significantly updated *JOIDES Resolution* (Spotlight 4); and mission-specific platforms (MSPs; Spotlight 11) furnished occasionally by the European Consortium for Ocean Research Drilling (ECORD), primarily to access shallow-water and high-latitude scientific targets not suitable for either of the other drillships.

This multi-platform vision was formally realized in late 2003 as the Integrated Ocean Drilling Program (IODP), whose operations began in summer 2004. The first decade of IODP was organized on a model with a significant component of international commingled funding and strong central management provided by IODP Management International Inc. (IODP-MI). Unfortunately, there were delays in launching *Chikyu* and in completing the major overhaul of *JOIDES Resolution* in 2006–2008. Within this first phase of IODP, available funding was not sufficient to achieve the original vision for full-time operations by the two drillships and one or two annual MSP operations. Nevertheless, the first IODP (2003–2013) made significant scientific and technological contributions toward an impressive list of ODP/IODP accomplishments; highlights are listed in a later section on Selected Achievements of Scientific Ocean Drilling (1968–2018), and achievements are documented in more detail by Stein et al. (2014).

For its second 10 years, IODP continued to provide the same two drillships and MSP opportunities, keeping the acronym but changing the program name to the International Ocean Discovery Program. This second phase of IODP significantly simplified the funding and advisory structure, resulting in more efficient operations with no central management organization (Spotlight 5) and an emphasis on regional ship track planning for *JOIDES Resolution* (Spotlight 8).

SCIENTIFIC OCEAN DRILLING AND ITS ADVISORY STRUCTURE

Scientific ocean drilling has always benefited from positive synergy between proposal writers (proponents), a program-based review system, and external peer review starting during ODP. During DSDP, all drilling was exploratory, the community was small, and development and review of drilling expedition plans was often top-down. However, during ODP and the various phases of IODP, all proposals have been reviewed in the context of a succession of community-driven, multi-year, overarching science plans (Spotlight 3). Program-based review panels and committees have evolved through the years, both in number and complexity, from a theme/region focus, with added engineering, logging, and technology panels/working groups, to the comparatively simple current model with a single panel of both "science" and "data" experts who vet all proposals for all platforms and integrate anonymous external peer review. An environmental protection panel, with some members serving for decades, stands guard over the safety of operations. Since the beginning of ODP ~35 years ago, the nurturing of proponents and their ideas has been the key to success, with spectacular results. The program is open to scientists located throughout the globe, and has fostered innovative and transformative science from the tropics to the poles, in every ocean basin, and over every epoch of the last 170 million years.

EDUCATIONAL CONTRIBUTIONS OF SCIENTIFIC OCEAN DRILLING

Spotlight 13 highlights the importance of current IODP efforts in training the next generation of geoscientists, but international scientific ocean drilling has had a long history in this regard since DSDP. Several of the authors of this paper—and many of our colleagues—participated in DSDP expeditions or site surveys during graduate school or early postdoctoral positions. The skills we developed through this participation have been crucial in our career development, and the international networks of scientific contacts we made then have developed into lifelong collaborations. During ODP and IODP, opportunities like this have been provided to graduate students, and many of them have gone on to highly productive careers in the geosciences. In addition, activities have been extended to undergraduates, K–12, and informal education venues. Educators now sail on drilling expeditions and organize many activities, some in real time, to engage students and the public as they study Earth's systems.

SELECTED ACHIEVEMENTS OF SCIENTIFIC OCEAN DRILLING (1968–2018)

Significant accomplishments of scientific ocean drilling in many subjects are explored in more detail in thematic articles in this issue. Major achievements from DSDP and ODP were nicely summarized in the "Major Achievements of Scientific Ocean Drilling" section of the IODP Initial Science Plan (Coffin et al., 2001, pp. 10–16). Stein et al (2014) carefully documented additional achievements from the first phase of IODP. We offer the following as a non-exclusive list of important overall contributions of 50 years of scientific ocean drilling.

Climate, Ocean, and Sea Level History

- Enabled development of the field of pre-Quaternary paleoceanography
- Helped define and refine the geomagnetic polarity timescale and its link to astronomical chronologies back to 66 million years ago, providing key constraints on today's standard Geological Time Scale
- Extended the marine sedimentary record back into the Middle Jurassic (~170 million years ago), allowing reconstruction of planetary history since then at million-year resolution or better
- Tracked changes in atmospheric CO_2 through the Cenozoic and linked these to Earth's surface temperature history
- Documented large carbon-cycle changes associated with marine black shales, anoxic events, and episodes of abrupt climate change such as the Paleocene-Eocene Thermal Maximum
- Linked Earth's orbital variability to long-term climate changes, including the expansion and contraction of global ice volume over millions of years as well as shorter glacial-interglacial cycles
- Enabled construction of a ~100-million-year history of the timing, rates, and estimated amplitudes of global sea level change, documenting the relative contributions to sea level made by tectonics, ice sheet fluctuations, and sediment supply
- Provided high-resolution records of the rates of sea level change of >50 mm yr^{-1} in the last 10–15 thousand years following the Last Glacial Maximum
- Showed that Antarctica was largely ice-free before 35–40 million years ago, with development of continental-scale ice sheets starting at 34–35 million years ago
- Documented the major role of the development of the Circum-Antarctic Current system in glaciation and global thermal evolution in the Cenozoic
- Showed that the Arctic Ocean was a semi-restricted warm sea for much of the early Cenozoic, transitioning through the Miocene to become an ice-covered ocean at about 6 million years ago in the "icehouse world" that continues to the present
- Established the sensitivity of monsoons to climate controls, particularly the linkages between the Indian and Asian monsoons to uplift of the Himalayas during the collision of India with Asia
- Recovered the most complete marine records of the Cretaceous/Paleogene mass extinction 66.05 million years ago (infamous for extinction of the non-avian dinosaurs), linking a large asteroid impact and the mass extinction, and showing that life reestablished robust ecosystems in the impact area within 30,000 years of the impact

> "Fifty years of scientific ocean drilling by teams of international partners has provided unparalleled advancements in Earth sciences."

Plate Tectonics and Geodynamics

- Provided early, direct confirmation of seafloor spreading and the theory of plate tectonics
- Nearly four decades later, long-term seismic observatories in scientific ocean drilling holes beneath the seafloor provided the first direct evidence for the age-dependent growth of the oceanic lithosphere—an essential tenet of plate tectonics
- Provided the first thick sequences of intact oceanic crust below thick layers of marine sediment, revealing the complexity of crustal construction processes, and demonstrating that crustal sections generated at slow-spreading, fast-spreading, and thickly sedimented ridges are distinctly different in architecture
- Advanced our understanding of continental breakup, faulting, rifting, and associated magmatism and processes, constraining the timing of the transition from rifting to seafloor spreading
- Showed that mantle plumes that feed volcanic hotspot systems like the Hawaii-Emperor island and seamount chain may not be stationary but can move at rates half those of plate motions, providing direct input into the debate on the geodynamic nature of Earth's mantle
- Sampled oceanic plateaus formed as large igneous provinces (LIPs) by massive Mesozoic volcanism over short periods, documenting links to Mesozoic anoxic events and suggesting links to

changes in convection in the outer core associated with the "Cretaceous Quiet Zone," during which reversals of Earth's magnetic field were very infrequent

- Illuminated fault zone behavior and related tectonic processes at active plate boundaries where Earth's largest earthquakes and tsunamis are generated
- Investigated the nature of and processes active within subduction zones by drilling through the subduction décollement to recover subducted sediments, formation fluid, and the igneous slab, allowing an initial inventory of Earth materials that are recycled into the mantle by subducting plates
- Revealed the presence of one of the world's largest and the most recent "salt giant" deposited in the late Miocene Mediterranean Sea as a result of a temporary closure or restriction of the connection to the Atlantic Ocean during the Messinian Salinity Crisis 5.97–5.33 million years ago

Biosphere and Subseafloor Hydrogeology

- Confirmed that a previously unsampled biosphere exists within sediments as deep as 2.4 km below the seafloor, within aerobic open-ocean sediments under low-energy extremes, and within the volcanic carapace of the oceanic crust
- Enabled development of first-order estimates on the extent and limits of life in the subseafloor environment, demonstrating through borehole observatories that subseafloor microbial communities are dynamic over time and play important biogeochemical roles in elemental cycling
- Revealed significant flows of fluids through virtually all parts of the seafloor, from mid-ocean ridges to deep-sea trenches
- Documented the relationships among fluid circulation and the alteration and aging of the oceanic crust
- Revealed for the first time the internal structure of seafloor massive sulfide deposits
- Successfully sampled subseafloor gas hydrate formations to investigate their role in the carbon cycle, climate, and slope stability
- Recovered deeply sourced (many kilometers) mantle serpentinites in subduction forearc mud volcanoes as well as associated slab-derived fluids with elevated pH, methane, and hydrogen concentrations that support unusual microbial and megafauna biota
- Developed subseafloor borehole hydrological observatory systems with long-term monitoring capabilities that enabled scientists to conduct short- and long-term in situ experiments within Earth's crust, revealing for the first time the actual directions of flow of subseafloor fluids.

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In Memoriam

Walter Munk (1917–2019) and Gustaf Arrhenius (1922–2019)

By Holly Given and Robert Monroe

Two pioneers of scientific ocean drilling, Walter Heinrich Munk and Gustaf Olaf Svante Arrhenius, passed away in February 2019. As colleagues at Scripps Institution of Oceanography, UC San Diego, Munk and Arrhenius both took part in the 1961 feasibility test for Project Mohole aboard the drilling platform *CUSS I* (Figure 1), which marked retrieval of the first cores of oceanic crust aided by the new invention of dynamic positioning.

There are many parallels in the lives of these two men, who were friends and neighbors, as well as colleagues, and who both lived to advanced ages before succumbing to pneumonia within one week of each other. Both were Europeans from privileged backgrounds who were brought to Scripps by famous mentors. Both stayed to build their legacies in the United States amid the heady explosion of science under federally funded research programs that grew from World War II.

Walter Munk was born October 19, 1917, into a wealthy Viennese banking family in the waning days of the Austro-Hungarian Empire. Out of concern over her bon vivant son, Munk's mother sent him to New York in 1932 to learn the banking business from a relative. Bored, Munk drove across the country to study geophysics at Caltech with Beno Gutenberg, and eventually received an invitation to La Jolla from oceanographer Harald Sverdrup, director of Scripps at the time, who became his mentor. Although Munk's scientific bibliography, beginning in the 1940s, firmly characterizes him as a physical oceanographer who occasionally dabbled in whole Earth geophysics, Munk is famous in the scientific ocean drilling community for his proposition at a 1957 meeting of the US National Science Foundation Advisory Panel for Earth Sciences to drill through the oceanic crust to reach Earth's mantle. A committee of the American Miscellaneous Society (AMSOC) began work on the proposal for Project Mohole at a champagne breakfast held on Walter's patio the following month. For a number of reasons, including cost overruns, the project was scuttled before the attempt could be made. Munk later called the evolution of this complex mission "Project No Hole," and said it was one of the main disappointments of his scientific career.

The AMSOC committee set up an Ocean Sediments Drilling Panel in 1962. This effort took hold, growing into the organized scientific ocean drilling programs we recognize today. Walter's involvement with scientific ocean drilling came full circle in 2012 when the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the Sloan Foundation hosted his visit to D/V *Chikyu*, and JAMSTEC Director Asahiko Taira honored him by re-naming the ship's library the Walter Munk Library (Figure 2).

Gustaf Arrhenius was born September 5, 1922, in Stockholm into an aristocratic heritage of explorers and scientists. His maternal grandfather, Gustaf Nordenskiöld, son of the great Swedish explorer Baron Adolf Erik Nordenskiöld, surveyed and cataloged artifacts of the Mesa Verde civilization of Colorado. His paternal grandfather, Nobel laureate

FIGURE 1. (a) From left facing camera: Roger Revelle, Walter Munk, and Gustaf Arrhenius aboard the oil drillship, *CUSS I*, during Project Mohole, 1961. Among participants was John Steinbeck, who covered the test cruise for *Life* magazine. (b) From left: Roger Revelle, Willard Bascom, Gustaf Arrhenius, and Walter Munk aboard *CUSS I* during Project Mohole, 1961. *Photo courtesy of UC San Diego Library*

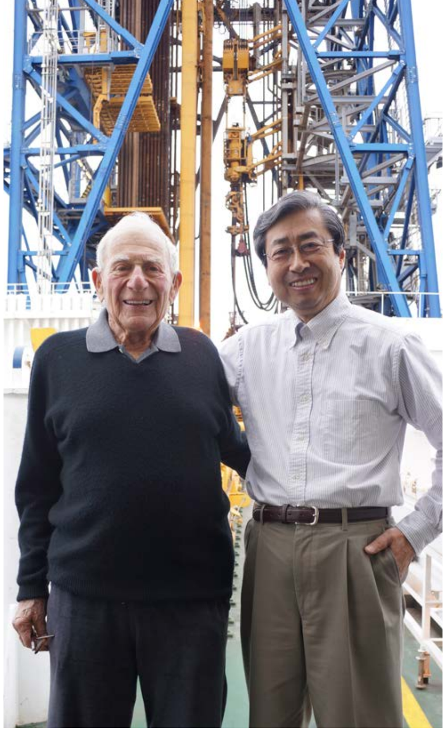

FIGURE 2. Walter Munk with JAMSTEC President Asahiko Taira on the deck of D/V *Chikyu*. *Credit: JAMSTEC*

FIGURE 3. Scientists, including Gustaf Arrhenius (back row, fourth from right) and Walter Munk (seated, second from right) on the fantail of R/V *Spencer F. Baird*, homeward bound from the Capricorn Expedition (1952–1953). Back row (left to right): Richard von Herzen, Roger Revelle, Willard N. Bascom, Theodore Robert Folsom, Alan Churchill Jones, Gustaf Arrhenius, Henri Rotschi, Robert Livingston, Russell Raitt. Seated (left to right): Philip E. Jackson, Richard E. Blumberg, Ronald Mason, Robert Floyd Dill, Arthur E. Maxwell, Winter Davis Horton, Walter Munk, and Helen Raitt. February 1953. *Photo courtesy of UC San Diego Library*

Svante Arrhenius, founded the field of physical chemistry and was the first person to publish—in 1896—on the prospect of anthropogenic global warming caused by industrial CO_2 emissions. Steeped in the family tradition of scientific exploration, Arrhenius signed up for *Albatross*, the legendary 1947–1948 Swedish expedition organized by oceanographer Hans Pettersson that used a new piston coring tool developed by Börge Kullenberg to retrieve the first long cores of ocean sediments from the equatorial Pacific. Because no one place in Sweden had enough laboratory space to process the more than 200 *Albatross* cores, Arrhenius offered his father's laboratory, and the samples became the basis for his PhD thesis. Based on his *Albatross* experience, Arrhenius was invited by Scripps Director Roger Revelle to join the famous 1951–1952 Capricorn Expedition that mapped the Pacific seafloor on the way back from the thermonuclear test in the Marshall Islands (an expedition that also included Munk; see *Oceanography* 17(2), https://doi.org/10.5670/oceanog.2004.53; Figure 3). Arrhenius developed analysis techniques and published extensively on the chemistry of pelagic sediments and interpretations for paleoceanography for almost 20 years before turning his attention to the evolution of the solar system and the origins of life as seen in the geologic record.

Aside from their contributions to scientific ocean drilling, Arrhenius and Munk inspired generations of scientists as visionaries and through their wider dimensions as human beings.

With his connections among the intellectual elite of Europe, Arrhenius was heavily involved in the establishment of UC San Diego in the 1960s. He was asked to lead the search for someone to head the new Literature Department, but was unsuccessful at recruiting novelist Wallace Stegner, because at that time UC San Diego lacked a library.

Building on the school he established with Sverdrup to teach wave height prediction to Navy personnel during World War II, Munk was largely responsible for the enduring ties between Scripps and the Office of Naval Research, and later cultivated a close relationship with geophysicist and philanthropist Cecil Green.

With Jenny de Hevesy Arrhenius, Judith Horton Munk, and Mary Coakley Munk, Gustaf and Walter organized informal intellectual "salons" for visiting scientists and graduate students in their ocean view La Jolla homes. These great men indeed personified the modern golden age of scientific inquiry and expressed what is best about the academic life—yes, the dedication to rigorous scientific inquiry and discovery, but also the intellectual camaraderie, the adventure, the global connections, and the downright fun of it all. They will be missed, but their legacies live on.

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SPOTLIGHT 2. Scientific Ocean Drilling, A Truly International Program

During the first part of the Deep Sea Drilling Project (DSDP), from 1968 to 1975, scientific ocean drilling was led and fully funded by the United States. However, guest scientists from around the world were invited to join *Glomar Challenger*'s 12-person scientific crew, some in co-chief scientist roles. The great success of DSDP led some countries to approach the United States about the possibility of a more formal relationship, and so began the International Phase of Ocean Drilling (IPOD) within DSDP in 1975. The Soviet Union, Germany, Japan, France, and the United Kingdom became partners, and scientists from those and other countries continued to sail on *Glomar Challenger*.

In 1983, DSDP ended and the next phase of ocean drilling, the Ocean Drilling Program (ODP), replaced it in 1985 and continued until 2003. It used the larger and more capable *JOIDES Resolution*, which could carry nearly 30 scientists and an equal number of technicians who oversaw and assisted with initial core analyses in the many sophisticated onboard laboratories. The United States was the dominant funder of the program, but additional funding also came from international members. The United States, Japan, Germany, the United Kingdom, France, and Canada were original regular members. The European Science Foundation Consortium for Ocean Drilling (ECOD) was formed in 1986 and represented Belgium, Denmark, Finland, Iceland, Ireland, Italy, The Netherlands, Norway, Portugal, Spain, Sweden, and Switzerland. In 1988, Canada formed a consortium with Australia, and Korea and Chinese Taipei (Taiwan) joined them in the AusCan consortium in 1997. When it concluded in 2003, ODP had 22 member countries.

In 2003, the Integrated Ocean Drilling Program (IODP) began its 10-year run, with access to more drilling platforms and with more capabilities. An integrated management system for all platforms was provided, and two new core repositories were established in Europe and Japan to complement those long established in the United States. Now the United States, Japan, and Europe were the major players; some 15 European countries plus Canada participated in the self-funded European Consortium for Ocean Research Drilling (ECORD). Associate Members, who joined at different stages, were China, Korea, Australia, India, and Brazil. New Zealand was a member country within the Australia and New Zealand IODP Consortium (ANZIC).

In 2013, a renewed version of IODP, the International Ocean Discovery Program, was established for another 10 years, with the same access to three drilling facilities and core repositories, but no longer with an integrated management system. Each platform provider—the United States, Europe, and Japan—now manages its own program, but the proposal review system remains integrated, assuring a coordinated approach. The same membership generally continued on, and it is widely hoped that when IODP ends in 2023, scientific ocean drilling will evolve into a new equally exciting program, continuing to address global scientific problems for which ocean drilling is an essential tool.

The ongoing internationalization of ocean drilling has added scientific expertise and funding to this hugely successful and globally cutting-edge research program. The international science plans for each phase of activity have changed over time, with new technology and new scientific ideas and capabilities leading to general modification and broadening of the program.

– Neville Exon

Group photo from International Ocean Discovery Program Expedition 371. Tasman Frontier Subduction and Climate. The shipboard scientific party included 11 from the United States and 19 from other countries. *Photo credit: Tim Fulton, IODP JRSO*

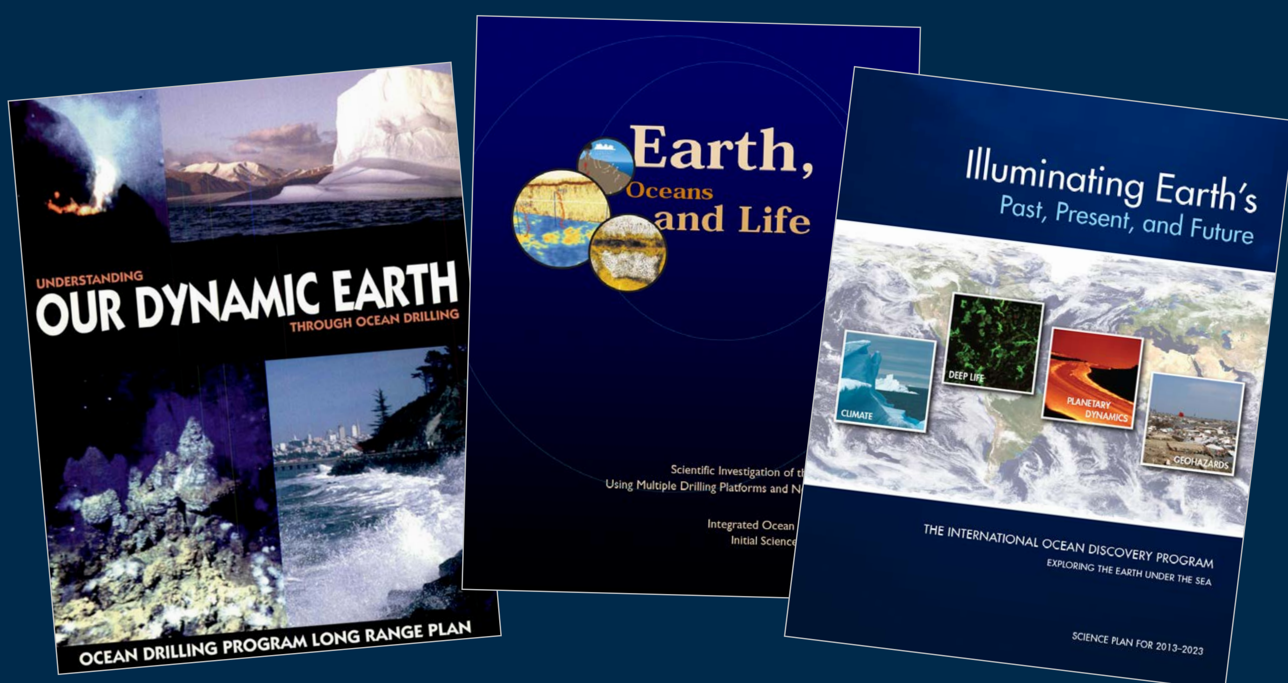
SPOTLIGHT 3. A History of Science Plans

The Deep Sea Drilling Project (DSDP) was foremost exploratory, and science planning was almost ad hoc, yet DSDP legs maximized geographic coverage and resulted in a global array of drill sites. With the advent of the Ocean Drilling Program (ODP), the approach changed toward hypothesis-driven science. New projects were now considered using a peer-review system that evaluated submitted proposals against a science plan. This plan was based on a survey of the international scientific ocean drilling community designed to establish new science themes, challenges, and priorities. From the mid-1980s through 2003, several long-range guiding documents encouraged studies that supported multiple and evolving themes; these included the *Report of the Second Conference on Scientific Ocean Drilling* (1987), *A Record of Our Changing Planet* (1990), and *Understanding Our Dynamic Earth through Ocean Drilling* (1996). Using such documents to guide proposal submission and peer review was deemed highly successful, so the successor program, the Integrated Ocean Drilling Program (IODP), was guided by a new science plan, *Earth, Oceans and Life: Scientific Investigation of the Earth System using Multiple Drilling Platforms and New Technologies, from 2003–2013* (2001). With this plan, the study of microbial life forms in the ocean's substrate became part of the research portfolio, leading to three themes: The Deep Biosphere and Subseafloor Ocean; Environmental Change, Processes, and Effects; and Solid Earth Cycles and Geodynamics.

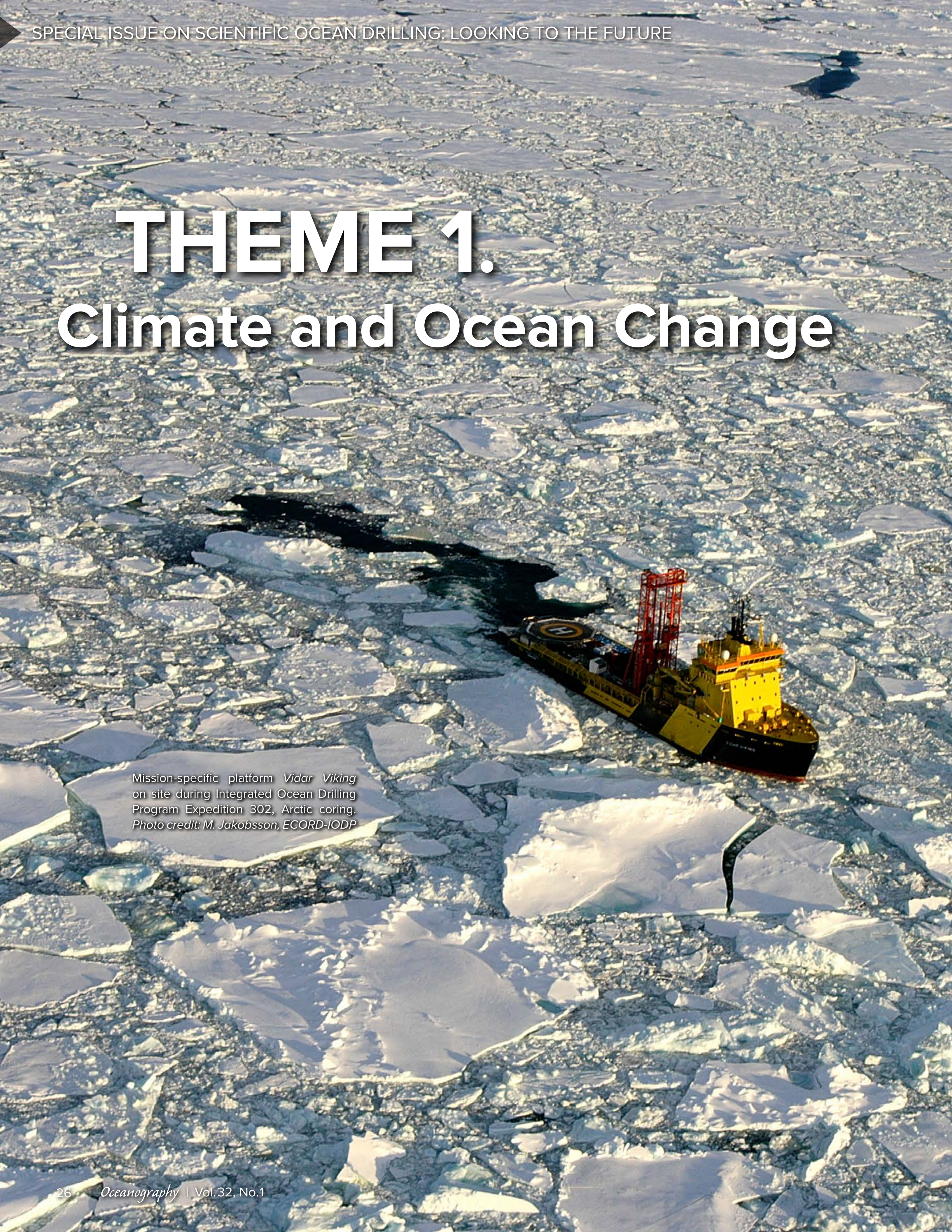
In the second phase of IODP, during the International Ocean Discovery Program, the number of themes grew to include new research avenues toward better understanding of processes and natural hazards on human timescales. The current science plan (2013–2023), *Illuminating Earth's Past, Present and Future*, contains four themes: Climate and Ocean Change, Biosphere Frontiers, Earth Connections, and Earth in Motion.

Beyond 2023, a new or modified science plan is envisioned; planning for that document by the international scientific ocean drilling community is now underway. New research themes and challenges are again being identified, including, for example, a focus on the habitability of Earth and other planetary bodies; integrated research across the shoreline, including both onshore and offshore drilling objectives; the carbon cycle, sequestration and storage; gas hydrates as a resource; freshwater beneath the ocean; landslides; and more.

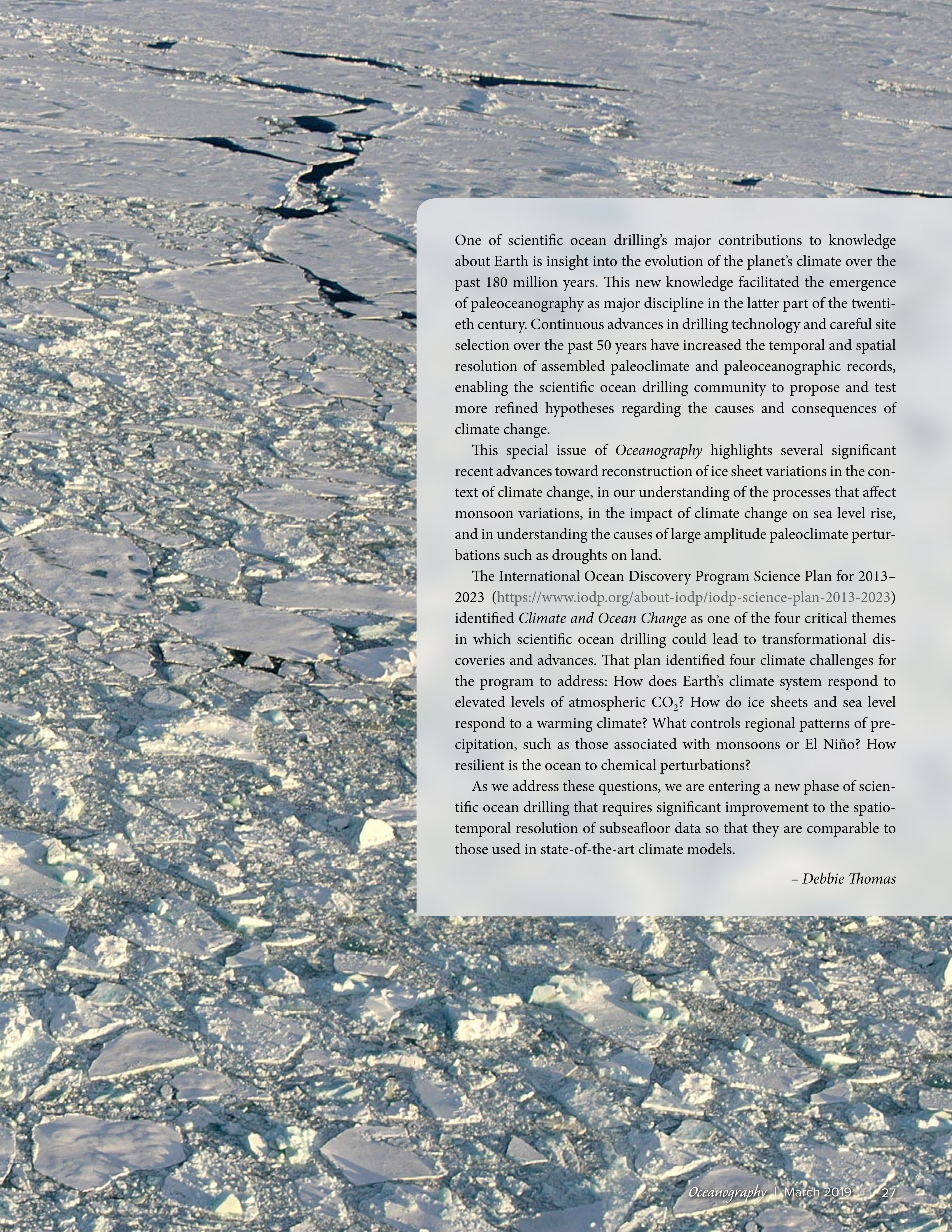
— Anthony A.P. Koppers and James A. Austin Jr.



THEME 1.
Climate and Ocean Change



Mission-specific platform *Vidar Viking* on site during Integrated Ocean Drilling Program Expedition 302, Arctic coring. *Photo credit: M. Jakobsson, ECORD-IODP*



One of scientific ocean drilling's major contributions to knowledge about Earth is insight into the evolution of the planet's climate over the past 180 million years. This new knowledge facilitated the emergence of paleoceanography as major discipline in the latter part of the twentieth century. Continuous advances in drilling technology and careful site selection over the past 50 years have increased the temporal and spatial resolution of assembled paleoclimate and paleoceanographic records, enabling the scientific ocean drilling community to propose and test more refined hypotheses regarding the causes and consequences of climate change.

This special issue of *Oceanography* highlights several significant recent advances toward reconstruction of ice sheet variations in the context of climate change, in our understanding of the processes that affect monsoon variations, in the impact of climate change on sea level rise, and in understanding the causes of large amplitude paleoclimate perturbations such as droughts on land.

The International Ocean Discovery Program Science Plan for 2013–2023 (https://www.iodp.org/about-iodp/iodp-science-plan-2013-2023) identified *Climate and Ocean Change* as one of the four critical themes in which scientific ocean drilling could lead to transformational discoveries and advances. That plan identified four climate challenges for the program to address: How does Earth's climate system respond to elevated levels of atmospheric CO_2? How do ice sheets and sea level respond to a warming climate? What controls regional patterns of precipitation, such as those associated with monsoons or El Niño? How resilient is the ocean to chemical perturbations?

As we address these questions, we are entering a new phase of scientific ocean drilling that requires significant improvement to the spatiotemporal resolution of subseafloor data so that they are comparable to those used in state-of-the-art climate models.

– Debbie Thomas

Reading All the Pages in the Book on Climate History

By Ted Moore and Jan Backman

ABSTRACT. In recent decades, the scientific ocean drilling community has prided itself in being able to achieve the full recovery of hundreds of meters of the sedimentary section through coring, allowing scientists to decipher the history of Earth's climate in its fullest resolution. The Deep Sea Drilling Project, the Ocean Drilling Program, the Integrated Ocean Drilling Program, and the International Ocean Discovery Program provided the impetus for the rapid growth of paleoceanography as a new field of study and contributed significantly to modern-day paleoclimate studies. These new fields are based upon a long progression of technical developments over decades and hundreds of drilling expeditions. Here, we briefly review the technical and coring strategy advances that today allow us to read all the pages in the book on climate history.

THE ISSUE OF CORING SOFT SEDIMENT

At its beginning, the Deep Sea Drilling Project (DSDP) had as its ambitious goal the sampling of deep ocean sediments and upper oceanic crust using state-of-the-art offshore oil drilling technology. However, unlike drilling for oil, where the main objective is to create a hole that extends to a purported reservoir, DSDP had the primary goal of collecting core samples of sediment and rock from subsurface formations. There was one big problem with the standard oil drilling and coring bits: the ratio of the diameter of the bit face to the central opening for the core barrel was about 5 to 1. This meant that in relatively soft sediments, the bit acted like a funnel, rapidly pushing sediments into the core barrel as the drill string descended into the section. After a few sedimentary sections had been continuously cored with the intention of collecting the entire sedimentary section, biostratigraphers noted that most of their biostratigraphic boundaries fell between cores or in the catcher sample at the very base of the core (Moore, 1972). This was clear evidence that the complete core barrel had been quickly filled in the first meter or two of lowering the drill string; subsequently, sediment was simply shoved aside. Something better had to be devised.

DEVELOPMENT OF THE HYDRAULIC PISTON CORER

Toward the end of DSDP, the program's project engineers designed and built a 5 m long piston corer. Using this device, the drill pipe was pressurized, and at a given release pressure, a coring tube was shot out in front of the drill bit into the sediment. This Hydraulic Piston Corer (HPC) brought back a virtually undisturbed sample of sub-bottom sediment (Figure 1). This was a major advance in recovering deep-sea sedimentary sections that permitted observation of detailed changes in the ocean environment. Building on this success, during the

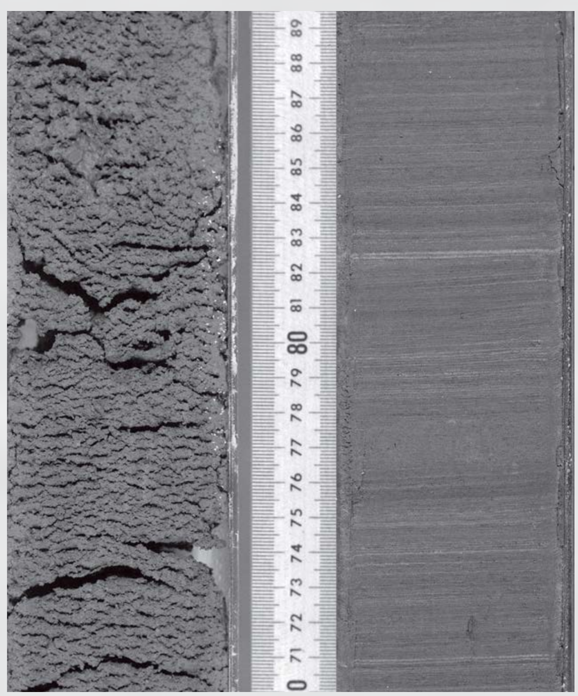
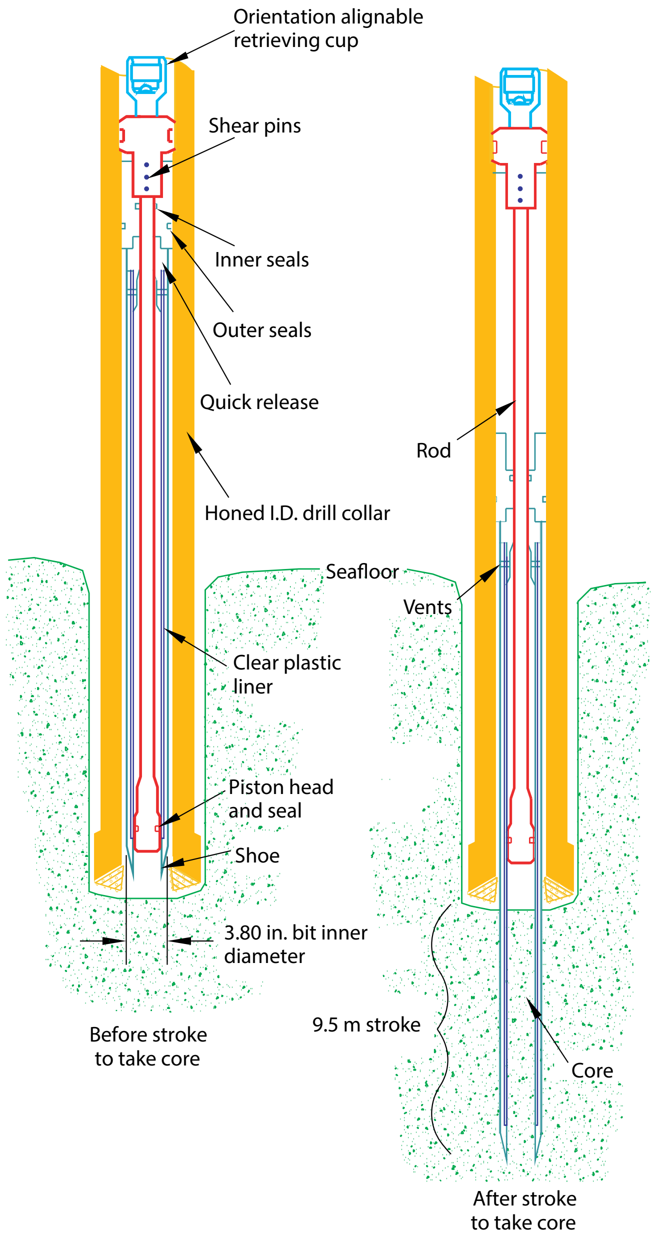


FIGURE 1. Comparison of sediment core quality between rotary drilling and piston coring.

latter days of DSDP and the early days of the Ocean Drilling Program (ODP), engineers improved the HPC design and increased the length of the core barrel to 9 m. This Advanced Piston Corer (APC) is still in use today (Figures 2 and 3). In addition, the newer Extended Core Barrel (XCB) can cut through semi-lithified sediments that are too hard to be cored with the APC (Figure 3). With these new and innovative tools, scientists could be assured of collecting a nearly undisturbed sedimentary section down several hundred meters into the deep-sea blanket of sediments.

ENSURING FULL RECOVERY

But was this recovered section really complete? Cores were taken sequentially in 9 m steps, but suspicious stratigraphers feared that there still might be gaps between cores caused by inaccuracies in positioning the drill string. By coring multiple holes a few tens of meters apart at each site and by offsetting the core intervals in each hole, two things were achieved. First, this practice demonstrated that indeed there were gaps between successive cores, even in continuously cored sections. Second, it allowed the scientists to construct a composite section that was demonstrably complete, based on physical property data. This combination of improvements in hardware and drilling strategy opened the door to the most detailed investigation of paleoceanographic and paleoclimatic changes that the resolution of the sediment itself would allow.



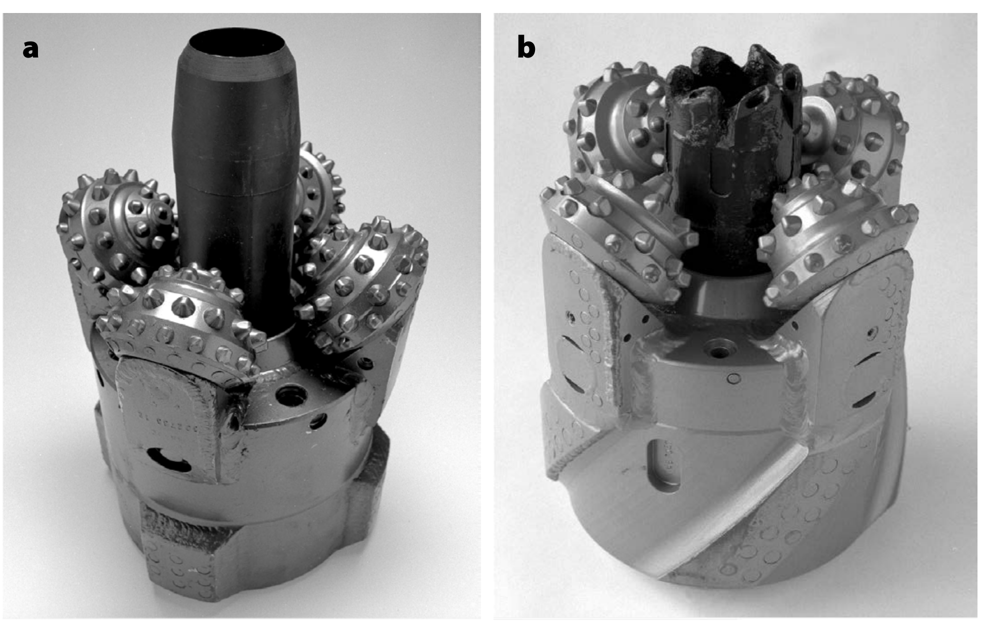


FIGURE 2 (above). Schematic of the Advanced Piston Corer (APC) before and after stroking out the inner core barrel to take a core. Pump pressure inside the drill string severs the shear pins and allows the inner core barrel to stroke out 9.5 m in 2–3 seconds with ~27,000 lb of force.

FIGURE 3 (left). (a) APC piston shoe extending through APC/Extended Core Barrel (XCB) drillbit. (b) XCB cutting shoe extending through APC/XCB drillbit.

ACHIEVING ORBITAL TUNING

During this time of improvements in section recovery, there were parallel improvements in continuous logging of the physical and chemical properties of the recovered sediments, revealing the often pervasive cyclicity that could be correlated not only from hole to hole, but also from site to site within large regions of the ocean. Once tied to a robust biostratigraphy and a paleomagnetic timescale, these cycles were found to have concentrations of variance (spectral power) at frequencies very close to the Milankovitch orbital frequencies. Scientists then used this concordance to "tune" cyclic sedimentary records to the calculated orbital frequencies (Shackleton et al., 1995). The result is a chronostratigraphy that allows us to compare the rates of environmental change in 30 million year old sediments with the same precision as in 3 million year old sediments, something unheard of when we depended solely on interpolations and extrapolations of biomagnetostratigraphic data. The cyclostratigraphic "tuning" approach provides independent age estimates that do not rely on linear interpolation within single geomagnetic chrons (Hays et al., 1976).

RESULTING SCIENTIFIC ACHIEVEMENTS

These tools and techniques, when paired with our growing ability to decipher the nature of changes in the ocean environment, have led to a steadily increasing understanding of these changes. With multiple measurements on the core samples that approximate ocean productivity, seawater temperature, bottom water source area, the chemical "age" of bottom waters, and the changing biogeography of the ocean's flora and fauna, we have learned:

- How major changes in ocean gateways have affected ocean environments and global climate
- How the meridional overturning of the ocean has varied with time
- How the links between tectonics, ocean chemistry, and atmospheric CO_2 have driven our climate system
- How the cyclic changes in the ocean environment give evidence of the feedback processes between the ocean and the atmosphere
- How some large changes in the global climate system can occur very rapidly (e.g., the Paleocene-Eocene Thermal Maximum and the Eocene-Oligocene transition)

Initiation of the Integrated Ocean Drilling Program (IODP) brought scientists the ability to sample new regions of the oceanic environment. In addition to deep drilling, the use of specialized, mission-specific drilling platforms allows us to sample sedimentary records in shallow, nearshore areas and in ice-covered polar oceans. The former represents a dynamic region of the ocean where biologic productivity is high (and highly variable), where chemical and physical exchanges between the land and the ocean occur, and where changes in sea level have the largest environmental impact. The ice-covered oceans, particularly the Arctic Ocean as the only true polar ocean, remain mysterious. Today's climate conditions in both high southern and northern latitude regions are changing rapidly, and scientific ocean drilling in both these areas have clearly shown that Earth's climate was radically different over the past millions of years.

LOOKING INTO THE FUTURE AND GAPS IN OUR KNOWLEDGE

Now that we are able to obtain complete, undisturbed sections of marine sedimentary records from nearly all ocean areas, we are well on the way to understanding the broad outlines of ocean history for at least the last 100 million years (Zachos et al., 2001). In addition, we also are able to delve into the details of how sudden cataclysmic changes (e.g., the Cretaceous-Paleogene bolide impact; see Lowery et al., 2019, in this issue) as well short-term cyclic changes (e.g., the multiple Eocene hyperthermals) affect the ocean environment and, in turn, global climate. There are still key regions of the ocean basins that have yet to be adequately sampled and studied. Certainly, the Arctic and Southern Oceans are such areas. Understanding the history of continental ice sheets is another allied area. There is also a need for a better understanding of the role of intermediate ocean waters. These are the source waters for both coastal and equatorial upwelling, yet their history and origins have yet to be fully documented. Detailed study of these waters would involve coring the shallow oceanic plateaus and rises (e.g., Manihiki, Magellan, Rio Grande) that contain records of late Mesozoic as well as Cenozoic paleoclimate. As we bring to light any further details of the marine record, we can hope to better understand how the ocean-atmosphere climate system works now, how it has worked in the past, and how the system might change in the future.

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SPOTLIGHT 4. *JOIDES Resolution*

The riserless *JOIDES Resolution* (JR) is currently one of three scientific drilling platforms used by the International Ocean Discovery Program (IODP). It was the sole drilling vessel for the Ocean Drilling Program (ODP) and was later used, along with the Japanese drilling vessel *Chikyu* and other mission-specific drilling platforms, throughout the Integrated Ocean Drilling Program.

The JR was first launched in 1978 as Sedco/BP 471, a petroleum exploration vessel, and then converted for scientific ocean drilling to begin operations for ODP in January 1985. The ship was modernized during 2007–2008 and returned to active service in February 2009 following extensive renovation of laboratory facilities and quarters. The *JOIDES Resolution* Science Operator at Texas A&M University operates the JR on behalf of the US National Science Foundation as a research facility for IODP.

The JR employs continuous wireline coring and logging techniques to recover cores and geophysical data from beneath the seafloor. The ship operates in water depths between 76 m and nominally 5,800 m, and drilling has penetrated a maximum depth of just over 2,100 m beneath the seafloor. The longest drill string deployment was 6,919 m in 5,724 m water depth. To date, the JR has recovered more than 342 km of core (see table).

The JR is outfitted with analytical equipment, software, and databases, with an emphasis on instrumentation that captures safety data and ephemeral properties and allows intelligent drilling decisions at sea along with characterization of the core for future investigators. The laboratory space includes facilities for visually describing core at macro- and microscales; microscopes for petrological sediment analysis and biostratigraphic assessment; instrumentation for measuring physical properties, paleomagnetism, and the geochemistry of pore waters, sediment, and rocks; and equipment for cutting and sectioning samples from rock and sediment cores. The downhole measurements laboratory provides an area for obtaining in situ records of subseafloor formation properties that range from borehole well logs to formation temperature and pressure.

ODP (1985–2003) included 111 expeditions with the JR operating at 669 sites. During the Integrated Ocean Drilling Program (2003–2013), there were 35 expeditions and drilling at 145 sites. To date, IODP (which began in 2014) has logged 22 expeditions with 106 sites drilled, and 12 expeditions have already been scheduled into 2021. In addition to conducting scientific coring and logging operations, long-term borehole monitoring began with the installation of a broadband seismometer in Hole 794D in 1989. Subsequently, more than 30 long-term borehole observatories, ranging from simple to complex, have been installed.

– Mitch Malone and Brad Clement

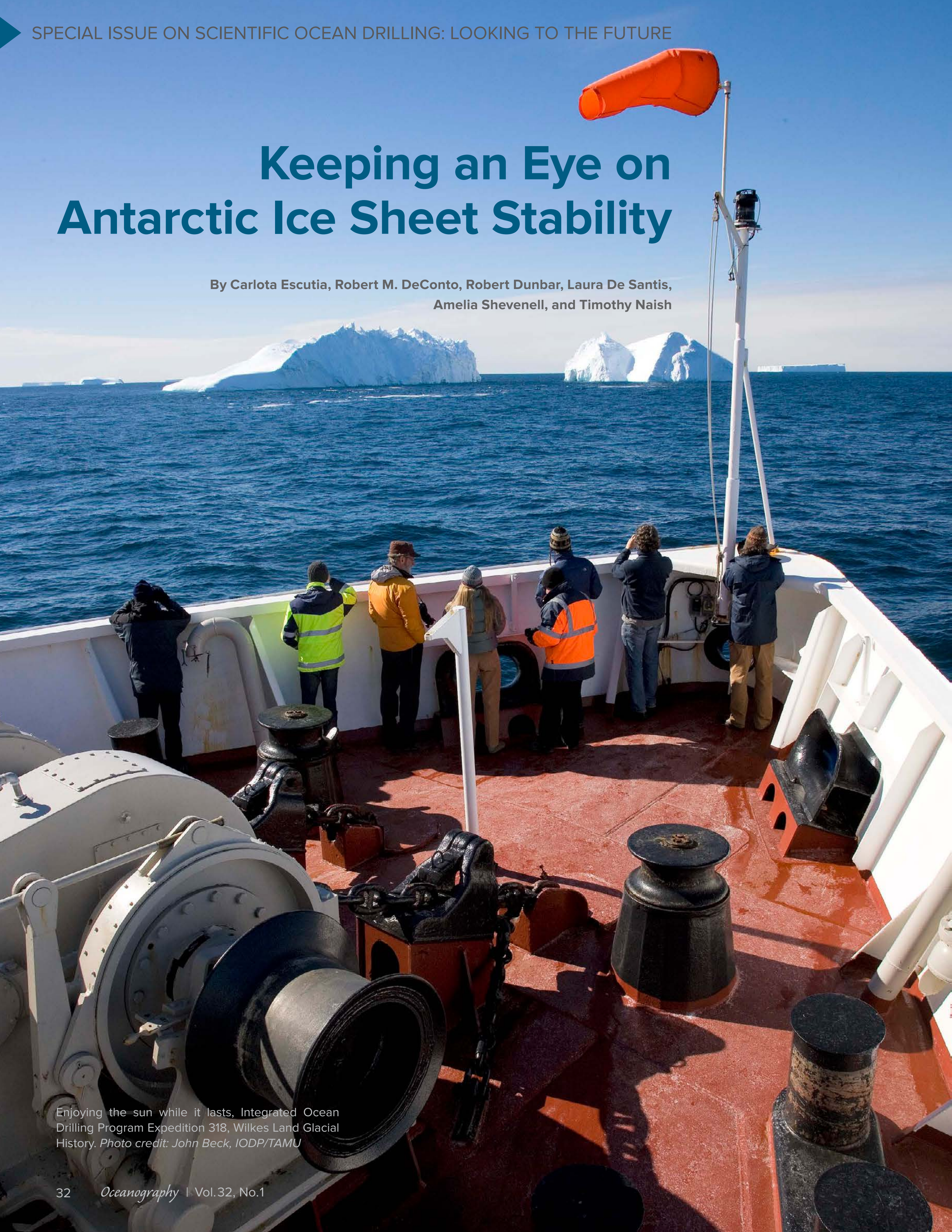
JOIDES RESOLUTION STATISTICS

	Ocean Drilling Program (1985–2003)	Integrated Ocean Drilling Program (2003–2013)	International Ocean Discovery Program (2013–Present*)	Totals
Expeditions	111	31	22	**164**
Operational Days	6,591	1,836	947	**9,374**
Distance Traveled (nmi)	355,781	126,889	62,054	**544,724**
Sites	669	145	106	**920**
Holes	1,797	439	304	**2,540**
Cores	35,772	8,491	8,125	**52,388**
Core Recovery (m)	222,704	57,289	62,054	**342,047**
Shallowest Water (m)	38	96	87	
Deepest Water (m)	5,980	4,479	4,858	
Deepest Hole (m)	2,111	1,928	1,806	
Northernmost Site	80.5°N	67°N	32.4°N	
Southernmost Site	70.8°S	66.4°S	76.6°S	
Most Sediment Recovered on a Single Expedition (m)	8,003	6,135	6,956	
Most Basement Recovered on a Single Expedition (m)	866	799	469	

* stats through May 2018 (Expedition 376)

Keeping an Eye on Antarctic Ice Sheet Stability

By Carlota Escutia, Robert M. DeConto, Robert Dunbar, Laura De Santis, Amelia Shevenell, and Timothy Naish



Enjoying the sun while it lasts, Integrated Ocean Drilling Program Expedition 318, Wilkes Land Glacial History. *Photo credit: John Beck, IODP/TAMU*

ABSTRACT. Knowledge of how the Antarctic Ice Sheet (AIS) responded in the geologic past to warming climates will provide powerful insight into its poorly understood role in future global sea level change. Study of past natural climate changes allows us to determine the sensitivity of the AIS to higher-than-present atmospheric carbon dioxide (CO_2) concentrations and global temperatures, thereby providing the opportunity to improve the skill and performance of ice sheet models used for Intergovernmental Panel on Climate Change (IPCC) future projections.

Antarctic and Southern Ocean (south of 60°S latitude) marine sediment records obtained over the last 50 years by seven scientific ocean drilling expeditions have revolutionized our understanding of Earth's climate system and the evolution and dynamics of the Antarctic ice sheets through the Cenozoic (0–65 million years ago). These records document an ice-free subtropical Antarctica between ~52 and 40 million years ago when CO_2 was ~1,000 ppm; the initiation of continental-scale Antarctic ice sheets ~34 million years ago as CO_2 dropped below 800 ppm; evidence for a dynamic, largely terrestrial, ice sheet driving global sea level changes of up to 40 m amplitude between 34 and 15 million years ago; and colder periods of highly dynamic, marine-based ice sheets contributing up to 20 m of global sea level rise when CO_2 levels were in the range of 500–300 ppm between ~14 and 3 million years ago.

Notwithstanding these discoveries, paleoenvironmental records obtained around Antarctica are still limited in their geographical coverage and do not provide a basis for comprehensive understanding of how different sectors of Antarctica respond to climate perturbations. Transects of drill cores spanning ice-proximal to ice-distal environments across the continental margin and at sensitive locations that have been identified by models and recent observations are needed to fully understand temporal and spatial ice volume changes that result from complex ice sheet-ocean-atmosphere interactions. These records are also critical for reconstructing equator-to-pole temperature gradients through time to better understand global climate change, interhemispheric long-distance transmission of changes through the atmosphere and ocean (teleconnections), and the amplification of climate signals in the polar regions.

Future Antarctic scientific ocean drilling will remain key to obtaining records of past Antarctic Ice Sheet dynamics that can be integrated into coupled ice sheet-climate models for improved projections of sea level change. Thus, keeping an eye on ice sheet stability is critical for improving the accuracy and precision of predictions of future changes in global and regional temperatures and sea level rise.

INTRODUCTION

The Antarctic cryosphere and the Southern Ocean are key components of Earth's climate system. By influencing Earth's average albedo, sea ice extent, atmospheric and oceanic circulation, marine nutrient distribution, and global sea level, the growth and decay of Antarctic ice sheets plays an important role in regional and global climate. Moreover, it has been estimated that the full melting of all Antarctic ice has a sea level equivalent (SLE) of ~58 m (Fretwell et al., 2013). Despite the critical role of Antarctica and the Southern Ocean in the global climate system, our understanding of ice-ocean-atmosphere interactions that control the dynamics and stability of the ice sheets is still rudimentary, lacking in fundamental knowledge required for confident predictions of future change. To improve understanding of the role Antarctica and the Southern Ocean play in Earth's climate system and global sea level, it is essential to have a more complete understanding of the region's past climate variability, the ensuing responses of the ice sheet, and the hemispheric and global consequences. However, key geological and geophysical data from the Antarctic region have not yet been obtained due in part to the remoteness and inaccessibility of the Antarctic continent. Also, because Antarctica's massive ice sheets cover all but 0.18% of the continent, terrestrial records, which provide valuable snapshots into past climate conditions and ice sheet dynamics, are geographically sparse, difficult to obtain, and also problematic as they lack accurate age controls.

Scientific ocean drilling of the more accessible marine sedimentary archives around the Antarctic continental margin has revolutionized our understanding of Earth's climate system through the Cenozoic (0–65 million years ago [Ma]). These sediment cores illuminate an ancient history in which Antarctica was subtropical and ice-free, allow determination of the onset of the continental-scale Antarctic ice sheets, provide long detailed orbitally paced records of ice advances and retreats, and offer insight into the ice sheets' stability thresholds and contributions to global sea level. This knowledge has been acquired by seven scientific ocean drilling expeditions conducted south of 60°S latitude since the Deep Sea Drilling Project (DSDP) began operations in 1968 (Figure 1). In addition, valuable coastal and marine sedimentary sections from the Ross Sea, the Antarctic Peninsula, and the Amundsen Sea regions (Figure 1) have been recovered by other scientific ocean drilling programs (i.e., the international Cenozoic Investigation in the Western Ross Sea [CIROS] project, the Cape Roberts Project [CRP], the ANtarctic geological DRILLing [ANDRILL] project, the US SHALlow DRILling [SHALDRIL] project, and work with the German Meeresboden-Bohrgerät [MeBo] drilling rig). However, even taken together, existing drill core coverage remains extremely sparse relative to the large size of the Antarctic continent (i.e., 14 million square kilometers, about twice the size of Australia) and the geological complexity of Antarctica and its ice sheets. Most drill sites track either ice-proximal (coastal/shelf) or ice-distal conditions, but rarely both, and many sectors of the Antarctic margin have yet to be drilled (Figure 1). As a result, critical questions regarding

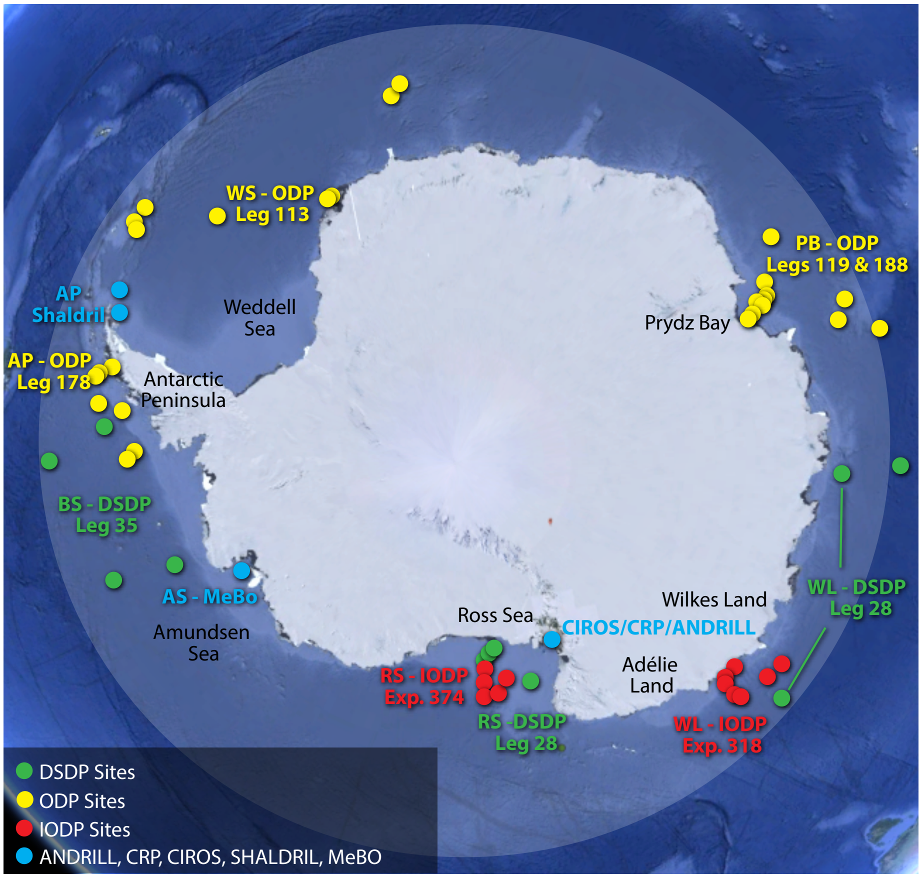


FIGURE 1. Map showing the drill site locations of the seven scientific ocean drilling expeditions (DSDP/ODP/IODP) undertaken around Antarctica and the Southern Ocean south of 60°S (within the lighter shaded circle) since 1973. Also indicated are the locations of expeditions by other scientific drilling programs (blue dots): the international Cenozoic history of the Ross Sea (CIROS) Project, Cape Roberts Project (CRP), and ANDRILL Programs, all in the Ross Sea; the US SHALDRIL program around the Antarctic Peninsula (AP); and the German MeBo drilling in the Admunsen Sea (AS). Deep Sea Drilling Project (DSDP) sites appear in green, Ocean Drilling Program (ODP) sites in yellow, and Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) sites in red. WL = Wilkes Land. RS = Ross Sea. PB = Prydz Bay. BS = Bellinghausen Sea. WS = Weddell Sea.

the nature, cause, timing, and rate of processes involved in the growth and decay of the Antarctic Ice Sheet (AIS) remain.

Significant gaps persist in our knowledge of past climate, ocean, and ice sheet dynamics over a variety of timescales. Ice core records of Earth's past atmospheric characteristics are one of the most valuable climate recorders, revealing that carbon dioxide levels today are the highest over the last 800,000 years. Ice-proximal marine sedimentary records are needed to provide paleoclimate and ice sheet dynamics records that overlap the ice core records, but then extend back millions of years, to times when temperatures and CO_2 concentrations were like those projected by the IPCC (2014) within this century and beyond. Future Antarctic scientific ocean drilling will remain key to obtaining records of past Antarctic ice sheet dynamics that can be integrated into coupled ice sheet-climate models. Both improving and expanding those models is critical for improving the accuracy and precision of predictions of future changes in global and regional temperatures and sea level rise.

MARINE RECORDS OF ANTARCTIC ICE SHEET HISTORY AND DYNAMICS

Prior to the first scientific ocean drilling of the Antarctic continental margin in 1973, the prevailing hypothesis was that Antarctica had glaciated at the onset of the Pleistocene (~2.6 Ma). In 1973, DSDP Leg 28 accomplished the first scientific ocean drilling in two areas of the Antarctic margin, the Wilkes Land abyssal plain and the Ross Sea continental margin (Figure 1). Leg 28 provided the first physical evidence for glaciation extending back at least to the late Oligocene (~25 Ma; Hayes et al., 1975). Sediments also recorded an increase in ice volume around 14 Ma, interpreted to represent the development of a largely stable East Antarctic Ice Sheet (EAIS; Kennett et al., 1975; Kennett and Shackleton, 1975).

The oxygen isotope ($\delta^{18}O$) record of foraminifers from sediments collected in the southwest Pacific (about 48°–52°S) during DSDP Leg 29 indicated that mean annual temperatures at these latitudes were near freezing in the early Oligocene, conditions under which Antarctic glaciers would descend to sea level and sea ice would expand (Shackleton and Kennett, 1975). This led to the hypothesis that the tectonic separation of South America and Australia from Antarctica resulted in the development of the Antarctic Circumpolar Current (ACC), which thermally isolated Antarctica and encouraged ice sheet development (Kennett, 1977). This hypothesis remained the leading paradigm for Antarctic ice growth until ice sheet numerical model simulations revealed that a threshold in declining atmospheric CO_2 concentrations may have exerted a larger first-order control on Antarctica's ice sheets (DeConto and Pollard, 2003).

After 1973, 13 years passed before the successor to DSDP, the Ocean Drilling Program (ODP; 1983–2003), returned to Antarctica for drilling during Legs 113 and 119 in the Weddell Sea and Prydz Bay, respectively. The goal of these legs was to determine Antarctica's glacial history in different sectors of the continent. The Antarctic Earth science drilling community quickly realized that remoteness and challenging weather and ice conditions around the continent, coupled with proposal pressure to drill in other areas of the globe, placed scientific drilling in

Antarctica on a long time cycle, with several decade(s) between major drilling programs. This infrequency in Antarctic research campaigns has impeded the timely acquisition of new knowledge about the initiation, evolution, and stability of the Antarctic ice sheets and related sea level changes. In fact, most knowledge of ice sheet and sea level history came from indirect ice volume and temperature estimates derived from lower latitude foraminifer isotopic stratigraphy and sea level reconstructions from low-latitude passive continental margins (e.g., Zachos et al., 2001a; Miller et al., 2012). To address the limitations associated with inferences from far-field data sets, the Antarctic science community, guided by ice sheet models and existing direct records from the Antarctic margin, has been developing and promoting coordinated plans for drilling around the Antarctic margin since the 1990s.

The first coordinated set of drilling proposals under SCAR-ANTOSTRAT (Scientific Committee for Antarctic Research-Antarctic Offshore Seismic Stratigraphy) aimed to derive the history of the ice sheet and to understand terrigenous sediment glacial transport and deposition under a glacial regime (Barker et al., 1998). ANTOSTRAT brought together research groups responsible for collecting offshore geological and geophysical data to collaborate in studies of Cenozoic paleoenvironments and to promote scientific ocean drilling around Antarctica (Cooper and Webb, 1992). ANTOSTRAT followed the Madrid Protocol on Antarctic Environmental Protection to the Antarctic Treaty (ATCM, Antarctic Treaty System, 1991), which established a 50-year moratorium on resource exploration and exploitation. Under the auspices of the ATCM (Recommendation XVI-12), the Antarctic Seismic Data Library System (SDLS) for Cooperative Research was formalized as a model for collaboration and equitable sharing of Antarctic multichannel seismic reflection data for geoscience studies.

The ANTOSTRAT project, with crucial SDLS support, established the groundwork for circum-Antarctic seismic, drilling, and rock coring programs designed to decipher Antarctica's tectonic, stratigraphic, and climate histories. Using data from the SDLS, scientists involved in the ANTOSTRAT project developed a strategy for drilling continental shelf-to-rise transects at key sites around Antarctica based on data from numerical models of ice sheet behavior (e.g., Huybrechts, 1993; Barker et al., 1998). The strategy required direct sampling of both continental shelf sediments and the more continuous and easily age-dated sediments of the continental rise (Figure 2). Shelf sediments are typically discontinuous and harder to date because of erosion by the advances and retreats of the ice sheet across the shelf as well as issues regarding recovery of glacial deposits during drilling. Nevertheless, preserved shelf sediments are the only direct records of variability in the extent of the ice sheet, because they can reveal the grounding line (or maximum extent of) ice sheet advances and retreats. Continental shelf records can be coupled with less direct but more continuous and better-dated continental rise records of glacial-interglacial cycles and related paleoceanographic changes (Figure 2). Data from the two types of settings can be then combined and used for providing new scientific ocean drilling targets through numerical ice sheet models. Of the five key regions identified by ANTOSTRAT (Barker et al., 1998), two were drilled during ODP Legs 178 and 188 west of the Antarctic Peninsula and in Prydz Bay, respectively (Figure 1).

Between 2000, when ODP Leg 188 drilled in Prydz Bay, and 2010, when Integrated Ocean Drilling Program (IODP) Expedition 318 drilled along the Wilkes Land margin, scientific priorities within the Antarctic community had evolved under the umbrella of two SCAR research programs that succeeded ANTOSTRAT: the international Antarctic Climate Evolution (ACE) and the Past Antarctic Ice Sheet (PAIS) programs. With these two new programs, scientists sought to advance confidence

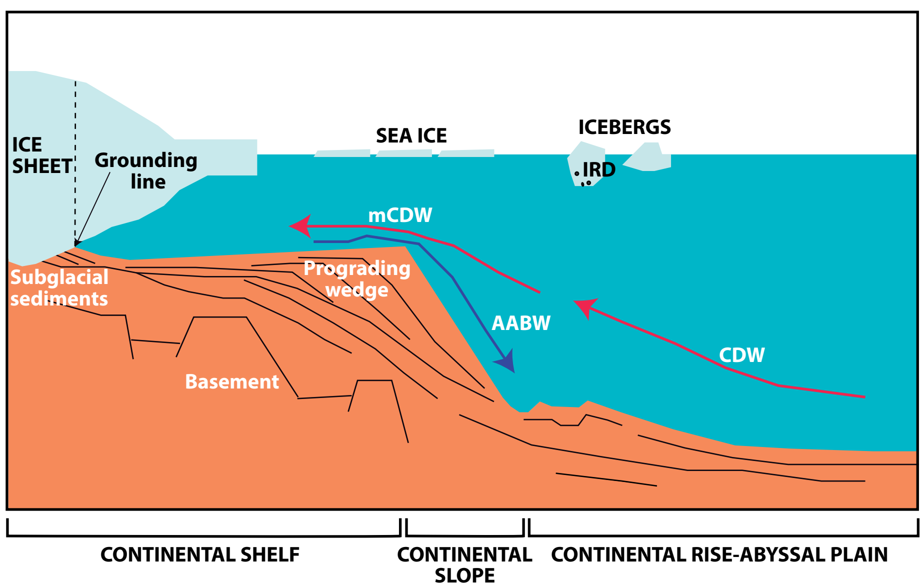


FIGURE 2. Conceptual cross section across the Antarctic margin. Subglacial to ice-proximal (coastal-shelf) to ice-distal depositional environments that contain the sedimentary record of past ice sheet dynamics result from changing atmosphere-ice sheet-ocean interactions. The figure also shows various components of a polar margin referred to in the text (i.e., grounding line, subglacial sediments, etc.). Oceanic processes in this sketch represent a two-dimensional snapshot showing enhanced modified Circumpolar Deep Water (mCDW) intrusion across the continental shelf. However, intrusion positions shift with the positions of the westerlies during glacial and interglacial cycles. AABW = Antarctic Bottom Water. IRD = Ice-rafted debris.

in predictions of ice sheet and sea level responses to future climate and ocean warming by improving understanding of the sensitivity of the Antarctic ice sheets to a broad range of past climatic and oceanic conditions. Both programs highlighted the need to integrate geological reconstructions of past ice sheet behavior with numerical ice sheet modeling. Consequently, drilling programs were designed to target areas of the Antarctic margin shown by the models to be most sensitive to climate change, in most cases, in areas where the ice sheet is grounded on land that lies below sea level (i.e., marine-based; Figure 3). These drilling programs targeted study of specific intervals and events, including past "greenhouse" climates warmer than today, and more recent episodes of warming and ice sheet retreat during glacial terminations. In addition, programs were developed to collect cores along depth and latitudinal transects to provide information about ice sheet-ocean interactions, which play a critical role in the current ice sheet mass imbalance (e.g., Shepherd et al., 2018; Rignot et al., 2019). A coordinated plan was developed to expand the existing core coverage with near-coastal drill targets complementing existing deep-water sites, and vice versa, and with the goal of targeting unsampled areas of the Antarctic margin. IODP Expedition 318 (January–March 2010) drilled one unexplored margin of East Antarctica, the eastern Wilkes-Adélie Land (Escutia et al., 2011, 2014). Eight years later, this expedition was followed by International Ocean Discovery Program (IODP) Expedition 374 (January–March 2018) to the Ross Sea (McKay et al., 2018). Two additional drilling expeditions are being carried out in early 2019 to increase drilling coverage of the Antarctic continental margins, IODP Expedition 379 to the Amundsen Sea and IODP Expedition 382 to the Scotia Sea (Figures 1 and 4).

Geological records obtained by scientific ocean drilling around the Antarctic continental margin have been key for providing boundary conditions and simulation targets, albeit localized, that greatly help calibration of the ice sheet models used to simulate future Antarctic contributions to global mean sea level for IPCC representative concentration pathways (Golledge et al., 2015; DeConto and Pollard, 2016). It is beyond the scope of this paper to outline in detail the findings of each one of the scientific ocean drilling expeditions in Antarctica; instead, we highlight some of the most relevant advances and contributions to our knowledge of greenhouse conditions, past Antarctic ice sheet dynamics and stability, and their relations to oceanographic and sea level changes.

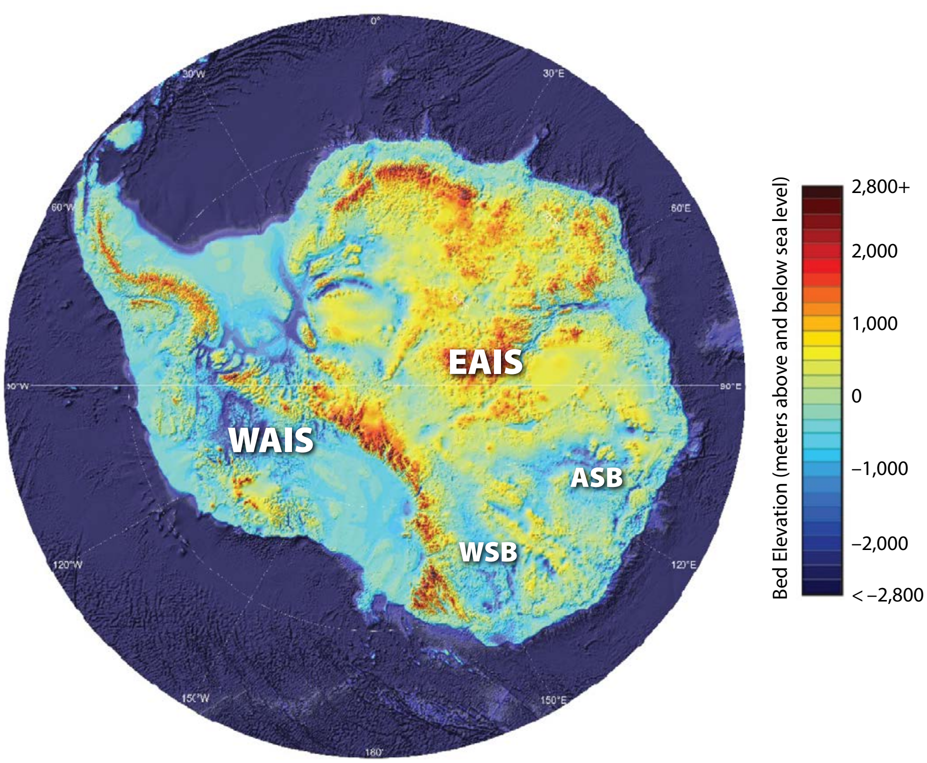


FIGURE 3. A BEDMAP 2 image, representing ice bed, surface, and thickness data sets, shows the locations where the bedrock on which the West Antarctic Ice Sheet (WAIS) and East Antarctic Ice Sheet (EAIS) rest is well below sea level. Two major subglacial basins referred to in the text are also labeled: the Wilkes Subglacial Basin (WSB) and the Aurora Subglacial Basin (ASB). *Modified from Fretwell et al. (2013)*

ADVANCES IN OUR KNOWLEDGE OF ANTARCTIC ICE SHEET DYNAMICS

Eocene Peak Greenhouse Conditions and Climate Deterioration

The warmest global climates of the past 65 million years occurred during the early Eocene epoch (about 56–4 Ma). Atmospheric carbon dioxide levels were in excess of one thousand parts per million by volume (>1,000 ppmv), which is within the range of IPCC projections for Earth's atmosphere over the next several centuries (Foster et al., 2017; Figure 5). Geological data from this period are therefore relevant to the response of Earth's ice sheets, climate, and biosphere to the high atmospheric carbon dioxide levels that are expected with unabated anthropogenic warming. However, these early Paleogene analogues of future climates are not necessarily straightforward comparisons, because climate system boundary conditions (e.g., plate tectonic configurations, ocean circulation) in addition to CO_2 have changed.

Sediments recovered in the Weddell Sea during ODP Leg 113 (December 1986 to March 1987) record cool subtropical climates, with average surface and deepwater temperatures between 16°C and 9°C in the early Eocene (Stott et al., 1990; Kennett and Stott, 1990). More than two decades later, biotic indicators (pollen, spores) and organic geochemical paleothermometers (bacterial branched tetraether lipids employed to indicate terrestrial paleotemperature) in sediments obtained during IODP Expedition 318 on the Wilkes-Adélie Land margin have yielded continental temperature reconstructions for this sector of the east Antarctic margin during peak greenhouse conditions ~55 Ma (Pross et al., 2012; Contreras et al., 2013). These temperatures suggest cold monthly mean temperatures >10°C, with the coldest estimates from organic geochemical paleothermometers of 24°–27°C. Paleogeographic reconstructions show the Wilkes Land coast to be already positioned at a high paleolatitude of about 70°S during the early Eocene (Pross et al., 2012). The recorded temperatures therefore suggested dramatically greater high-latitude warming than previously simulated by models of the Eocene greenhouse climates. These findings required additional modeling to identify the forcing and feedback mechanisms needed to maintain the higher degree and range of temperatures reconstructed from these sedimentary proxy records. Reconciliation of the mismatch between model and data temperature estimates requires some combination of very strong radiative forcing during the Eocene compared with modern conditions and/or enhanced climate sensitivity due to strong positive feedbacks (Caballero and Huber, 2013).

A 20 million year cooling trend followed the Early Eocene Climatic Optimum (Figure 5). In the Weddell Sea, ocean temperatures cooled from around 20°C to 8°C by the middle Eocene (45 Ma; Stott et al., 1990; Kennett and Stott, 1990). In Prydz Bay, cool environments were reported from shelf sediments recovered by ODP Leg 188 (Cooper et al., 2004). Along the Wilkes-Adélie Land margin, biotic indicators in sediments record a change to a temperate rainforest biome, implying a decline of around 2°–3°C in temperature from the early to the middle Eocene, with organic geochemical paleotemperature proxies suggesting the coolest temperatures to range from 17°–20°C (Pross et al., 2012; Contreras et al., 2013). This cooling has been postulated to coincide with cold waters from the Ross Sea Gyre flowing through the incipient opening of the southern Tasman Gateway, implying that the tectonic opening of this gateway provided a mechanism for cooling along the eastern Wilkes-Adélie Land margin following the Early Eocene Climatic Optimum (Bijl et al., 2013). These results imply that although atmospheric CO_2 forcing alone might provide uniform middle Eocene cooling, the early opening of the Tasman Gateway is more consistent with Southern Ocean surface water and global deep ocean cooling in the apparent absence of (sub-) equatorial cooling (Bijl et al., 2013).

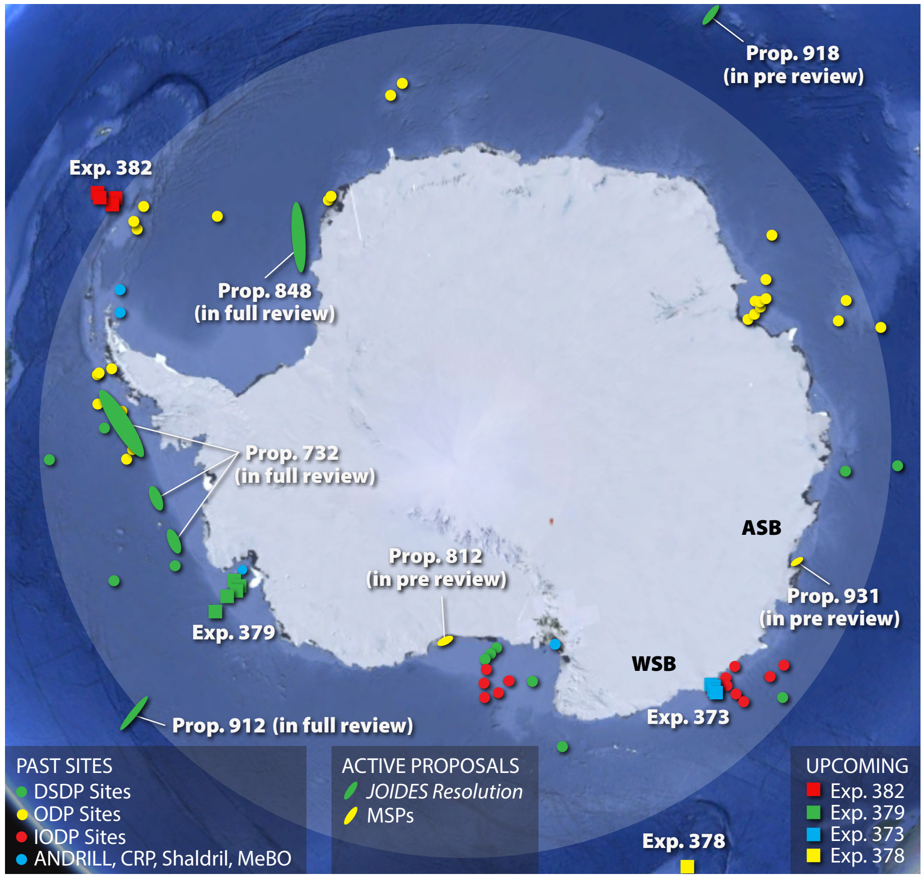


FIGURE 4. Past and future scientific ocean drilling sites around Antarctica. Past sites are marked by colored circles. Green ellipses are regions targeted in active proposals to be drilled with *JOIDES Resolution*, and yellow ellipses indicate regions targeted to be drilled with mission-specific platforms (MSP); three proposals are in "pre" review and three are in "full" review. Scheduled expeditions are marked by colored squares: Expedition 379-Amundsen Sea (green, JOIDES Resolution), Expedition 382-Iceberg Alley (red, JOIDES Resolution), and Expedition 373-Cenozoic Paleoclimate (blue, mission-specific platform). Expedition 378-South Pacific Paleogene Climate (yellow square) has been delayed. ASB = Aurora Subglacial Basin. WSB = Wilkes Subglacial Basin.

The Eocene-Oligocene Climate Transition and the Establishment of a Continent-Wide Ice Sheet in Antarctica

The Eocene warmth was followed by cooling, declining atmospheric CO_2 (Figure 5), and concurrent tectonic reorganizations that culminated in continental-scale glaciation of Antarctica at around 34 Ma (the Eocene-Oligocene transition; EOT). DSDP Leg 28 drilling in the eastern Ross Sea continental shelf was first to recover diamicts (ice-proximal glacial deposits), evidence that grounded ice from the West Antarctic Ice Sheet

(WAIS) first developed around 25 Ma (Hayes et al., 1975). Subsequent drilling from sea ice platforms (CIROS and CRP projects) revealed slightly older AIS glacial expansion in the earliest Oligocene (Barrett, 1989, 2007) that was restricted to the continent and was highly responsive to orbital forcing (Galleoti et al., 2016). Hints to the continental size of this first Antarctic ice sheet came from drilling of the Weddell Sea continental slope during ODP Leg 113. Ice-distal sediments suggested the presence of an East Antarctic Ice Sheet (EAIS) in this margin by at least the earliest Oligocene, based on evidence of the formation of cold deep waters and indirect indicators (i.e., ice rafted debris delivered by icebergs; Barker et al., 1988). ODP Leg 119 in Prydz Bay (December 1987 to February 1988) was, however, the first to recover diamicts from the east Antarctic continental shelf, providing direct evidence that the EAIS was delivering ice to the shelf edge since at least the early Oligocene (Barron et al., 1991; Hambrey et al., 1991). ODP Leg 188 recovered sediments from the shelf dating the arrival of ice sheets to the Prydz Bay continental shelf by 35 Ma (O'Brien et al., 2001; Cooper et al., 2004). A decade later, IODP Expedition 318 continental shelf diamicts and continental rise sediments also revealed the existence of an ice sheet on the Wilkes-Adélie Land sector of the east Antarctic margin by the earliest Oligocene (33.6 Ma, the Oi-1 event; Miller et al., 1991; Escutia et al., 2011, 2014). Sediments from this margin also indicated that ice growth was associated with a major restructuring of the Southern Ocean plankton ecosystem with the establishment of high seasonal primary productivity in a cooler environment and place where seasonal sea ice developed (Houben et al., 2013).

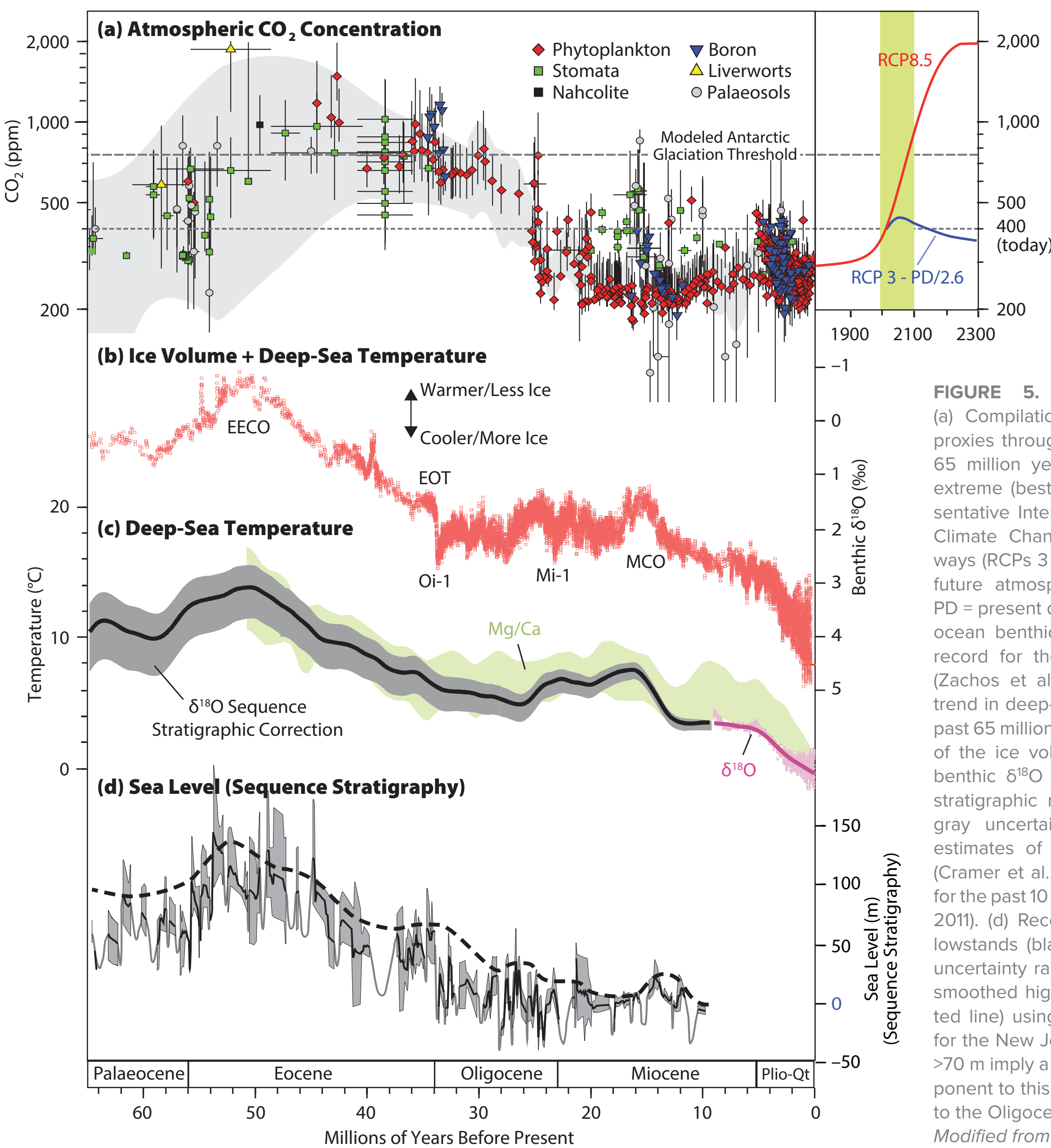


FIGURE 5. Data reconstructions: (a) Compilation of atmospheric CO_2 proxies throughout the Cenozoic (last 65 million years; left side). The two extreme (best and worst case) representative Intergovernmental Panel on Climate Change concentration pathways (RCPs 3 and 8.5) for historic and future atmospheric CO_2 (right side). PD = present day. (b) Composite deep-ocean benthic oxygen isotope ($\delta^{18}O$) record for the last 65 million years (Zachos et al., 2001a). (c) Long-term trend in deep-sea temperature for the past 65 million years based on removal of the ice volume component of the benthic $\delta^{18}O$ record using sequence stratigraphic records (black line with gray uncertainty band) and Mg/Ca estimates of deep-sea temperatures (Cramer et al., 2009) and scaled $\delta^{18}O$ for the past 10 million years (Miller et al., 2011). (d) Reconstruction of sea level lowstands (black lines) with minimum uncertainty ranges (gray shading) and smoothed highstand trend (black dotted line) using sequence stratigraphy for the New Jersey margin. Sea levels >70 m imply a significant tectonic component to this record, particularly prior to the Oligocene (Kominz et al., 2008). *Modified from McKay et al. (2015)*

The role of Earth deformation processes on near-field (i.e., close to the Antarctic continent) sea level changes and ice sheet dynamics was established through the integration of geological data from three Antarctic margins (Wilkes-Adélie Land, IODP Expedition 318; Prydz Bay, ODP Leg 188; and the Ross Sea, CRP) with models that couple ice sheet and glacial isostatic adjustment (GIA) (Stocchi et al., 2013). These data-model comparisons suggest that the growth of a continent-wide Antarctic ice sheet by the earliest Oligocene (33.6 Ma) induced crustal deformation and significant gravitational perturbations around the continent as water mass was transferred from the ocean and "piled up" in the ice sheets. These perturbations resulted in a complex spatial pattern of relative sea level change different from the expected eustatic signal, whereby sea level is rising instead of falling near the continent (Stocchi et al., 2013). These results highlight the relevance of local sea level change influencing the equilibrium state of an ice sheet grounding line, and with that the stability of local/regional ice sheets.

Ice Sheet Dynamics Under Warmer-than-Present Climates of the Icehouse World

Earliest Oligocene to Holocene sediments recovered from Antarctica's continental margins provide insights into the control exerted by changes in atmospheric CO_2 concentrations and Earth's geodynamic processes on the extent and volume of the AIS over long periods of time. In addition, these sedimentary records show that multiple systematic oscillations of Antarctica's ice sheets (i.e., advances-retreats of the AIS during glacial-interglacial cycles, respectively) have been strongly influenced by Earth's astronomical variations (i.e., Milankovitch cycles). Here, we summarize some of the most recent advances related to the behavior of the Antarctic ice sheets under warmer-than-present climates, including potential thresholds for changes in their behavior.

During the Oligocene (33.9–23.03 Ma) and Miocene (23.03-5.3 Ma), atmospheric CO_2 concentrations ranged between 400 ppmv and 650 ppmv (Figure 5; Foster et al., 2012; Badger et al., 2013; Zhang et al., 2016). Foster and Rohling (2013) inferred that within these atmospheric concentrations, global ice sheets were likely insensitive to climate change. In contrast, variability in the deep-sea benthic foraminiferal oxygen isotope ($\delta^{18}O$) records suggests that Antarctic ice volumes fluctuated considerably and were paced dominantly by the 100–400 thousand year (ka) orbital cycles (e.g., Pälike et al., 2006; Holbourn et al., 2007; Liebrand et al., 2011; Beddow et al., 2016). This latter observation is supported by drill cores from the Ross Sea and Prydz Bay continental shelves, the Weddell Sea slope, and the Wilkes-Adélie Land rise, thus providing evidence for a dynamic AIS (e.g., Hayes et al., 1975; Barker et al., 1988; Barron et al., 1989; O'Brien et al., 2001; Escutia et al., 2011; Galleoti et al., 2016; Levy et al., 2019). For example, sediment cores from the western Ross Sea provide direct evidence for orbitally controlled glacial-interglacial cycles between 34 Ma and 31 Ma (Galleoti et al., 2016). These sediments also show the ice sheet to be mostly terrestrial, with ice sheet calving at the coastline not taking place until ~32.8 Ma (Galleoti et al., 2016). Sediments recovered from the Wilkes-Adélie Land continental shelf also indicate an ice sheet reaching the coastline during the early Oligocene ~33.6 Ma (Escutia et al., 2011). However, sea-ice-related dinocyst species (e.g., *Selenopemphix Antarctica*) in sediments from the continental rise are only present during the first 1.5 million years of the early Oligocene and after the Miocene Climatic Optimum (17–14.8 Ma; Bijl et al., 2018). For the remainder of the Oligocene and Miocene, dinocyst assemblages in the Wilkes-Adélie Land margin resemble the present-day open-ocean, high-nutrient settings north of the sea ice edge, suggesting a more restricted seasonal sea ice environment (Bijl et al., 2018). These findings suggest that the ice sheets dominantly retreated to their terrestrial margins, which is in agreement with late Oligocene sedimentologic, geochemical, and biogeochemical data obtained from coeval sediments pointing to terrestrial ice sheets and warm oligotrophic waters (Hartmann et al., 2018; Salabarnada et al., 2018).

The first major expansion of terrestrial ice sheets across the Ross Sea continental shelf, based on ice-proximal marine sediments recovered by DSDP Leg 28, took place at 24.5–24 Ma (Levy et al., 2019). This expansion coincides with disconformities reported in the coastal CRP record (Naish et al., 2001). These records provide direct evidence for a major episode of global cooling and ice sheet expansion previously indirectly inferred from oxygen isotope data (known as the Mi-1 event; e.g., Zachos et al., 2001a,b; Hauptvogel et al., 2017; Figure 5). This significant transition from dominantly terrestrial to marine ice sheets corresponds with a drop in the levels of CO_2 below 600 ppm, which remained below this value for most of the Neogene (Levy et al., 2019). These results provide insight into the potential for a threshold behavior of the AIS at CO_2 concentrations of 600 ppm (e.g., Galleoti et al, 2016; Levy et al., 2019).

A period of global warmth reversed the previous ice growth on Antarctica with global temperatures and atmospheric CO_2 concentrations similar to those projected for the coming centuries. This time interval includes the Miocene Climatic Optimum (MCO; 17–14.8 Ma; Figure 5), a period of global warmth during which average surface temperatures were 3°–4°C higher than today. Drill cores collected from the ice-proximal ANDRILL site in the Ross Sea indicate open water to ice-proximal conditions during the MCO (Levy et al., 2016). Recent drilling on the Ross Sea continental shelf during IODP Expedition 374 also reveals the presence of shallow open water conditions during the MCO (McKay et al., 2018). In the Wilkes-Adélie Land, both dinocyst assemblages and paleotemperature data in sediments from IODP Expedition 318 indicate warm ocean conditions during the MCO, suggesting this marine-based sector of the East Antarctic Ice Sheet to be highly sensitive to ocean warming (Sangiorgi et al., 2018).

A combination of sedimentary evidence from an ANDRILL drill core in the Ross Sea (Levy et al., 2016) and numerical ice sheet modeling (Gasson et al., 2016) demonstrated the potential for tens of meters of early-mid Miocene sea level variability driven by AIS fluctuations. These studies substantially modified the conclusions of previous modeling, which showed a strong insensitivity of the continental AIS once it formed (Huybrechts, 1993; Pollard and DeConto, 2005).

The early Pliocene (~5–3 Ma) has received much attention because it is characterized by global temperatures comparable to those predicted for this century (IPCC, 2013) and atmospheric CO_2 concentrations similar to today (400 ppmv; Pagani et al., 2010; Figure 5). Foster and Rohling (2013) inferred atmospheric CO_2 values of 400 ppmv to represent a major threshold in the sensitivity of global ice sheets to climate change. They suggest that significant sea level rise (~9 m) is likely to occur at equilibrium under atmospheric CO_2 levels of 400–450 ppmv, implying significant melting in Antarctica. ODP Leg 119 drilling on the Prydz Bay continental shelf provided glimpses into the Neogene glacial history of East Antarctica and evidence for glacial fluctuations across the shelf during the late Miocene and the Pliocene (Barron et al., 1991; Passchier, 2011). On the western Antarctic Peninsula continental rise, ODP Leg 178 obtained a detailed record of glaciation, which suggested that the Antarctic Peninsula Ice Sheet was large enough to migrate regularly to the shelf edge over the past 10 million years (Barker et al., 1999), with extended periods of open water during the early Pliocene (e.g., Escutia et al., 2009). In Prydz Bay, elevated surface ocean temperatures of ~5°C were inferred in the early Pliocene (4.2–3.7 Ma) continental rise data obtained during ODP Leg 188 (Whitehead and Bohaty, 2003; Escutia et al., 2009). However, ice-proximal records from coeval intervals are still required from these two margin sectors to interpret the observed changes in terms of AIS grounding line dynamics and sea level.

Ice-proximal sediment cores recovered by ANDRILL from the Ross Sea contain intervals of diatomite that imply open water conditions and periodic retreat of the ice shelf over the drill site in Pliocene times (e.g., Naish et al., 2009; McKay et al., 2012a; Risselmann and Dunbar, 2013). As a result, there may have been a sea level rise greater the 6 m during Pliocene and early Pleistocene warm periods (Dutton et al., 2015), as supported by ice sheet modeling that simulates episodes of WAIS collapse (Pollard and DeConto, 2009). Sea level records based on paleo-shorelines and sequence stratigraphy on continental margins (e.g., Miller et al., 2013; Naish and Wilson, 2009) suggest Pliocene sea level could have been ~20 m higher than present, although the precise value remains highly uncertain (Rovere et al., 2014). This implies retreat of some sectors of the EAIS, thought to be more stable, in addition to melting of the Greenland and the West Antarctic Ice Sheets.

IODP Expedition 318 in the Wilkes-Adélie margin drilled one of the sectors where the EAIS is marine-based (Escutia et al., 2011, 2014; Figure 3). Iceberg debris accumulation in the sediment recovered from the continental rise provides a record of ice sheet growth and decay that is orbitally paced (Patterson et al., 2014). In addition, the geochemical provenance of detrital material recovered from this deepwater site provides evidence for repeated retreat of the marine-based EAIS inland into the Wilkes Subglacial Basin during the early warm Pliocene (5–3 Ma; Cook et al., 2013), supporting the notion of high Pliocene sea level. Importantly, some episodes of landward retreat of the ice sheet are also recorded in some coeval sediments recovered from the Wilkes-Adélie Land continental shelf, indicating repeated times with no sea ice and open marine conditions (Orejola et al., 2014; Reinardy et al., 2015).

The outcomes from drilling in Wilkes Land (Cook et al., 2013) and in the Ross Sea (Naish et al., 2009) forced a new generation of continental-scale ice sheet models that simulate glaciological (i.e., hydro-fracturing, marine ice sheet instability [MISI], and marine ice cliff instability [MICI]) and oceanographic processes, and better reconcile reconstructions of proximal ice sheet extent and far-field sea level from geological data (Gasson et al., 2016; Pollard et al., 2015; Golledge et al., 2017). The paleodata calibrated ice sheets models now reproduce 13–17 m of sea level rise from Antarctica, which better reconcile with reconstructions of proximal ice sheet extent and far-field sea level records of ~20 m (Miller et al., 2012; Dutton et al., 2015), providing revised global sea level predictions for IPCC scenarios. They also identify ~400–500 ppm CO_2 as a potential threshold for marine-based ice sheet stability (e.g., Gasson et al., 2016; Levy et al., 2016). Moreover, extremely low concentrations of cosmogenic ^{10}Be and ^{26}Al isotopes have been found in quartz sand extracted from a land-proximal marine sediment core from ANDRILL (Shakun et al., 2018). This record indicates that land-based sectors of the EAIS that drain into the Ross Sea have been stable throughout the past eight million years, meaning that 30 m is likely an upper bound for maximum Pliocene sea level, when combining the 22 m from the AIS plus 7 m from Greenland ice sheet melting (Shakun et al., 2018).

Pleistocene warmer-than-present interglacials are relevant to understanding ice sheet sensitivity to very small increases in global or hemispheric surface temperature. Reconstructions suggest global sea levels were 6–9 m higher during Marine Isotopic Stage (MIS) 5 (128–116 ka) and 6–13 m higher during MIS 11 (410 ka; e.g., Dutton et al., 2015).

Marine sedimentological and geochemical records from IODP Expedition 318 in the Wilkes-Adélie Land margin provide evidence for ice margin retreat in the vicinity of the Wilkes Subglacial Basin during MIS 5, MIS 9 (337 ka), and MIS 11 (Wilson et al., 2018). Retreat occurred when Antarctic air temperatures were at least 2°C warmer than pre-industrial temperatures for 2,500 years or more. This study points to a close link between extended Antarctic warmth and ice loss from the Wilkes Subglacial Basin, providing ice-proximal data to support a contribution to sea level from a reduced East Antarctic Ice Sheet during warm interglacial intervals. Sediments from the Ross Sea suggest that the WAIS collapsed during at least one Pleistocene interglacial (Scherer et al., 1998), but high-quality continuous (or at least more complete) Quaternary sediment records are still lacking, clouding the timing and magnitude of specific Pleistocene retreats (e.g., McKay et al., 2012b). All these records, however, point to sensitivity of the AIS under pre-industrial levels of CO_2. Proximal drill core records capturing "super-interglacials" of the past one million years are critically needed to validate models implying AIS collapse as recently as ~125,000 years ago.

Ultra-high resolution marine sedimentary records from the last deglaciation during the Holocene (comprising the last ~12,000 years) have been collected from Antarctica's margins by ODP Leg 178 at Site 1098 (Domack et al., 2001; Shevenell and Kennett, 2002; Leventer et al., 2002; Shevenell et al., 2011) and IODP Expedition 318 at Site U1357 (Escutia et al., 2011). These records have enabled comparisons between ice core and sediment records, which are fundamental to understanding the impacts of past climate changes on the ice-proximal marine environment. These records are key to understanding the evolution of climate teleconnections presently impacting Antarctica's ice sheets and sea ice (e.g., Yuan, 2004; Rignot et al., 2019), such as recently shown by geological observations of oceanic forcing of marine-based ice sheets (e.g. Hillenbrand et al., 2017; Etourneau et al., 2019).

Additional data are expected to come from the most recent IODP expedition to Antarctica, Expedition 374 (January–March 2018). This expedition aimed to evaluate the Neogene to Quaternary West Antarctic Ice Sheet variability and the associated oceanic forcings and feedbacks (McKay et al., 2018). Cores recovered span the early Miocene to the late Quaternary. Sediments recovered from continental shelf sites are expected to allow reconstruction of past glacial and open-marine conditions in the early and middle Miocene and of the first major continental shelf-wide expansion and coalescing of ice streams advancing from both East and West Antarctica, and also allow testing the hypothesis that ocean heat flux onto the continental shelf is important for ice sheet mass balance (McKay et al., 2018). Sediments recovered from the continental slope and rise are of Pliocene and Pleistocene age and will allow comparison with coeval shelf sediments in order to establish ice sheet dynamics-ocean linkages.

In addition, there are two scheduled IODP expeditions in 2019, Expedition 379 to the West Antarctica's Amundsen Sea, and Expedition 382 to the Weddell Sea (Figure 4). Amundsen Sea drilling on the continental slope and rise is aimed at a broad time window, from the Paleogene to present, but with a key objective of constraining the recent behavior and sensitivity of the WAIS and connections between ice sheet retreat and ocean temperature. Complementary drilling in the Weddell Sea, in the path of frequent icebergs traveling in the Weddell Gyre, will target a record of ice-rafted debris and its provenance as far back as the Miocene. Together, these drilling expeditions will provide an improved picture of WAIS variability on a range of timescales relevant to both geological and societal perspectives.

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LOOKING TO THE FUTURE

Knowledge gained from drilling marine sediments in and around Antarctica and the Southern Ocean is providing valuable insights into some of society's most pressing environmental concerns, including ice sheet stability and global sea level rise. However, this knowledge currently relies on data from only a few locations around the large Antarctic continent (Figure 1). Nevertheless, what has emerged over the last 50 years of scientific ocean drilling and from modern observations is that different Antarctic glacial catchments respond differently to climate perturbations (e.g., Golledge et al., 2012, 2017). The sparsity of paleoenvironmental records obtained to date hampers full understanding of temporal and spatial patterns and drivers of Antarctic ice volume change. These records provide only the basic framework for understanding past Antarctic Ice Sheet behavior.

The Antarctic and Southern Ocean Science Horizon Scan carried out under the auspices of the Scientific Committee on Antarctic Research identified several high-priority scientific questions that need to be addressed in the next 20 years and beyond (Kennicutt et al., 2014). The Horizon Scan was followed by the Council of Managers of National Antarctic Programs (COMNAP) Antarctic Roadmap Challenges (ARC) project designed to examine the steps necessary to enable the community to conduct research that will answer these high-priority questions (Kennicutt et al., 2016). Both exercises consulted the international Antarctic research community to define a collective vision of one possible future path and the necessary requirements to fully realize the promise of Antarctic research. Two of the most pressing priorities of relevance to society and policy are understanding the response of Antarctica's ice sheets and the Southern Ocean to climate change, and improving estimates of the ice sheets' contributions to global sea level rise. These topics have also been listed as priorities in the National Academies of Sciences, Engineering, and Medicine (2015) report *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research*. Furthermore, the IPCC's Fifth Assessment Report (2014) identified the future evolution of the Antarctic Ice Sheet, particularly of its portions grounded on land that are below sea level (marine-based), as one of the most dramatic unknowns in global climate predictions, hampering reliable estimations of future sea level rise.

Improved predictions of ice sheet variability and its responses to climate change drivers are essential, because both polar regions are the fastest warming areas on Earth (e.g., Church et al. 2003). The integration of a broad spatial range of geological data into coupled models (e.g., ice sheet-glacial isostatic adjustment-ocean-atmosphere) will be critical for describing and predicting realistic ice sheet dynamics and thus improving projections of future sea level rise. To gain a better understanding of the mechanisms and processes responsible for observed changes in Antarctica's ice sheets and the Southern Ocean (i.e., the influence of bed topography and glacial substrates, ice sheet and sea ice extent variation, oceanic and continental temperatures, meltwater, and other basic parameters) requires obtaining samples from key locations, which will improve knowledge of boundary conditions for numerical models (e.g., Colleoni et al., 2018). There needs to be an emphasis on obtaining, when possible, high resolution records (i.e., orbital to annual) of cryosphere-ocean-atmosphere interactions leading up to and during past deglaciation episodes. These records are key to understanding how past changes in atmospheric circulation influenced the transport of ocean heat to the ice sheet grounding lines (Hillenbrand et al., 2017; Etourneau et al., 2019). They also are important for helping to define the nonlinear or variable ice margin retreat during climate warming, rather than having to assume a simple switch in the ice sheet models between advanced and retreated states. This will allow evaluation of the rates and magnitudes of sea level rise in future warming scenarios, a policy-relevant open question. These records are also critical for reconstructing equator-to-pole temperature gradients through time to better understand polar amplification and interhemispheric teleconnections (e.g., tropical-Antarctic teleconnections such as the El Niño-Southern Oscillation, Southern Annular Mode, and bipolar ocean see-saw).

Because different regions of the Antarctic ice sheet undoubtedly will reveal different glacial histories, the spatial and temporal coverage of Antarctic drilling is presently too limited to establish the temporal and spatial ice volume changes resulting from past complex ice sheet-ocean-atmosphere interactions. As mentioned above, the sedimentary sections recovered to date represent either coastal or offshore conditions, but rarely both in close proximity, and many sectors are still unsampled (Figure 1). To reconstruct the sensitivity of East, West, and Antarctic Peninsula Ice Sheets within a broad range of climatic (i.e., varying CO_2 atmospheric concentrations and temperatures) and oceanic (i.e., oceanic forcing of marine-based ice sheets) conditions requires drilling in different sectors of the Antarctic margin and in different paleoenvironmental settings (i.e., subglacial, ice, coast, continental shelf, continental rise, abyssal plain settings; see Figure 2). Scientific drilling in the Southern Ocean, from the coastline to the deep sea, using multiple platforms, to collect the geological records of climate and ice sheet history is needed to study ice-ocean interactions and the tectonic evolution of Antarctica/Gondwana and its influence on Earth's climate system. Scientific ocean and continental drilling are essential for obtaining these paleoclimate records, targeting, in particular, land (subglacial drilling)-to-coastal-to-deep-sea transects through amphibious drilling projects. Sectors of interest are those that will reveal ice mass loss and enhanced glacier flow increases closest to the sources of subsurface warmer modified circumpolar deep water (e.g., Rintoul et al., 2016; Figure 6). These sectors are likely to dominate sea level rise around Antarctica in the (near) future as more Circumpolar Deep Water is pushed against the glaciers by enhanced polar westerlies (Rignot et al., 2019).

For planning future Antarctic drilling projects for ice sheet reconstructions, the collection of new geophysical data around the margin through national and international partnerships is also critical. There are little or no existing data for many areas of the Antarctic margin, but these data are needed to assess the potential relevance of specific regions and sedimentary sections to understanding Antarctic Ice Sheet dynamics and related sea level changes. Such data are also

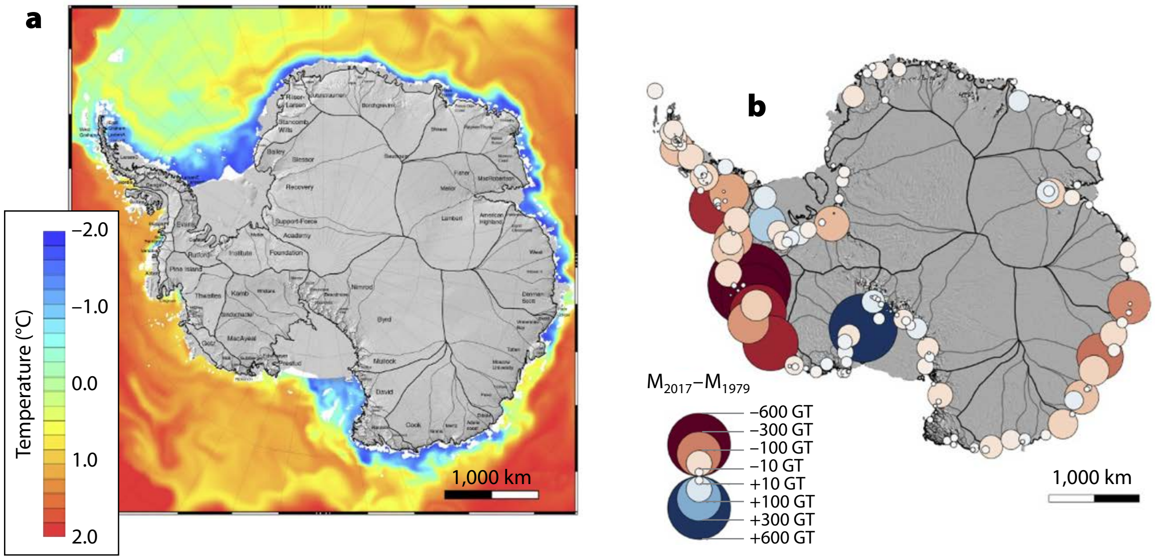

FIGURE 6. (a) Ocean temperatures at 310 m depth from the Southern Ocean State Estimate (SOSE) color-coded in °C from cold (blue) to warm (red). The white colors correspond to areas that are shallower than 310 m depth. (b) Total change in ice mass of major basins for 1979–2017. Blue colors = mass gain, red = loss. Circle radii are proportional to the absolute mass balance. *Modified from Rignot et al. (2019)*

needed for the development of paleotopographic and paleobathymetric reconstructions for key intervals that are critical for modeling ice sheet extension and retreat and the related surrounding ocean circulation. The availability of icebreakers is indispensable for providing access to research sites in year-round, ice-covered areas for high-resolution bathymetric mapping, geophysical data collection, and scientific ocean drilling.

As in the past, innovations in drilling technology, proxy development, and modeling will facilitate new scientific advances. For example, improvements that would allow the high-quality recovery of shelf glaciomarine sediments are needed. Continental shelf strata are the best archives for establishing the ages of grounding line advances and retreats of the Antarctic ice sheets, information that is key for understanding spatial and temporal changes in the continent's marine-based ice sheets and related sea level change. Recovery of these sediments to date by scientific ocean drilling has been challenging because of the physical characteristics of glacial tills and related marine deposits; the combination of soft sediments and gravel hinders successful sediment coring because these deposits "clog" the rotating drilling mechanisms. It is therefore essential for future scientific ocean drilling programs to continue to advance a technological agenda. In addition, new environmental data can be obtained by mining of legacy cores with innovative proxies. However, there are limitations to the use of legacy samples because they do not always contain the continuous and/or high-resolution sections that are necessary to progress in paleoclimate/paleoceanography/global sea level reconstructions. It is essential that scientific drilling programs have the technology in hand to lead these societally relevant research programs.

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SPOTLIGHT 5. The New IODP Advisory Structure

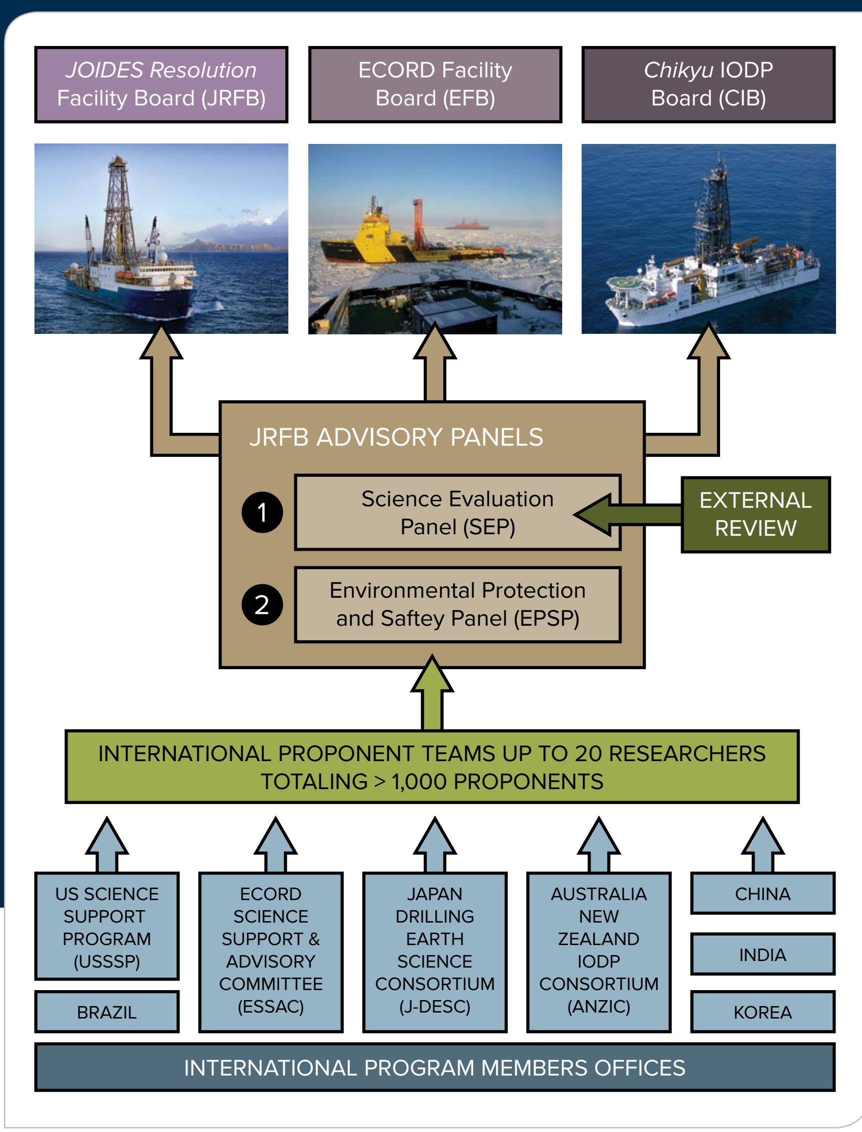
With the introduction of the International Ocean Discovery Program (IODP) in 2013 came a new advisory structure that is designed to be more agile, allow for regional planning while maintaining a global focus, and speed up the proposal submission and review cycle. Each drilling platform is now overseen by both a Platform Provider (e.g., a funding agency) and a Facility Board that determines scheduling of expeditions and oversees operations (see the chart below). The two are tightly connected through international collaborations under the auspices of the IODP Forum, which provides a venue for exchanging ideas and views on the scientific progress of the IODP.

In this second phase of IODP, proposal evaluation involves a simple but comprehensive two-step process governed by policies and guidelines developed and approved by the *JOIDES Resolution* Facility Board (JRFB); the European Consortium for Ocean Research Drilling (ECORD) Facility Board (EFB) and the *Chikyu* IODP Board (CIB) make use of the JRFB evaluation system as well. For the first step, proponent teams of no more than 20 scientists write proposals responding to two program deadlines per year and submit them to the Science Evaluation Panel (SEP) via the proposal database maintained by the IODP Science Support Office (SSO; http://iodp.org). For each proposal, SEP vets the science objectives and their concordance with the IODP Science Plan (https://www.iodp.org/about-iodp/iodp-science-plan-2013-2023), the hypotheses to be tested, drilling strategies, and the availability, quality, and applicability of the required site characterization data. SEP allows for one pre- and one full proposal; the latter may be revised only once. Finally, SEP also incorporates the outcome of a round of external anonymous peer reviews. After applying this extensive review process, SEP determines if the proposal is scientifically exciting and the drilling strategy sound, rates the proposal, and then forwards it to the appropriate Facility Board(s) for scheduling and implementation.

For the second step, each proponent team submits a safety package to the Environmental Protection and Safety Panel (EPSP). This package is presented during an EPSP meeting, allowing the proponent team to describe the sites to be drilled using 2D/3D multichannel seismic and other supportive geophysical data. The EPSP determines if the selected primary and alternate drill sites can be safely occupied, and if not, they reject sites or alter the target depth and/or location of these sites. Over the last five years, SEP and EPSP reviewed a total of 145 proposals from 1,650 proponents, with proposals taking on average 4.5 years from first submission to execution; the fastest proposal went through this new system in 2.5 years.

This nimble IODP advisory system allows the program to react to new and exciting opportunities by implementing expeditions rapidly, for example, to collect samples and critical geophysical data concerning a recent event such as a major earthquake. Minutes are posted on http://iodp.org as are lists of the current membership of the JRFB and the SEP/EPSP advisory panels; links to other IODP websites provide additional information. All scientists, shipboard participation, workshops, panel meetings, and small IODP-related proposal grants are supported through the various international program member offices.

– Anthony A.P. Koppers and James A. Austin Jr.



Blowing in the Monsoon Wind

By Pinxian Wang, Steven C. Clemens, Ryuji Tada, and Richard W. Murray

ABSTRACT. From *Maswin* (Arabic), to *Monção* (Portuguese), to *Moesson* (Dutch), to *Monsoon* (English), the etymology of the word is not entirely clear, nor is its definition precise, although these different terms all refer to seasonal changes in wind and rainfall, depending on where they occur. However, it is clear that monsoonal climates are characterized by strong seasonality in wind and rainfall patterns, typically with onshore winds and increased rainfall during summer and offshore winds and reduced rainfall during winter. The Northern Hemisphere monsoons are one of the most prominent examples of Earth system interactions in which the solid Earth influences the circulation of the atmosphere and ocean, consequently forcing aspects of both regional and global climate. The monsoons also represent a climate phenomenon that has large direct and indirect societal impact. In this paper we review the contribution of scientific ocean drilling to our understanding of Earth's current monsoons as well as those through geological history, back to tens of millions of years ago.

Windsock on *JOIDES Resolution* at sunset during International Ocean Discovery Program Expedition 353, Indian Ocean Monsoon. *Photo credit: Edmund Hathorne, IODP JRSO*

INTRODUCTION

Historically, monsoonal circulation has been widely studied by both the climatology and the paleoclimate research communities. With increasing recognition of climate change, so has its social relevance grown. Until the nineteenth century, an understanding of monsoon winds was crucial for navigation. Later, when steamboats replaced sailboats, monsoon precipitation became a major social concern because of its association with floods, droughts, and food production. Today, monsoons are recognized as being central to the global hydrological cycle, but they remain insufficiently understood.

Monsoons have likely been prominent features of Earth's climate system throughout much of geologic time, and their influence as global climate changes is as critical as that of the ice sheets, sea ice, and sea level. Although monsoon precipitation accounts for only one-third of the total modern global rainfall, it is the most mutable component in the global hydrological cycle. Together with the El Niño-Southern Oscillation (ENSO) and trade winds, the global monsoon is a major low-latitude component of the global climate system, and thus its study on timescales ranging from interannual to geological enhance our understanding of key factors that control the hydrological cycle. Transitions between water's physical phases pervade and drive the entire climate system, but in the past, the paleoclimate community focused on solid/liquid (i.e., ice/water) phase transitions, while liquid/gaseous transitions went almost unexplored until very recently, largely due to difficulties in research approaches and insufficient proxies (P. Wang et al., 2017).

Although achieving a better understanding of ocean-atmosphere processes has been a scientific ocean drilling goal since the beginning of the Deep Sea Drilling Project (1968–1983), the focus on monsoons did not emerge until the early 1980s. At that time, analysis of sediments recovered from the ocean showed that deposits reflecting upwelling-enhanced productivity and eolian transport were linked to monsoon winds and the westerlies from Asia to the North Pacific, respectively (see Rea, 1994, for a review). The first expedition designed specifically to reconstruct Asian monsoon history was Ocean Drilling Program (ODP) Leg 117 to the northeast Arabian Sea in 1987 (Prell et al., 1989). ODP Leg 184 to the South China Sea followed in 1999, also aimed at monsoon reconstruction. Both of these drilling legs resulted in new insights into the history of Asian monsoon climates from tectonic to orbital timescales, showcasing the application and effectiveness of using proxies to resolve monsoon-related processes (e.g., Kroon et al., 1991).

In the twenty-first century, monsoons have received greater attention from both the paleo- and modern climatology communities. In the modern world, monsoonal circulation exists, to varying degrees, on all continents except Antarctica. The Asian monsoon is the most active among all the regional systems and includes three different subsystems: the Indian tropical, the Southeast Asian tropical, and the Northeast Asian subtropical (Figure 1). The Northeast Asian monsoon reaches the highest latitude (45°N) and is the most complicated of the subsystems.

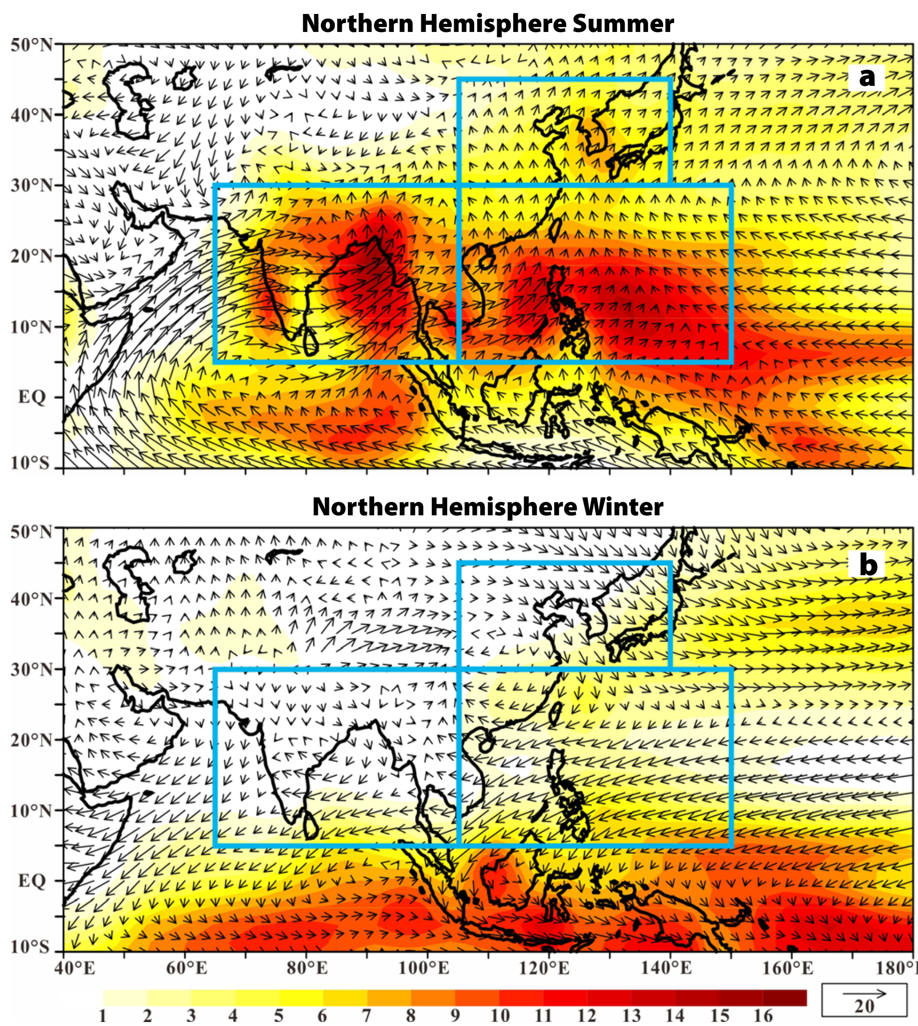


FIGURE 1. Climatological mean precipitation rates (shading in millimeters per day) and lower-level wind vector (arrows) in the Asian monsoon region. (a) July–August. (b) January–February. The three boxes define the major summer precipitation areas of the Indian tropical, Southeast Asian tropical, and the Northeast Asian subtropical monsoons. *Modified from B. Wang et al. (2003)*

Six Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) expeditions were completed between 2013 and 2017 to explore the Cenozoic history of all three monsoon systems (Figure 2), and to date, a total of nine ODP/IODP cruises have been implemented to specifically address Asian monsoon variability and impacts (Table 1). The deep-sea sediment sequences recovered from these expeditions provide invaluable climate archives for studying the evolution of the Asian monsoon since the Oligocene.

Monsoon Proxies

Wind and rainfall patterns vary strongly across the monsoon regions, imparting different chemical, physical, biological, and isotopic signals to the underlying sediments. Thus, a variety of ocean sediment proxies are used in different regions, depending on which aspect of the monsoon is being reconstructed. For example, the dominant monsoonal signals in the Arabian Sea region derive from the low level Findlater jet and eolian transport of lithogenic materials from the surrounding deserts. Here, the Findlater jet develops during the summer season, flowing from the southwest along the Somali coast (Figure 1a), driving Ekman-induced upwelling along the coastline, while lithogenic dust is transported to the Arabian Sea. In this case, lithogenic grain size changes in the ocean sediments, and planktonic foraminifera species associated with upwelling environments (e.g., *Globigerina bulloides*; Figure 3d) can be used as proxies for changes in summer monsoon wind strength. In scientific ocean drilling cores, these monsoon processes result in alternating light-dark bands (Figure 3a), indicating dilution of light-colored biogenic carbonates (summer monsoon productivity) by dark-colored terrestrial dust input, driven by glacial-interglacial changes in vegetation cover and increased deflation potential (i.e., the removal of fine sediments and organic materials by strong winds). Changes in oceanic upwelling strength also drive changes in underlying oxygen minimum zone (OMZ) denitrification that can be reconstructed using nitrogen isotopes, with increased upwelling causing an increase in $\delta^{15}N$ in bulk organics in northern Arabian Sea sediment cores. The extent to which multiple independent proxies converge on similar results provides a measure of confidence, given that each proxy may be biased in some way by processes unrelated to monsoon variability (e.g., diagenesis, dissolution, physical disturbance).

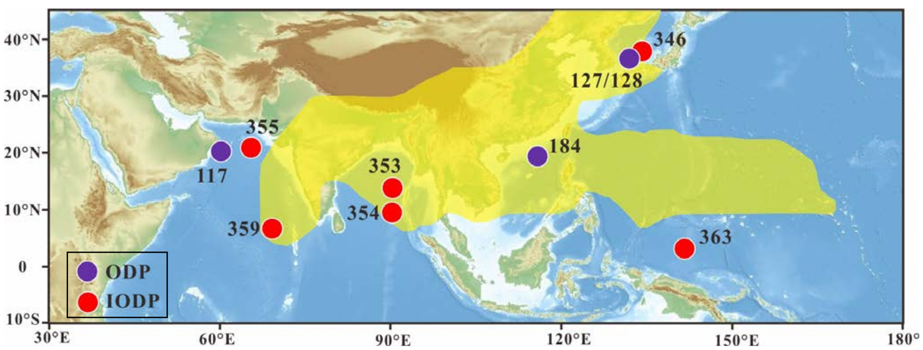


FIGURE 2. Scientific ocean drilling expeditions that have addressed the Asian monsoon. Purple dots indicate Ocean Drilling Program (ODP) legs, red dots Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) expeditions. Yellow coloring denotes the modern Asian monsoon region.

TABLE 1. IODP and ODP expeditions addressing the Asian monsoon.

Expedition	Drill Area	Age*	Year	Drill Sites	References
IODP 363	West Pacific Warm Pool	Miocene/Oligocene	2016	U1482–1490	Rosenthal et al., 2018
IODP 359	Maldives	Miocene/Oligocene	2015	U1465–1472	Betzler et al., 2017
IODP 355	Arabian Sea	17.7 million years	2015	U1456–1457	Pandey et al., 2016
IODP 354	Bengal Fan	Late Miocene	2015	U1449–1455	France-Lanord et al., 2016
IODP 353	Bay of Bengal	Cretaceous	2014/15	U1443–1448	Clemens et al., 2016
IODP 346	Sea of Japan, East China Sea	12 million years	2013	U1422–1430	Tada et al., 2015
ODP 184	South China Sea	33 million years	1999	1143–1148	P. Wang et al., 2000
ODP 127/128	Sea of Japan	20 million years	1989	744–749	Pisciotto et al., 1992
ODP 117	Oman Margin	17 million years	1987	720–731	Prell et al., 1989

* "Age" indicates the oldest age of recovered sediments

In contrast to the Arabian Sea record, the primary monsoon signal in ocean sediments in the Bay of Bengal region derives from strong summer rainfall (Figure 1a). Here, the monsoon signal can be teased out in scientific ocean drilling cores by observing changes in lithogenic influx and seawater $\delta^{18}O$ as obtained from the $\delta^{18}O$ mass spectrometry analyses of the planktonic foraminifer *Globigerina ruber* (Figure 3c) that in turn is coupled with temperature reconstructions, both of which vary as a function of rainfall and runoff. In addition, the δD (hydrogen isotopic) composition of terrestrial leaf wax (Figure 3b) can be used to monitor the isotopic composition of monsoon rainfall on land, which is useful in the South China Sea, East China Sea, and Japan Sea where rivers enter these marginal basins and dilute ocean waters. Monsoon proxies from terrestrial archives are abundant as well, but the correlation between various proxies remains a subject of debate and is outside the scope of this work.

TECTONICS-CLIMATE LINKAGE

Tectonic-Climate Links and the Uplift-Monsoon Hypothesis

Theoretically, it is expected that the seasonal reversal of surface winds driven by basic atmospheric processes should have produced monsoonal climates in the lower latitudes throughout geological history. Yet, the onset and cause of the modern pattern of regional monsoons remains a fundamental outstanding question of considerable interest. Early research suggested that Himalayan-Tibetan plateau uplift was responsible for monsoon evolution in Asia/India, leading to the uplift-monsoon hypothesis (Prell and Kutzbach, 1992).

Today, three tectonic factors have been proposed as exercising control over the evolution of the Asian monsoon: plateau uplift, changing sea-land distributions, and the opening and closing of oceanic gateways. In the Himalaya-Tibet region, plateau uplift alone may involve various mechanisms that affect monsoon circulation, including thermal forcing at the plateau surface, mechanical barriers related to regional orography, and "candle heating" in the middle troposphere (see P. Wang et al., 2017, for a review). General circulation models (Figure 4a) predict the inception of strong monsoons (similar to the modern-day Asian monsoon) when the uplift of Himalaya-Tibet is at least half that of the present (Prell and Kutzbach, 1992). Increases in the presence of the monsoon upwelling indicator, *Globigerina bulloides*, at ODP Arabian Sea Site 722 suggest the onset of strong monsoonal conditions began ~8 million years ago (Figure 4b; Kroon et al., 1991), coincident with a major phase of uplift of the Himalayan mountain range 10.9–7.5 million years ago (Amano and Taira, 1992). This uplift-monsoon hypothesis was supported by terrestrial records of enhanced wet/dry seasonality, including accelerated loess deposition in China (Ding et al.,

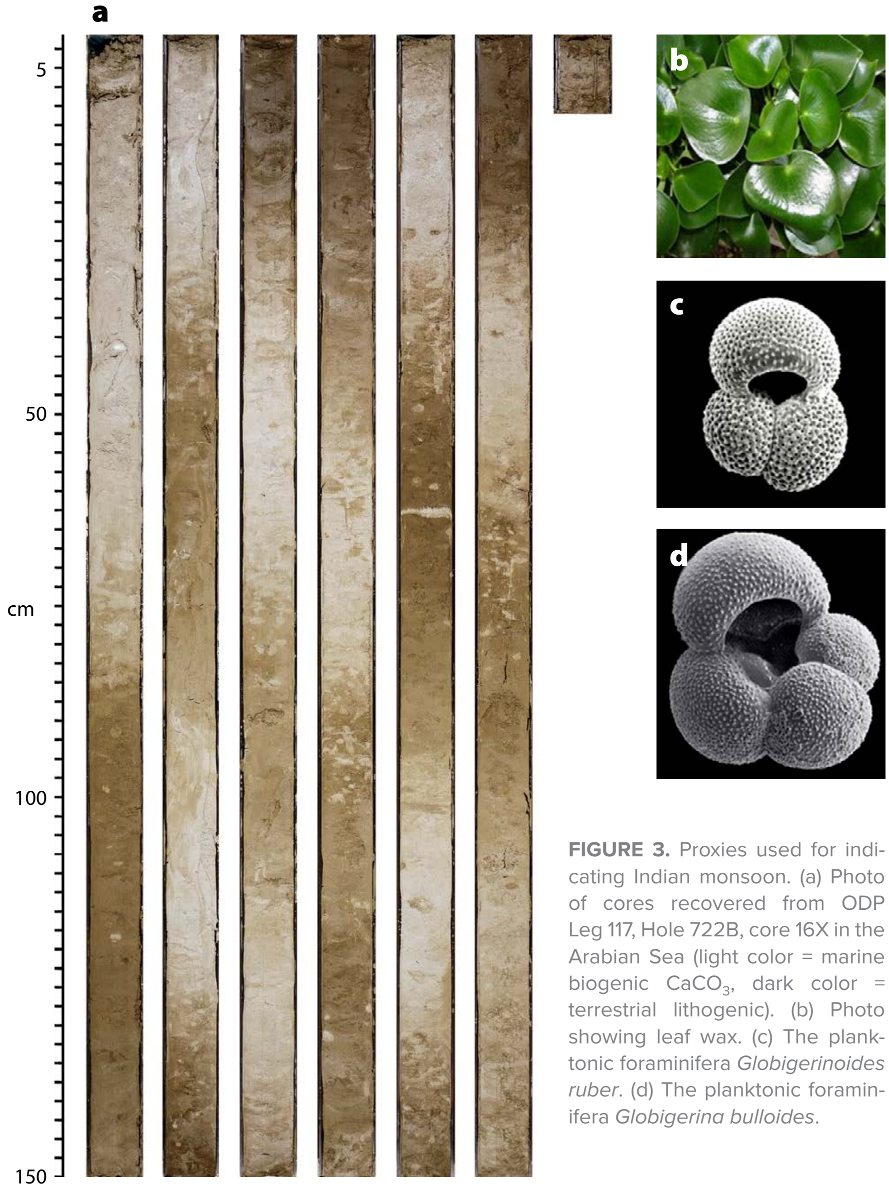


FIGURE 3. Proxies used for indicating Indian monsoon. (a) Photo of cores recovered from ODP Leg 117, Hole 722B, core 16X in the Arabian Sea (light color = marine biogenic $CaCO_3$, dark color = terrestrial lithogenic). (b) Photo showing leaf wax. (c) The planktonic foraminifera *Globigerinoides ruber*. (d) The planktonic foraminifera *Globigerina bulloides*.

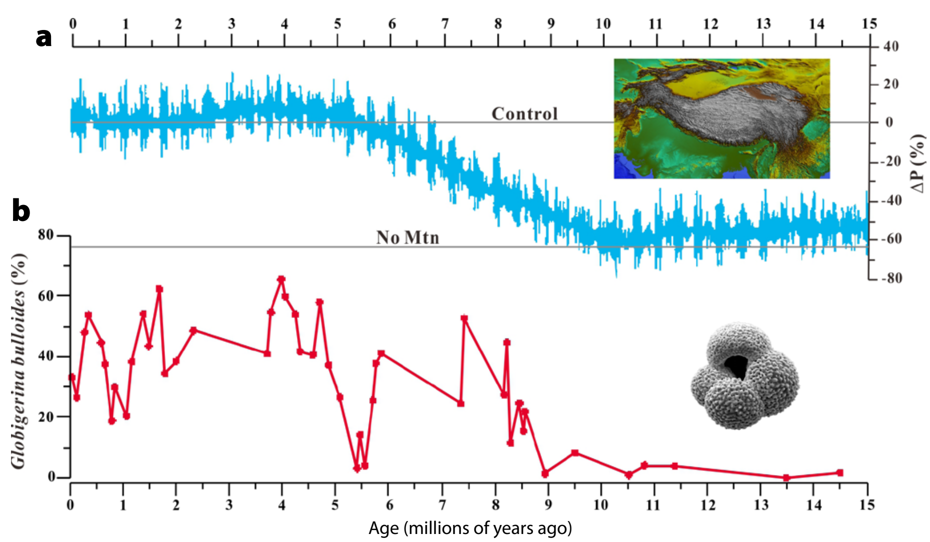


FIGURE 4. Tibetan uplift and development of the Indian monsoon. (a) Model of the uplift showing percentage changes in monsoon precipitation (%ΔP, mm d^{-1}). (b) Time series of upwelling indicator species of planktic foraminifer *Globigerina bulloides* from ODP Site 722. *Modified from Prell and Kutzbach (1992)*

1998) and an ecological transition from C_3- to C_4-dominated vegetation (when plants started to fix CO_2 twice in their cell structures) in Northern Pakistan around that time (Quade et al., 1989).

However, not all long-term changes to the Asian monsoon have resulted from direct tectonic forcing. An example is intensification of Asian aridity and monsoon at about 3 million years ago, as convincingly documented both on land and in the ocean. Almost all data suggest that this event was not related to uplift but to changes in global climate resulting from the permanent glaciation of Greenland (P. Wang et al., 2005).

East Asian Monsoon

Continued investigation of the causal relationship between uplift and the strength of the Asian monsoons revealed a much more complicated and dynamic Earth system, particularly in eastern Asia. The discovery of older loess dating to the Early Miocene (Guo et al., 2002) and the reorganization of the climate system in China around the transition from the Oligocene to the Miocene provides evidence for enhancement or perhaps establishment of the East Asian monsoon around 23 million years ago (Sun and Wang, 2005). A 33-million-year sequence of hemipelagic sediments recovered from the South China Sea at ODP Site 1148 provided an ideal record for investigating the timing of the onset of Asian monsoons. For example, the isotopic composition of black carbon ($\delta^{13}C_{BC}$) and chemical alteration indices from Site 1148 suggest major changes in seasonal precipitation since the early Miocene (Figure 5a, Wei et al., 2006), significantly predating the original ~8 million year monsoon initiation age derived from earlier studies. The strong $\delta^{13}C_{BC}$ fluctuations were ascribed by Jia et al. (2003) to the initiation of the modern East Asian monsoon, in agreement with terrestrial records. These authors also attributed the general trend of $\delta^{13}C_{BC}$ toward much more positive values in the early Pleistocene to a drying in East Asia, and maybe a temporary ceasing or de-intensifying of the monsoon, supported also by geochemical indices, such as the chemical index of alteration (CIA; Figure 5b). Similar patterns in Rb/Sr and CIA at South China Sea ODP Site 1146 (Figure 5c,d; Wan et al., 2010) support the regional nature of the drying trend in East Asia.

Both the South China Sea records and the North Asian terrestrial data indicate a strengthening of the East Asian monsoon, marked by the transition from zonal to monsoonal climate patterns around 23 million years ago. Clift et al. (2014) proposed that after the strengthening of the East Asian monsoon at ~23 million years ago, another extended period of monsoon maximum in East Asia occurred between 18 and 10 million years ago, but weakened around 8–7 million years ago, showing an opposite trend to the Arabian Sea wind strength record that informs our understanding of the Indian monsoon (Figure 4b). It remains unclear, however, whether the development of East Asian and Indian monsoons was synchronous at the tectonic timescale, and whether the two monsoon subsystems shared a common tectonic forcing. Another factor that must be reconciled is whether the drying trend in the Neogene was related to global-scale cooling. The major obstacle to resolving these issues is the absence of long-term records of the Indian monsoon; hopefully, ongoing investigations of the Eocene-Pleistocene sequences recovered from IODP Expeditions 353, 354, 355, and 359 to the Bengal Fan will shed light on this issue.

Indian Monsoon

While relatively long and continuous sediment records exist to investigate the East Asian monsoon, early studies of Indian monsoon history were hindered by the lack of long sediment sequences. Among the recent IODP expeditions addressing Indian monsoon history, IODP Expedition 359 to the Maldives recovered a record back to 25 million years ago (Betzler et al., 2017). The cores display an abrupt change in sedimentation pattern, also marked by a large decrease in

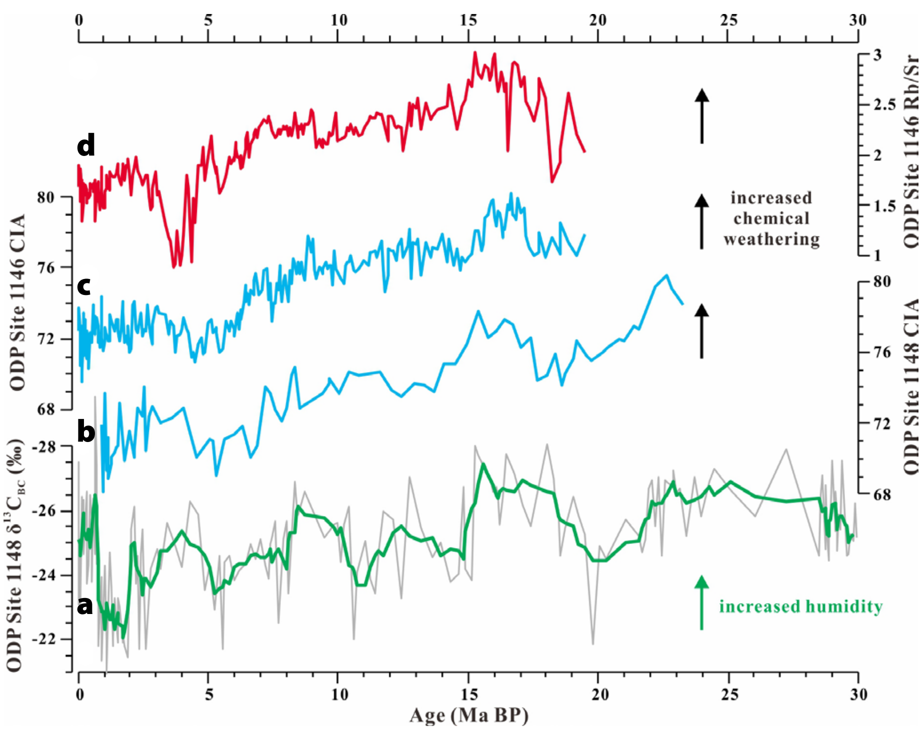


FIGURE 5. Late Cenozoic climate records from the South China Sea. ODP Site 1148: (a) Isotopic composition of black carbon over the past 30 million years (Jia et al., 2003). (b) Chemical index of alteration (CIA) over the past 25 million years (Wei et al., 2006). ODP Site 1146: (c) Rb/Sr ratio and (d) CIA over the past 20 million years (Wan et al., 2010).

manganese concentration at 12.9 million years ago, likely indicating the onset of the Indian monsoon (Betzler et al., 2018). Here, wind-driven upwelling during the summer monsoon generates an OMZ in the Arabian Sea, whereby the amount of manganese buried with the sediment varies with changes in OMZ intensity. The Mn/Ca ratio from analysis of interstitial waters can therefore be used as a proxy to indicate the summer Indian monsoon (Figure 6b; Betzler et al., 2016, 2018). In contrast, a discontinuous ~10.2-million-year record of denitrification in the eastern Arabian Sea within the OMZ recovered from IODP Expedition 355 indicates a persistently weakened Indian monsoon from ~10.2 to 3.1 million years ago (Figure 6a; Tripathi et al., 2017). This monsoonal weakening trend from the eastern Arabian Sea contrasts with the maximum monsoon between 10.2 and 3.8 million years ago, as interpreted from the Maldives record (Figure 6b; Betzler et al., 2018), likely highlighting the importance of regional variability throughout the larger Asian monsoon system.

Although it is premature to draw conclusions about the impact of tectonics on overall Asian monsoon evolution, some long-term records from recent expeditions may shed light on this crucial issue. IODP Expedition 354 to the Bengal Fan, for example, drilled seven sites and recovered a comprehensive record of Himalayan erosion over the Neogene and Quaternary (France-Lanord et al., 2016). Major and trace element geochemistry show relatively stable compositions throughout the period, and the low weathering intensity suggests that a monsoon-style erosion regime, with rapid sediment transfer through the floodplain, was established since at least the Early Miocene (France-Lanord et al., 2017).

ORBITAL FORCING AND THE MONSOON

Interpreting Orbital-Scale Records

Compared to tectonic timescales (millions of years), our knowledge of the large-scale Asian monsoon evolution at orbital timescales (less than tens to hundreds of thousands of years) is more complete. The study of orbital-scale climate change is unique in that the signal-to-noise ratio is large and the insolation forcing (i.e., changes in the amount of sunlight warming a given area on Earth) is well known over the past 20 million years (see Littler et al., 2019, in this issue). For the late Pleistocene, this knowledge has significantly improved the resolution at which we understand the distribution of greenhouse gases (carbon dioxide and methane) and terrestrial ice volume (Loulergue et al., 2008; Petit et al., 1999; Lisiecki and Raymo, 2005) and their effects on global climate.

Changes in insolation derive from three orbital parameters: (1) eccentricity (e) that describes the deviation of Earth's orbit from circularity, (2) obliquity (ε) or tilt of Earth's rotation axis, and (3) the precession index (esinω), which is a function of eccentricity and describes the orientation of Earth's rotation axis relative to the fixed stars, where ω is the longitude of perihelion measured relative to the moving vernal equinox (Berger, 1978). Therefore, it should be possible to assess the underlying mechanisms driving monsoonal climate change at the orbital timescale. One approach to interpreting orbital-scale monsoon reconstructions is to assess the coherence and phase of the proxy records relative to the external (insolation) and internal (e.g., greenhouse gas, terrestrial ice volume) climate forcing mechanisms at each of the primary orbital periods: eccentricity (~100,0000 years), obliquity (41,000 years), and precession (23,000 years). Given statistically significant coherence within discrete orbital periods, differences in phase offer measures of relative climate sensitivity and the underlying physics driving monsoonal climate change.

Here, we examine the precession-band response, as insolation is dominated by precession-band variance in monsoonal regions, and we use the phase wheel as a convenient means of depicting the timing of the monsoon response relative to known forcings (Clemens et al., 1991; Figure 7a). The maximum external forcing in terms of precession occurs during the June 21 perihelion. In the phase wheel, this is set at 0° (top) and represents the timing of the strongest Northern Hemisphere summer monsoon insolation, maximum sensible heating of the Indo-Asian landmass. If monsoon circulation responded only to this external insolation forcing, all monsoon proxy responses would

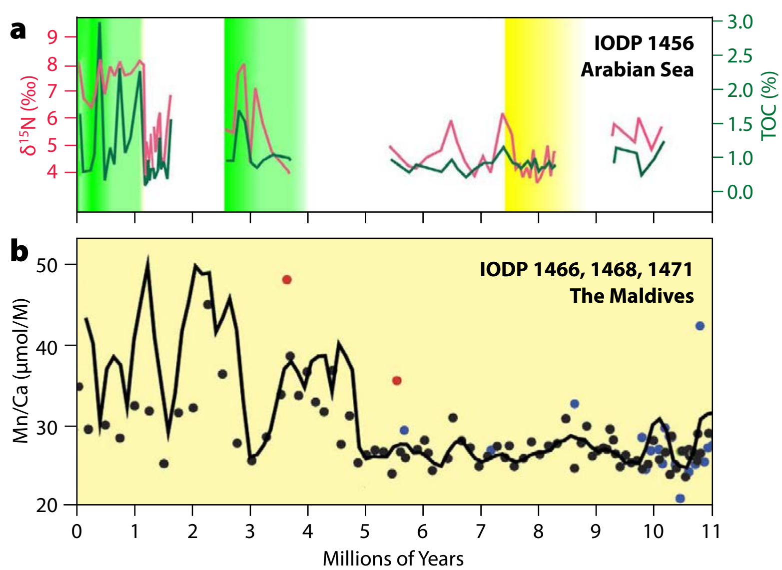


FIGURE 6. Comparison between two ~10-million-year IODP records. (a) $\delta^{15}N$ and total organic carbon (TOC) at IODP Site 1456, Eastern Arabian Sea (Tripathi et al., 2017). (b) Mn/Ca ratio at IODP Sites 1466, 1468, and 1471, Maldives (Betzler et al., 2018).

plot near 0°, coherent and in phase with the maximum sensible heat forcing. In Figure 7, the precession-band timing of *potential* monsoon forcing mechanisms are depicted with red dots and associated labels, including insolation through Northern Hemisphere sensible heating, the greenhouse gases CH_4 and CO_2, minimal terrestrial ice volume, and latent heat export from the Southern Hemisphere subtropical Indian Ocean (Figure 7b).

The precession timing of the monsoon proxy reconstructions are shown in blue in Figure 7, illustrating selected Late Pleistocene results from scientific ocean drilling sites in the northwest Arabian Sea (Clemens et al., 1991, 2003), Bay of Bengal (Bolton et al., 2013; Gebregiorgis et al., 2018), northern South China Sea (Thomas et al., 2014), and northeastern East China Sea (Clemens et al., 2018). To a first approximation, proxies from the South China Sea and East China Sea derived from ODP Leg 184 and IODP Expedition 346 indicate strengthened monsoonal circulation between the timing of maximum Northern Hemisphere summer insolation, the internal CH_4 and CO_2 greenhouse gas forcings, and the climatic boundary conditions associated with the growth and decay of high-latitude ice sheets (Figure 7b). In contrast, proxy records from the northwest Arabian Sea and the Bay of Bengal derived from ODP Legs 117 and 121 and IODP Expedition 353 reach their maxima between the minimum ice volumes and the maximum latent heat exports from the southern subtropical Indian Ocean, consistent with the cross-equatorial flow path of modern winds and moisture (Figure 1).

From this synthesis, a picture is slowly emerging in which (1) the timing of strengthened circulation in the East Asian monsoonal system appears sensitive to direct Northern Hemisphere summer insolation forcing and changes in greenhouse gases/ice volume that is (2) decoupled from the Indian monsoonal system, which appears more sensitive to changes in greenhouse gases/ice volume as well as the import of latent heat from the southern subtropical Indian Ocean. This decoupling is consistent with the apparent asynchronous intensification and weakening of the East Asian and Indian monsoons at longer timescales as evidenced in many ODP and IODP sediment cores.

Neogene Monsoon and Eccentricity Cycles

The above discussion focused on precession-band variance. However, the precession amplitude is (strongly) modulated by Earth's orbital eccentricity in long paleoclimate sequences that span many eccentricity-driven modulation periods at 95,000, 124,000, and 404,000 years. There is a clear advantage in using scientific ocean drilling for such studies, because the program's global-class drilling platforms are capable of recovering long sediment archives that span the entire Cenozoic and into the Cretaceous, and across large ocean expanses. The middle Miocene records from ODP Site 1146, northern South China Sea, and IODP Site 1237, Southeast Pacific, for example, show high coherence between the benthic $\delta^{13}C$ and the long (404,000 year) and short (95,000 and 124,000 year) eccentricity cycles (Figure 8). The "Monterey" carbon-isotope excursion (16.9–13.5 million years ago) consists of nine 400,000-year cycles, implying carbon reservoir changes linked to eccentricity forcing, possibly mediated through enhanced biological productivity and increased organic carbon burial in continental margin

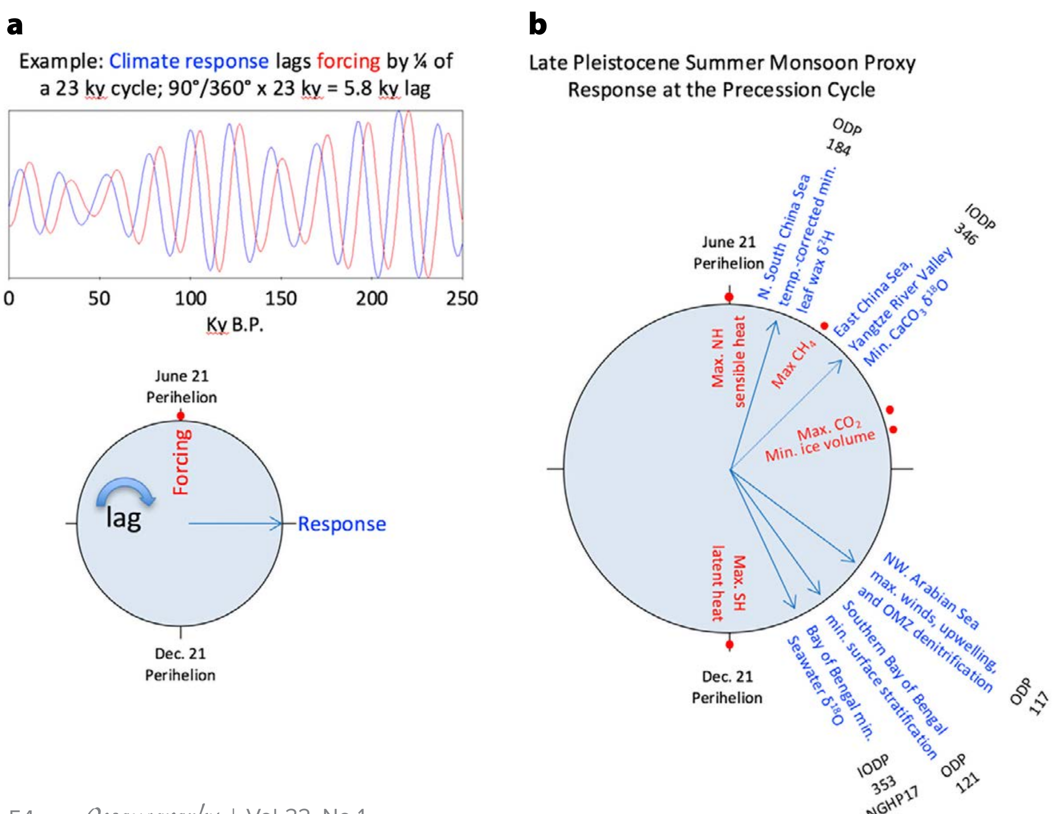


FIGURE 7. Precession-band phase wheel. (a) Example: Time series of a forcing parameter (red) operating on a 23,000-year cycle, and climate response (blue) that lags the forcing by one-fourth of a cycle, or 58,000 years. On the phase wheel, the forcing time series is represented as a red dot, while the lagged climate response is represented by a blue vector. Time lags are measured in the clockwise direction. (b) Precession band response of late Pleistocene summer monsoon reconstructions from the Indian and East Asian systems plotted relative to potential forcing parameters. OMZ = oxygen minimum zone. NH = Northern Hemisphere. SH = Southern Hemisphere.

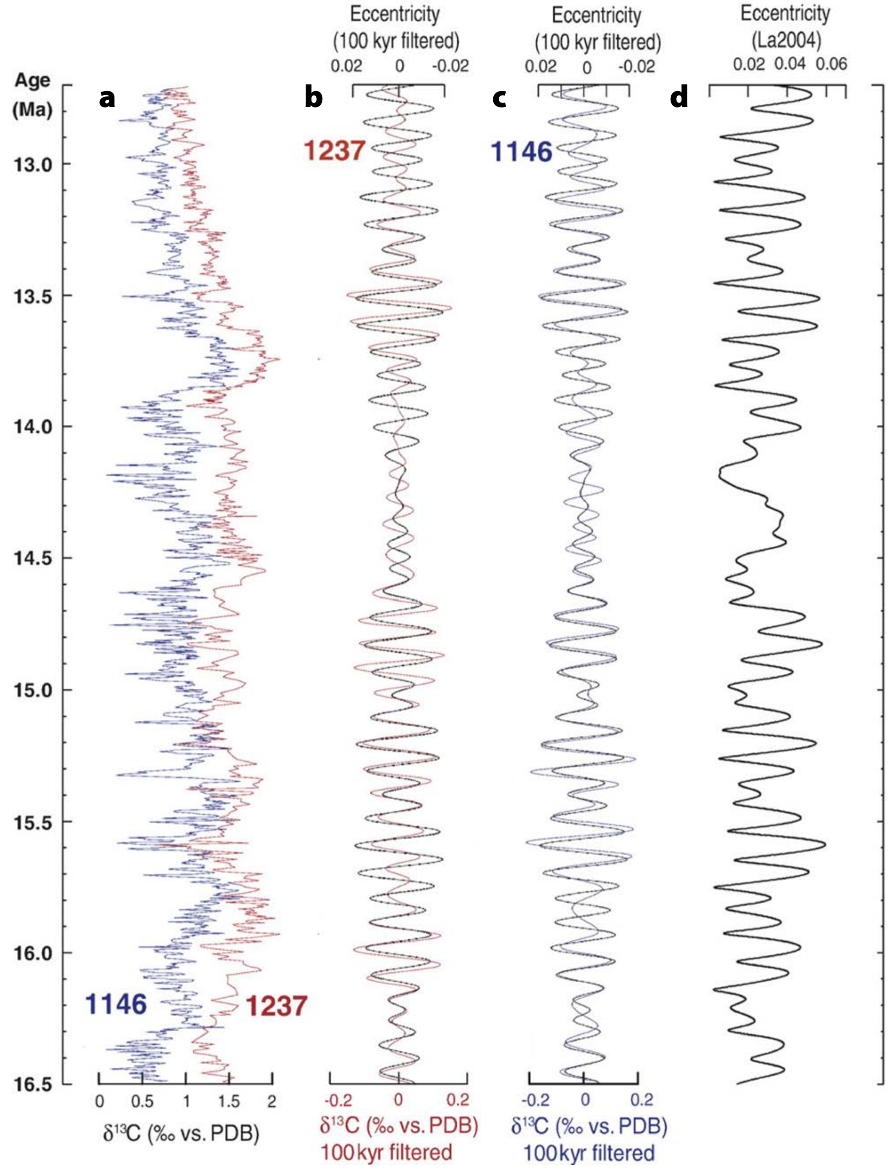


FIGURE 8. Eccentricity rhythms in benthic foraminiferal $\delta^{13}C$ in the middle Miocene at ODP Site 1146, South China Sea, and IODP Site 1237, Southeast Pacific. (a) Benthic foraminiferal $\delta^{13}C$ at Sites 1146 and 1237. (b–c) Comparison of 100,000 year filtered 1237 $\delta^{13}C$ (red; b) and 1146 $\delta^{13}C$ (blue; c) with eccentricity from the La2004 numerical solution (black). (d) Eccentricity (Holbourn et al., 2007).

sediments. ODP 1146 is located in the Southeast Asian monsoon region and IODP 1237 in the South American monsoon region. Their common feature in responding to eccentricity forcing may be indicative of a common "global" monsoon origin (Figure 8; Holbourn et al., 2005, 2007) over these long timescales.

The 400,000-year eccentricity cycles are also observed in the Pliocene carbon isotopes and carbonate preservation in the South China Sea and Bay of Bengal, as well as in eolian dust records of the Arabian Sea (Figure 9). The strong imprint of the 400,000-year cyclicity in these low-latitude climate proxy records is interpreted in terms of a response to low-latitude insolation changes and hence monsoon variability. Similar to the Miocene records, the long eccentricity cycles in the Pliocene carbon reservoir, and during other geological periods, again may point to a common driver, the "global" monsoon. Although all of the Pliocene records show maximum $\delta^{13}C$ values at the eccentricity minima every 400,000 years, this $\delta^{13}C$ max-400,000-year relationship became obscured after ~1.6 million years in the Pleistocene, probably associated with restructuring of Southern Ocean circulation (Figure 9; P. Wang et al., 2010).

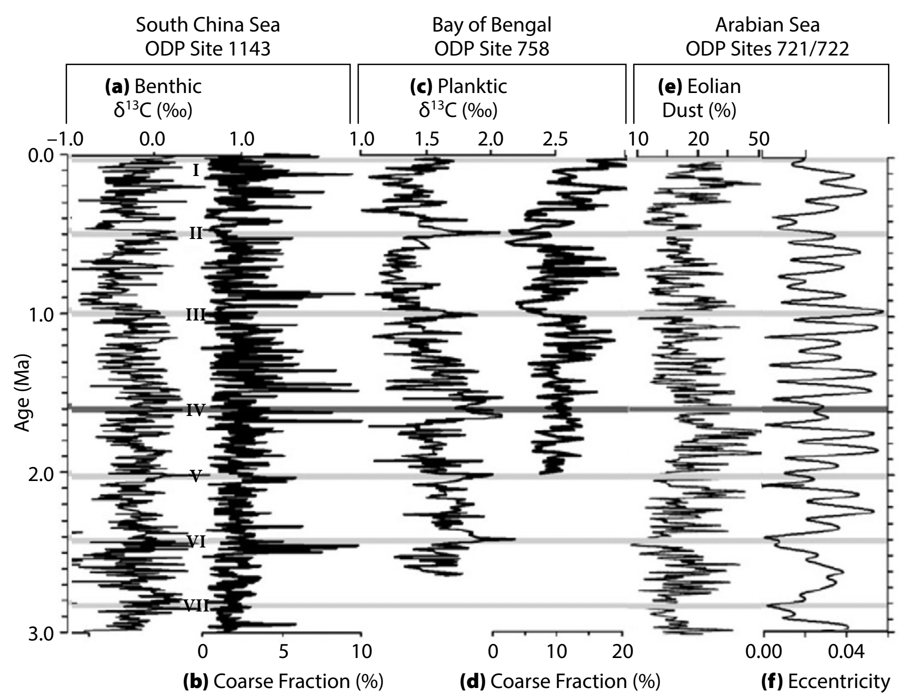


FIGURE 9. Long eccentricity cycles in carbon isotope and paleomonsoon records over the past 3 million years (from B. Wang et al., 2003). South China Sea, ODP Site 1143: (a) benthic carbon isotope (‰), (b) coarse fraction in sediments (%). Bay of Bengal, ODP Site 758: (c) planktic carbon isotope (‰), (d) coarse fraction in sediments (%). Arabian Sea, ODP Sites 721/722: (e) Eolian dust (%), (f) Eccentricity (P. Wang et al., 2010).

MILLENNIAL-SCALE VARIABILITY

Typically, suborbital climate variations of the late Quaternary are the focus of high-temporal-resolution studies that analyze short deep-sea piston cores recovered by conventional research vessels. In contrast, the focus of scientific ocean drilling expeditions is recovery of much longer sediment records. In those longer cores, millennial to centennial variability is recorded in deep time as evidenced by the alternations of dark and light layers in deepwater sediments of the Sea of Japan in cores from ODP Legs 127/128 and IODP Expedition 346. Because of the semi-enclosed nature of the Sea of Japan basin, periodic sea level fluctuations influence water column stratification, leading to euxinic bottom water conditions (water that is both anoxic and sulfidic) characterized by meter-thick dark layers deposited during glacial maxima (Tada et al., 1999, 2015, 2018). Furthermore, the alternating centimeter- to decimeter-scale dark and light layers reflect millennial-scale variations that can be associated with Dansgaard-Oeschger cycles (rapid climate fluctuations) during colder glacial periods, with each dark layer corresponding to an interstadial (i.e., the less cold, short periods within these cycles). Here, the critical mechanism involves strong modulation of salinity, nutrient supply, and strength of inflow through Tsushima Strait caused by changes in the discharge rate of monsoonal rivers flowing into the East China Sea.

Millennial-scale variations in the Sea of Japan were first observed through analysis of alternations of dark and light layers in the Quaternary section of sediment cores recovered by ODP Leg 127/128 in 1989 (Figure 10; Tada et al.1999). In 2013, IODP Expedition 346 extended the high-resolution record back to the Miocene, resulting in a long sediment sequence dating back ~12 million years (Figure 11; Tada et al., 2015). Thanks to the new half piston core system engineered by the *JOIDES Resolution* Science

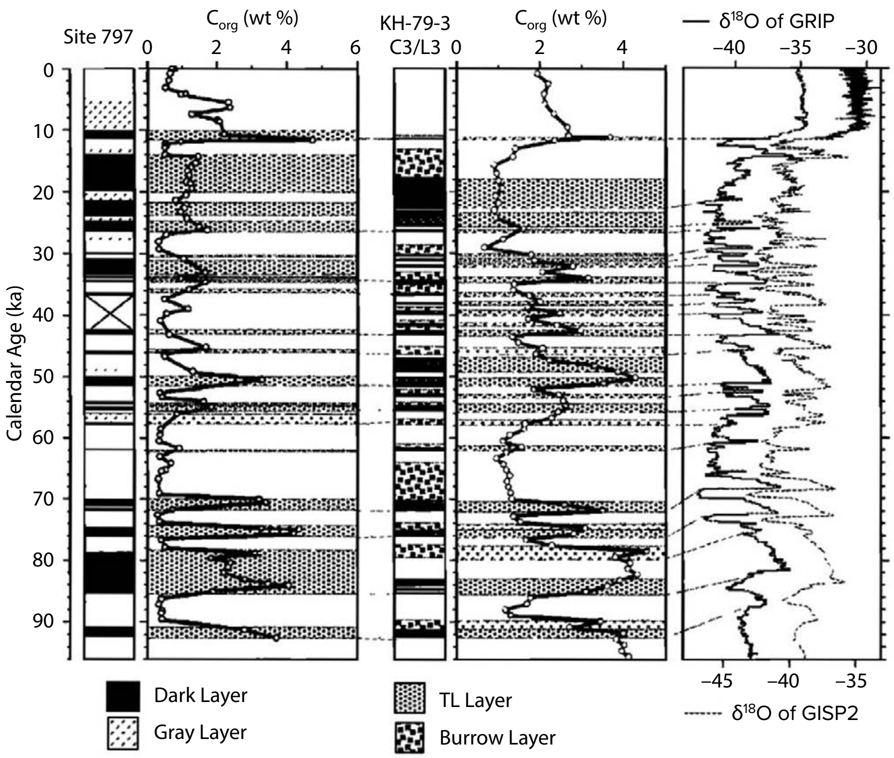


FIGURE 10. Millennial-scale variability of the East Asian monsoon determined from deep-sea records of the Sea of Japan. Comparison of the dark and light layers and their C_{org} profiles at ODP Leg 127, Site 797 and Core KH79-3 with $\delta^{18}O$ records from the Greenland Ice Core Project (GRIP) and Greenland Ice Sheet Project Two (GISP2) (Tada et al., 1999).

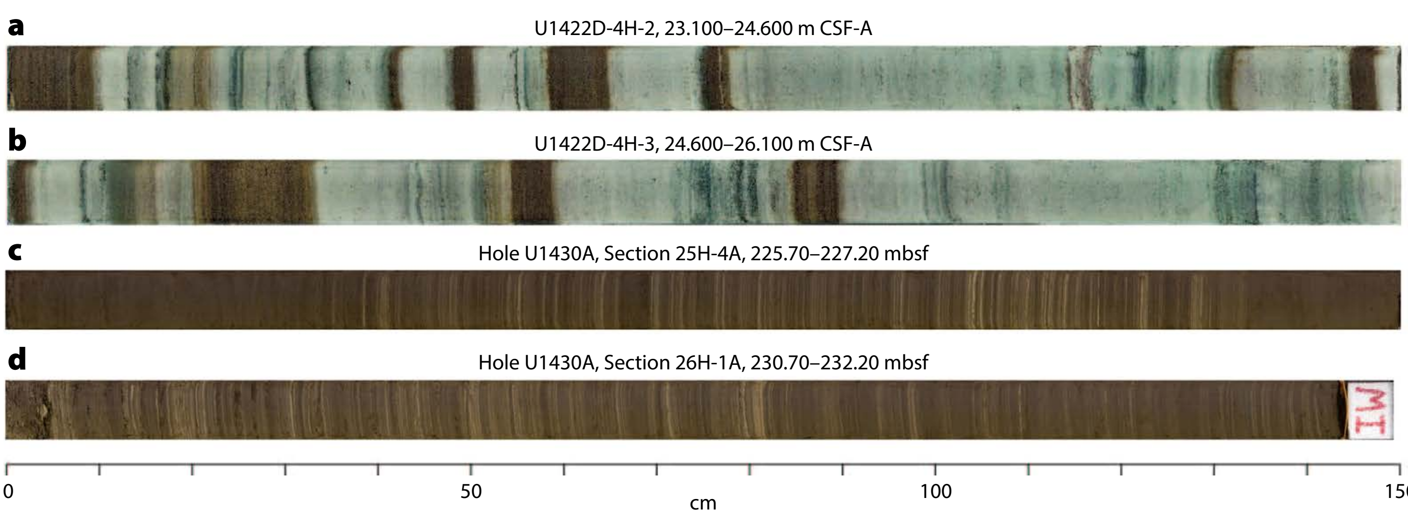


FIGURE 11. Representative dark and light layers in Sea of Japan cores. (a–b) Pleistocene section at IODP Site U1422 (with the color contrast enhanced). (c–d) Miocene section at IODP Site U1430 (Tada et al., 2015).

Operator, the deepest continuous piston core record in DSDP/ODP/IODP history (490.4 m) was recovered in Hole U1427A during IODP Expedition 346. The total 6,135.3 m of core provides a wealth of sediment to enable assessment of the extent to which the Plio-Pleistocene uplift of the Himalaya and Tibetan Plateau, and/or the emergence and growth of the Northern Hemisphere ice sheets, or the establishment of the two discrete modes of westerly jet stream circulation, caused the millennial-scale variability of the East Asian summer monsoon and amplification of Dansgaard-Oeschger cycles (Murray et al., 2014; Tada et al., 2015, 2018).

Highly resolved millennial-scale variability has also been documented from the Arabian Sea OMZ (ODP Site 722B on Leg 117; Higginson et al., 2004) as well as East China Sea surface waters (IODP Site U1429 on Expedition 346, Figure 12; Clemens et al., 2018). These sediment records further illustrate the strong influence of high-latitude North Atlantic dynamics on the low-latitude monsoon systems, presumably via an atmospheric teleconnection associated with the planetary Westerlies.

A NEW CHALLENGE FOR FUTURE SCIENTIFIC OCEAN DRILLING

Over the last two decades, there has been a dramatic increase in research activities devoted to monsoon variability. In addition to modern-day satellite records that have extended monsoon observations beyond the continents and into data-scarce oceanic regions, detailed records from speleothems, ice cores, and deep-sea and terrestrial sediment records have enhanced the resolution of monsoon proxy records to an unprecedented level. Traditionally, monsoon variability was studied almost exclusively on regional scales. However, the "global monsoon" concept has now been introduced as a global-scale seasonal reversal of the three-dimensional monsoon circulation that can be associated with the migration of rainfall in the monsoon trough and the Intertropical Convergence Zone (Trenberth et al., 2000; B. Wang and Ding, 2006).

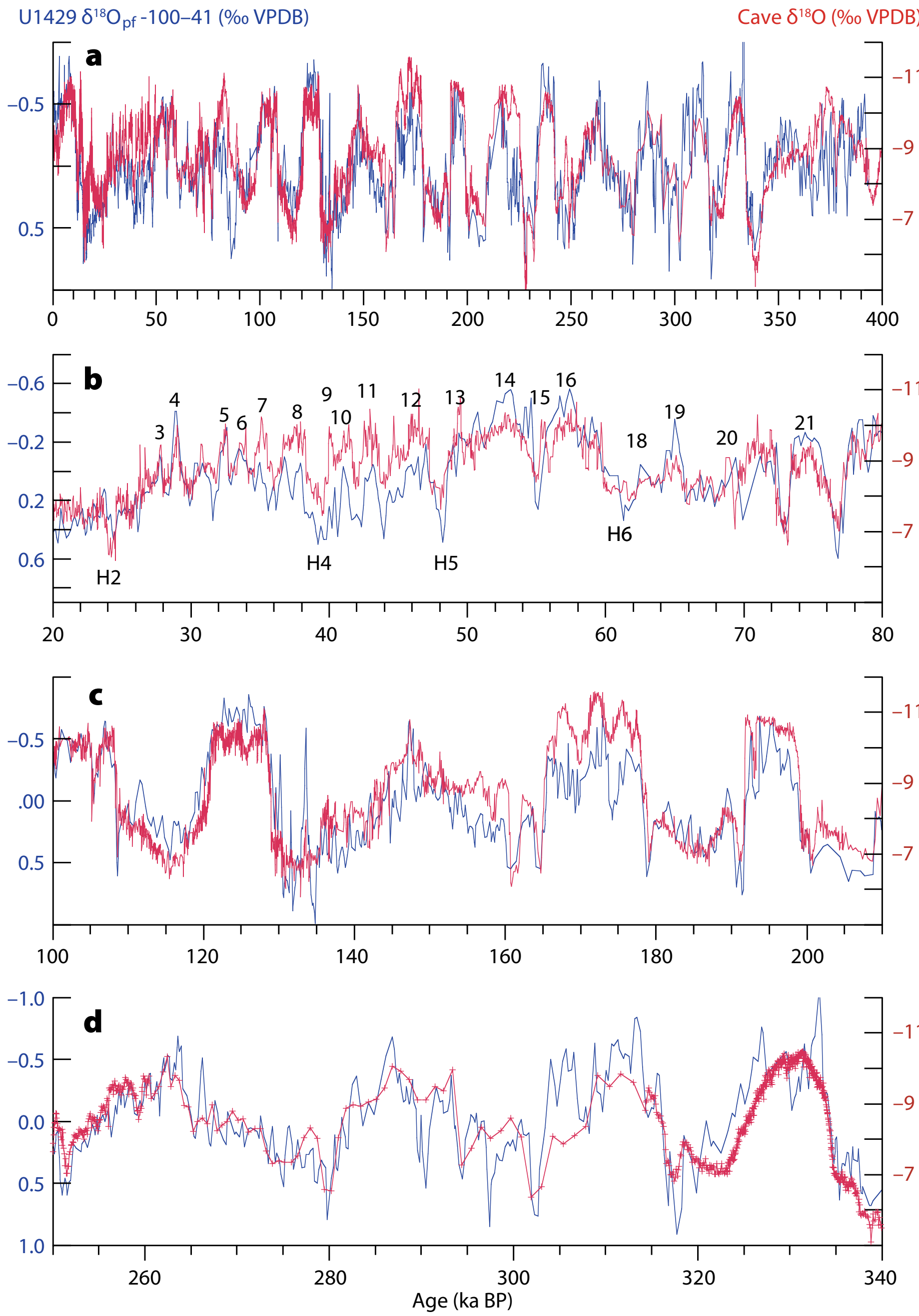


FIGURE 12. Millennial-scale structure in notched $\delta^{18}O_{pf}$ compared to $\delta^{18}O_{cave}$. (a) Notched IODP Site U1429 $\delta^{18}O_{pf}$ on the cave-based age model. (b) Expanded 20,000–80,000 years ago interval with millennial-scale Dansgaard–Oeschger (DO) and Heinrich events numbered. (c) Expanded 100,000–210,000 years ago interval. (d) Expanded 250,000–340,000 years ago interval showing structure not previously resolved in $\delta^{18}O_{cave}$. *From Clemens et al. (2018)*

In view of the ever-increasing complexity of monsoon variability in paleoclimate records, international working groups have been organized to review research progress and perspectives. Twenty years ago, the SCOR-IMAGES Evolution of Asian MONSoon (SEAMONS) working group was set up to assess the current status and outstanding issues in paleoclimate study of the Asian monsoon (Clemens et al., 2003; P. Wang et al., 2005). In 2007, the Past Global Changes (PAGES) project "Global Monsoon and Low-Latitude Processes: Evolution and Variability" working group was established, bringing together paleo- and modern-day climatologists in an effort to improve our understanding of the dynamics of monsoon variability (P. Wang et al., 2012, 2014, 2017). In September 2017, the IODP-PAGES workshop on "Global Monsoon in Long-term Records" was held in Shanghai, China, to review the achievements of the most recent monsoon-related IODP expeditions (P. Wang et al., 2018). Future IODP efforts will need to significantly extend the spatiotemporal coverage of monsoon records, as high-resolution deep-time monsoon records are required to reveal monsoon changes at the "hot-house to ice-house" transitions, as well as the tectonic background of when and how the modern monsoon systems was established.

These new program emphases will be enhanced by community efforts to continue to develop, test, and verify new proxies designed to better assess the impact of seasonality on our interpretation of past monsoonal circulation (summer vs. winter circulation) and better assess the extent to which proxies can differentiate changing wind patterns, rainfall patterns, and surface circulation patterns, all of which are related to changing monsoonal circulation.

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Finding Dry Spells in Ocean Sediments

By Stephen J. Gallagher and Peter B. deMenocal

ABSTRACT. Ocean basins are the ultimate repositories of sediment. Their slow, continuous accumulation over geologic history provides valuable archives that document major climate events and transitions in Earth history. Mineral dust plumes borne by prevailing winds are dominant sources of terrigenous sedimentation off regions such as the Saharan, Arabian, Kalahari, Patagonian, and Australian deserts. Scientific ocean drilling off Africa and Arabia has recorded consistent glacial-stage increases in eolian dust fluxes throughout the Pliocene-Pleistocene, where elevated dust flux values during glacial periods and stadia have been interpreted as reflecting real hydroclimate progression toward greater glacial aridity. International Ocean Discovery Program Expeditions 356, 363, and 369 (conducted in 2015, 2016, and 2017, respectively) recovered extensive sedimentary climate archives off Australia. Ongoing analyses of these strata reveal a marine record of the onset of continental aridity as Australia migrated northward by 25° over the last 50 million years. These Southern Hemisphere oceanic records will continue to yield key information on global climate evolution, allowing us to understand how deserts and monsoonal systems have evolved through time.

INTRODUCTION

Terrestrially derived sediment and dust are ultimately stored in oceanic basins. Gradual, yet continuous, accumulation of these sediments through geological time has created superb archives of global climate variability, transitions, and events in Earth history. Plumes of mineral dust carried by prevailing winds are the main terrigenous sediment source off subtropical hyperarid areas such as the Arabian, Australian, Saharan, Kalahari, and Patagonian deserts. Charles Darwin commented on these African dust storms in 1846 during the first leg of his *Beagle* voyage: "During our stay of three weeks at St. Jago [Cape Verde], the wind was N.E. as is always the case this time of year; the atmosphere was often hazy, and very fine dust was almost constantly falling, so that the astronomical instruments were roughened and a little injured." This paper reviews the dust and aridification archives accumulated off the African continent and finishes with a look to future revelations to be obtained from recent scientific ocean drilling records off western Australia.

OUT OF AFRICA AND ARABIA: OCEANIC DUST ARCHIVES REVEAL ARIDIFICATION AND DESERT HISTORY

Downcore changes in eolian sediment abundance are used to chart the (geo)historical variability of northwest African aridity. Nearly 180 million tons of African dust are transported by the winds to the ocean each year from Saharan source areas (Yu et al., 2015). The potential utility of mineral dust fluxes for recording hydroclimate is supported by strong historical correlations between Sahelian rainfall anomalies and eolian dust flux measurements recorded in Barbados (Prospero and Lamb, 2003) and in a marine core just offshore from the Senegal River near the Mauritania canyon (16°50'N, 16°44'W, Mulitza et al., 2010).

Noting a close correspondence between glacial cycles and elevated dust concentrations, Parkin and Shackleton (1973) influenced decades of researchers by proposing links between high-latitude ice cover and low-latitude aridity. Scientific ocean drilling off Africa and Arabia has recorded consistent glacial-stage increases in eolian dust fluxes throughout the Pliocene-Pleistocene (Figure 1a,b; Clemens and Prell, 1991; Tiedemann et al., 1994; deMenocal, 1995). Elevated dust flux values during glacial periods and stadia (relatively cold periods within a glacial period) have been interpreted as reflecting real hydroclimate changes toward greater glacial aridity.

Recent advances in grain size data analysis document that the glacial sediments not only have higher dust concentrations and burial fluxes but also have much coarser grain size distributions. By "unmixing" grain size spectra into finer-grained fluvial and coarser eolian end-members, Tjallingii et al. (2008) noted that glacial stages and shorter stadial (Heinrich) events were characterized by much coarser and more abundant eolian grain sizes, consistent with stronger, more competent transporting wind speeds during cooler periods. Current views suggest that the observed two- to fourfold increases in glacial-age dust fluxes observed across the global tropics and subtropics (Clemens and Prell, 1991; Tiedemann et al., 1994; deMenocal, 1995; Winckler et al., 2008) reflect glacial increases in dust transport due to stronger, more gusty winds associated with increased glacial pole-equator temperature gradients (McGee et al., 2010).

A fundamental challenge to interpreting sedimentary dust fluxes solely in terms of changes in aridity has emerged from hydrogen isotopic measurements of plant leaf waxes preserved in the same sediment cores where dust fluxes are measured. This organic geochemical paleohydrological proxy tracks regional rainfall gradients today and in the past (Tierney et al., 2017b). Analysis of northwest African sediment cores documents paleohydrological cycles paced principally by orbital precession, with only weak expression of glacial-interglacial 100,000-year and 41,000-year cycles observed in dust flux records (Figure 1c; Tierney et al., 2017a; Kuechler et al., 2018). These precessional plant wax wet-dry cycles match similar pacing observed in Mediterranean sapropel (organic sediment rich) cycles that extend back to the late Miocene.

Together, the eolian dust and plant wax isotopic data clarify interpretations of the deep-sea sedimentary record of continental climate change. Consistent with orbital theory, subtropical continental wet-dry cycles were mainly paced by orbital precession, whereas the glacial dust flux increases are mainly reflective of more effective dust transport due to stronger, gustier subtropical wind fields, not greater aridity (McGee et al., 2013). Hence, there is an opportunity to use these differential proxy responses to simultaneously explore monsoonal hydroclimate responses to orbital precession forcing within the Pliocene-Pleistocene context of increasing glacial climate variability after 2.8 million years ago. To date, studies indicate that the amplitude of monsoonal hydroclimate response to orbital forcing appears to have been large and persistent with no secular change over the last 5 million years (Rose et al., 2016; Kuechler et al., 2018).

A PORTRAIT OF AN ARID LAND: OCEAN DRILLING TO UNCOVER 50 MILLION YEARS OF AUSTRALIAN CLIMATE EXTREMES

International Ocean Discovery Program (IODP) Expeditions 356, 363, and 369 conducted from 2015 to 2017 cored up to 1 km into the seabed from 14°S to 34°S off western Australia (Figure 2). These expeditions recovered excellent records of climate and ocean conditions as Australia drifted northward by 25° latitude over the last 50 million years. Fossil and sediment information trapped in these layers contain a marine record of continental aridity, Australian monsoons, and westerly winds, permitting investigation of how the present climate extremes of Australia evolved (Figure 2).

The Australian Monsoon

North Australia is influenced by strong summer westerly and southwesterly winds that source warm, moist equatorial air, resulting in the monsoonal rains and cyclonic activity north of the monsoon shear line. Monsoonal seasonal runoff delivers large amounts of river sediment to the Australian continental shelf via the Fitzroy, De Grey, Ashburton, and Fortescue Rivers (Figure 2). In contrast, the trade winds off northwest Australia transport continental wind-blown dust when the trade winds dominate during the winter dry season (Figure 2; see also Stuut et al., 2014).

The Westerlies Regime

Strong westerly winds dominate the mid-latitude regions south of 26°S on the western margin of Australia. The north-to-south movement of the westerlies results in significant seasonal precipitation

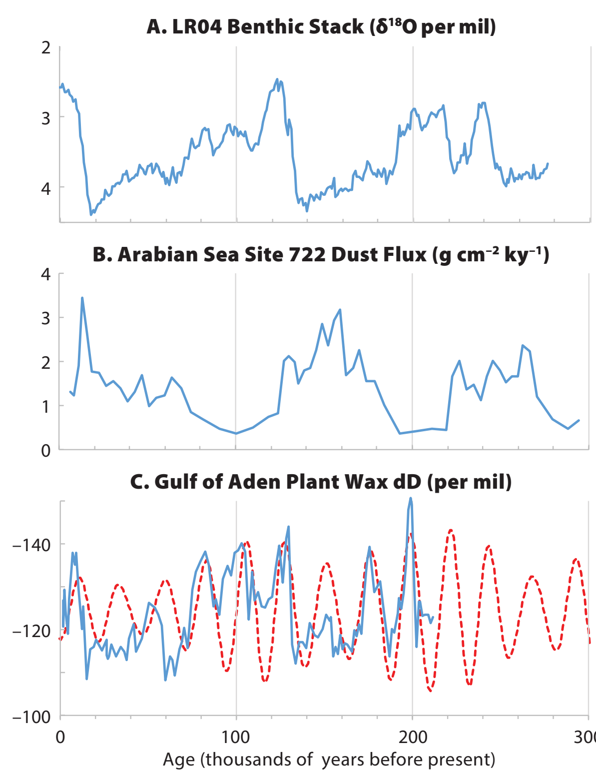

FIGURE 1. (A) Benthic oxygen isotope stack (Lisiecki and Raymo, 2005). (B) Mineral dust flux record from ODP Site 722, Arabian Sea (Clemens and Prell, 1991). (C) Stable hydrogen isotopic composition of plant waxes at core site RC9-166 in the Gulf of Aden (Tierney et al., 2017a), with orbital precession (red dashed line, negative values upward).

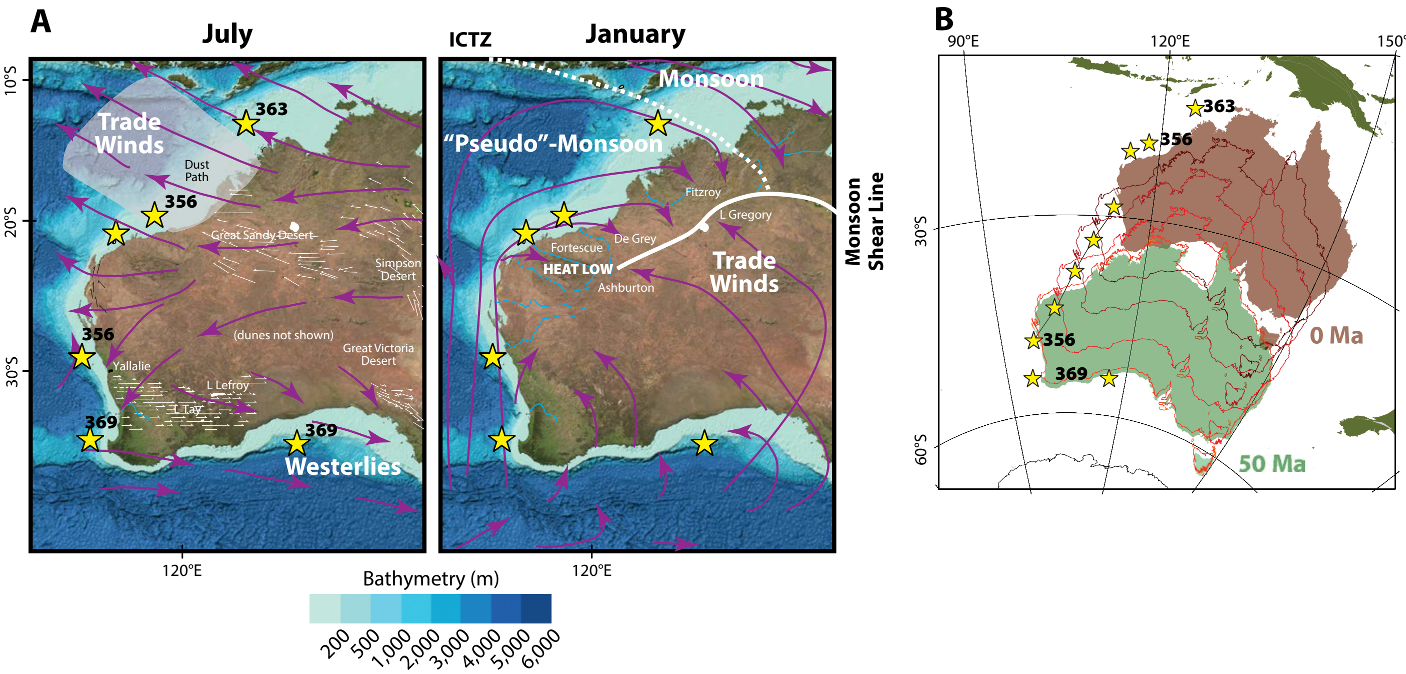

FIGURE 2. (A) Atmospheric circulation (purple arrows) for July and January (Gentilli, 1972), with the mean monsoon shear line (solid white line; McBride, 1986) and Inter Tropical Convergence Zone (ICTZ; dotted white line) noted. During austral summer (January), precipitation dominates, as the region is influenced by strong westerly and southwesterly winds that bring in moist equatorial air. Base map adapted from General Bathymetric Chart of the Oceans (GEBCO; https://www.gebco.net/). Dunefield map and dust path (white arrows) from Hesse et al. (2004). Stars indicate recent IODP expeditions. (B) Plate tectonic motion of Australia since 50 million years ago in 10 million year intervals, with the path line for Site U1459 (Exp. 356) adapted from Gallagher et al. (2017).

changes (winter wet, summer dry) in the southern half of Australia (McLaren et al., 2014; Groeneveld et al., 2017).

The Paleomonsoon and Northwest Australian Climate

Northern and interior Australia had seasonally wetter monsoonal precipitation 23 to 14 million years ago when the monsoonal front was in a similar position to today's (Herold et al., 2011). Arid conditions that persisted from 16 to 6 million years ago in northwest Australia (IODP Expedition 356; Groeneveld et al., 2017) transitioned to a wetter period, with year-round rainfall, at ~5.5 million years ago (IODP Expedition 356; Christensen et al., 2017; De Vleeschouwer et al., 2018), and then to seasonal (monsoonal) rainfall at ~3.3 million years ago. Indonesian Throughflow restriction and falling continental humidity culminated in arid conditions at ~2.4 million years ago, resulting in a seasonal (monsoonal) regime. Over the last 2 million years, interglacial wetter (strong monsoon) and arid glacial (weak monsoon) conditions persisted in Australia's northwest (Gallagher et al., 2014). Arid conditions intensified in a stepwise manner, with drying after ~1.5 million years ago and 0.6 million years ago coinciding with the contraction of megalakes in southeast Australia at ~1.5 million years ago (McLaren et al., 2014) and the expansion of the Simpson Desert at ~1 million years ago (Fujioka and Chappell, 2010).

Southwest Australian Climate and the History of the Westerlies

Compared to the northwest Australian region, little is known of the long-term history of the southwest Australian climate. Fossil and modern sand dunes and dust pathways reflect past wind strength and the relative strength of the westerly winds (Hesse et al., 2004). During the Last Glacial Maximum (18,000 years ago), the westerlies shifted ~3° northward, then returned to their present position after 8,000 years (Hesse et al., 2004), with a pattern similar to that of today. Forty to 25 million years ago, wetter conditions created extensive river systems (Martin, 2006). After 15 million years ago, these river systems dried up, suggesting more arid conditions. Floral fossils in lake sediment suggest a wetter climate compared to today in southwest Australia ~4 million years ago and a transition to arid conditions after 3 million years ago that ultimately led to the drying out of most lakes at around 600,000 years ago (Martin, 2006).

CONCLUSIONS

Analyses of oceanic dust archives off Africa and Arabia show the extremes of climate in these regions over the last several million years. These scientific ocean drilling cores record in great detail the variation in extent of the Sahara Desert and the African monsoon over glacial and interglacial periods. Analyses of recently obtained IODP drilling records off western Australia reveal over 50 million years of monsoonal and oceanic history and ultimately provide an account of

Australian aridification. These offshore ocean archives yield well-constrained histories that are rarely preserved in harsh arid terrestrial environments of continental regions and that will continue to bring key information on global climate evolution, allowing us to understand how deserts and monsoonal systems have evolved.

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Gauging Quaternary Sea Level Changes Through Scientific Ocean Drilling

By Yusuke Yokoyama, Anthony Purcell, and Takeshige Ishiwa

Mining-type drill bit used on Expedition 325, Great Barrier Reef Environmental Changes. *Photo credit: D.S. Smith, ECORD-IODP*

ABSTRACT. Indicators of past sea level play a key role in tracking the history of global climate. Variations in global sea level are controlled mainly by growth and decay of continental glaciers and temperatures that are closely correlated with the mean global climate state (glacial and interglacial cycles). Our understanding of global climate and sea level has benefited significantly from improvements in ocean floor sampling achieved by the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling and International Ocean Discovery Programs (IODP), as well as from the application of new analytical techniques and isotope mass spectrometry. This paper presents an overview of recent advances in paleo-sea level studies based on analysis of samples and data from deep-sea sediment cores and drowned coral reefs obtained through ODP and IODP. Future scientific ocean drilling will contribute further to studies of ice sheet dynamics under different climatic boundary conditions.

INTRODUCTION

Relative sea level change—the change in the sea surface relative to land—is determined by a combination of global and local environmental and geophysical factors, such as glacial ice volume, tectonic uplift and subsidence, and geoid adjustment (Lambeck, 1989). The advance and retreat of ice sheets over timescales of 10^3–10^5 years has dominated Quaternary sea level variations. During the Last Glacial Maximum (LGM, ~20,000–27,000 years before present), large ice sheets covered North America and Northern Europe (Figure 1). Between 20,000 and 6,000 years before present, melting of these ice sheets raised global mean sea level (GMSL) by more than 100 m (CLIMAP, 1981; Lambeck et al., 2014; Yokoyama et al., 2018). The Antarctic Ice Sheet, currently the largest ice sheet on Earth, was even larger at maximum extent, storing an additional 10–30 m GMSL equivalent above its present volume. These ice sheets play a key role in global climate because of their impact on albedo and ocean salinity and, hence, thermohaline circulation.

Past changes in global ice volume can be studied through the direct connection between ice volume and oxygen isotopes in the global hydrological cycle. This connection has been instrumental in providing a detailed and continuous picture of climate and sea level change over time (Shackleton, 1967; Hays et al., 1976). When water evaporates from the ocean, the heavier oxygen and hydrogen isotopes are preferentially left behind. Thus, the snow that builds glaciers will be relatively enriched in the lighter oxygen isotope ^{16}O while the ocean will have relatively more of the heavier oxygen isotope ^{18}O. Consequently, as ice sheets grow, the oxygen isotope ratio within the ocean changes. Deep-sea sediments contain an oxygen isotope record of seawater within the carbonate shells of foraminifera, a major class of marine microfossils (Shackleton, 1967). The relative amounts of the oxygen isotopes in the carbonate skeletons reflect temperature and the isotope ratio of the water when they formed, potentially providing information on ice volume changes. Thus, large-scale changes in GMSL can be broadly reconstructed from foraminiferal oxygen isotope records if temperature is known or assumed (Figure 2). This sensitive proxy has proven to be a game changer in understanding global sea level change over long periods of geological time.

In addition to oxygen isotope records, other indicators are used to determine past sea levels, including geological and biological samples dated through a variety of geochemical methods. A basic principle in determining sea level change

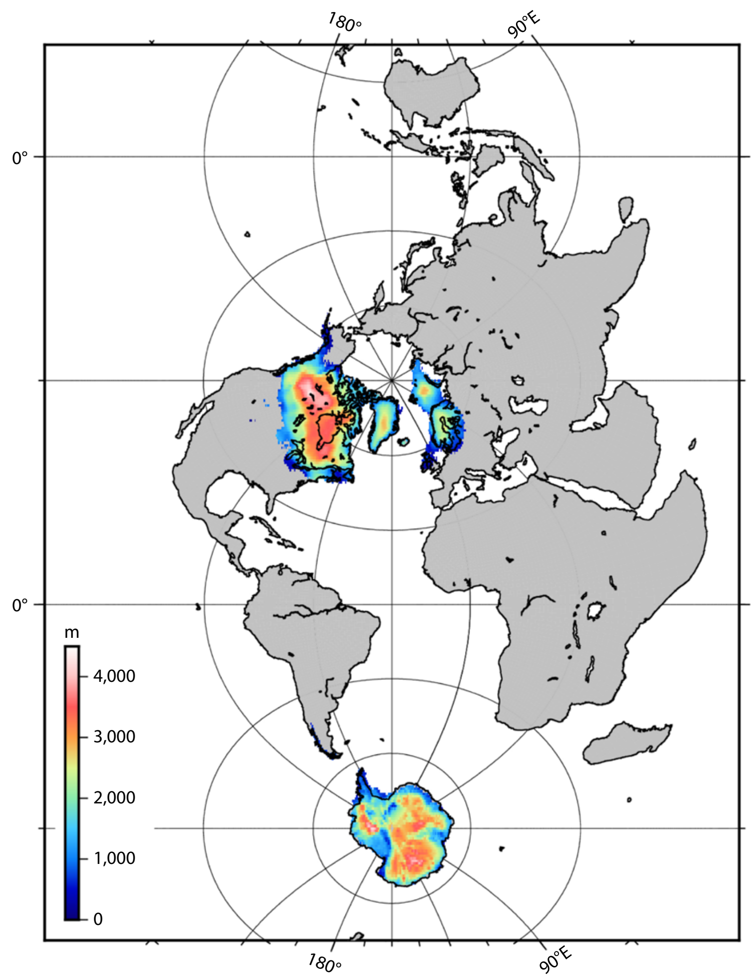

FIGURE 1. Global ice sheet distribution during the Last Glacial Maximum centered around 21,000 years ago according to ice model ICE6G (Peltier et al., 2015). The color bar indicates ice thickness in meters.

is to ensure that the collected sample was formed in situ and is thus indicative of sea level height, within a known uncertainty, and that a reliable age of formation can be determined. Biological carbonate samples, in particular from reef-building corals and coralline algae, are among the best sea level indicators because these organisms are sensitive to sea level and their carbonate skeletons are useful for both ^{14}C and U-series dating (e.g., Camoin et al., 2001; Woodroffe, 2002; Bard et al., 2010; Yokoyama and Esat, 2015).

Although cores collected during Ocean Drilling Program (ODP) and Integrated Ocean Drilling and International Ocean Discovery Programs (IODP) expeditions from the far-field can constrain GMSL, they do not provide information about the meltwater sources that caused sea level to rise. To capture the signals of melting events, scientific ocean drilling collected cores from around Greenland and Antarctica (Figure 3); the magnitude of changes can be deduced by comparing the results of core analyses with global data (e.g., Kanfoush et al., 2000; de Vernal and Hillaire-Marcel, 2008). Sediment cores obtained off East Antarctica provide evidence of the long-term stability of Antarctic ice sheets (e.g., Theissen et al., 2003), whereas cores obtained from Indian sector of the Southern Ocean record millennial-scale fluctuations of the Antarctic ice sheets during the last glacial period (e.g., Hodell et al., 2001).

An alternative approach to identifying meltwater sources that is particularly valuable for determining past ice sheet mass losses is to use modeled sea level signals from individual sources to derive a "sea level fingerprint" for each source. Matching the modeled fingerprints against observed sea level variations allows determination of the sea level contribution from each source (e.g., Clark et al., 2002). More generally, comparing modeled sea level contributions from past melting sourced from different ice sheets with intermediate- and far-field sea level observations from cores could potentially be used to identify past meltwater sources. This methodology requires both high-precision far-field sea level observations and the accurate modeling of the effects of glacial isostatic adjustment (GIA).

In addition to GIA, a factor that complicates determination of GMSL is that sea level is likely also influenced by solid Earth deformation on timescales >100,000 years (Austerman et al., 2013). This deformation can result from uplift (or subsidence) of a continental plate as it moves over upwelling (or downwelling) mantle or surface mass redistribution due to erosion and sediment deposition. The effect of these processes on sea level is negligible on shorter timescales but can amount to two to five meters over 100,000 years. From the geological record it is known that in the Pliocene and Miocene, sea levels were heavily influenced by dynamic topography, with amplitudes of on the order of tens of meters (Rovere et al., 2015). Observations of these effects gained through analysis of cores collected through scientific ocean drilling would provide information against which models of dynamic topography may be validated.

In this paper, we present an overview of sea level studies that have benefited from analysis of scientific ocean drilling cores of sediment and corals from drowned reefs collected by the Ocean Drilling Program, Integrated Ocean Drilling Program, and International Ocean Discovery Program from the 1990s to present.

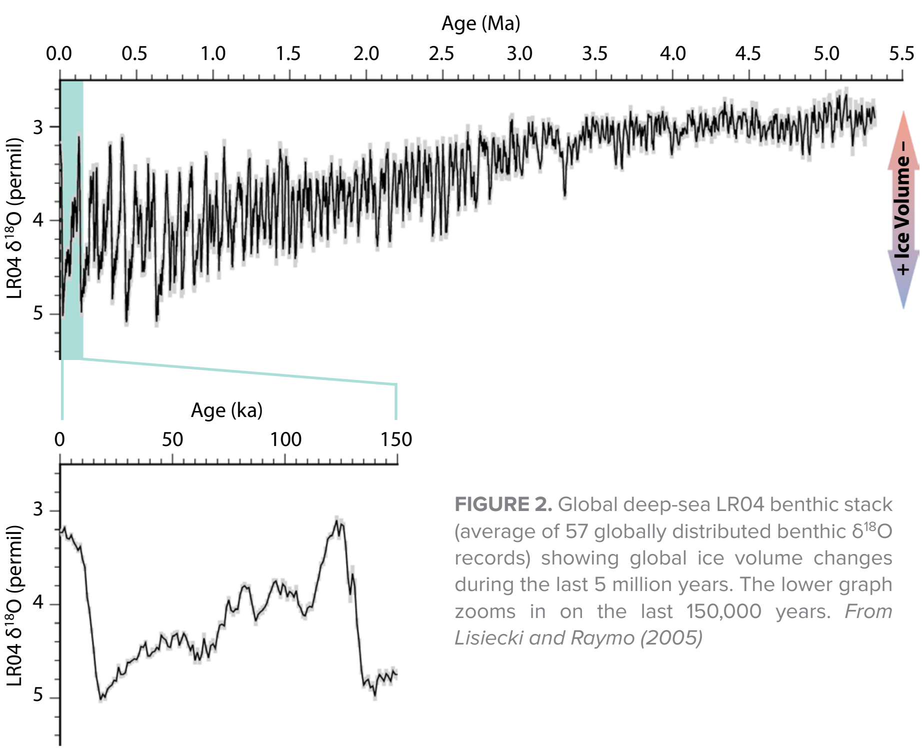

FIGURE 2. Global deep-sea LR04 benthic stack (average of 57 globally distributed benthic $\delta^{18}O$ records) showing global ice volume changes during the last 5 million years. The lower graph zooms in on the last 150,000 years. *From Lisiecki and Raymo (2005)*

PRE-QUATERNARY SEA LEVEL CHANGE FROM THE DEEP-SEA SEDIMENT RECORD

Global ice volumes for the last nine million years have been reconstructed from seawater oxygen isotope fluctuations (as $\delta^{18}O$, a measure of the ratio of ^{18}O to ^{16}O) recorded in the foraminiferal skeletons recovered from deep-sea sediment cores (Lisiecki and Raymo, 2005; Miller et al., 2011; Figure 2). Sea level records obtained from oxygen isotope data reveal that glacial and interglacial ice volume fluctuations shifted in cyclicity from 40,000 years to 100,000 years at around 0.8 million years ago (Lisiecki and Raymo, 2005).

However, extension of the $\delta^{18}O$ data to the pre-Quaternary is complicated by changes in global temperature.

Uncertainties arise in the oxygen isotope-sea level correspondence because oxygen isotope fractionation depends on ambient temperatures, resulting in ice volume errors of more than 20% (Raymo et al., 2018). Various attempts have been made to overcome these difficulties, including compiling oxygen isotope data from deep-sea cores drilled in different ocean basins and statistically processing the combined data (e.g., Ahn et al., 2017), combining oxygen isotope with other temperature proxies (such as trace element abundances; e.g., Rosenthal et al., 2011), and correlating deep-sea core derived oxygen isotope records with uranium-series-dated speleothem climate records (e.g., Cheng et al., 2009; Rohling et al., 2014).

SEA LEVEL SINCE THE LAST ICE AGE

One of the major outstanding scientific questions for both glaciology and climatology of the last glacial cycle is the so-called "missing ice problem," as presented in Andrews (1992). Estimates of the combined volume of the Northern Hemisphere ice sheets during the LGM using evidence from glaciological and geological studies predict a change in GMSL of 102 m (Denton and Hughes, 1981), while estimates of global ice volume deduced from sea level observations predict a change in GMSL of around 130–140 m from the LGM to present (CLIMAP, 1981; Andrews, 1992; Yokoyama et al., 2000; Lambeck et al., 2014). Thus, to match the global ice volume estimate requires placing more than 25 m of GMSL in the Southern Hemisphere, most likely in Antarctica. Yet, recent glaciological reconstructions seem to cluster toward smaller estimates of Antarctic ice sheet volume (typically 10–15 m of GMSL; e.g., Whitehouse et al., 2012). Determining whether the change in global ice volume during the LGM amounts to 130 m GMSL or not is key to understanding global climate boundary conditions during the last glacial period.

Samples of reef-building corals recovered through scientific ocean drilling provide information about relative sea level during the LGM and the subsequent period of deglaciation. Some of the first systematic sea level data were from radiocarbon dates and habitat depth information obtained from submerged corals recovered from drilling offshore Barbados (Fairbanks et al., 1989). Core sample analysis indicated that sea level was ~120 m lower than present during the LGM and that sea level rose in a sequence of rapid meltwater pulses (MWP) during deglaciation (Fairbanks et al., 1989). Later studies of coral and sediment cores confirmed and reinforced these initial findings (Hanebuth et al., 2000; Yokoyama et al., 2000; Bard et al., 2010; Camoin et al., 2012; recent work of author Ishiwa and colleagues). Comparison of these results with other climate archives such as ice cores not only produced refined sea level curves but also showed the need for higher temporal and spatial resolutions to better understand the relationship between global climate and polar ice sheets at millennial to centennial scales (e.g., Rovere et al., 2018). While it was hoped that systematic coral-based sea level reconstructions would solve various paleoceanographic issues, including the missing ice problem, there are also some uncertainties associated with using corals, including the role of tectonic uplift (e.g., Barbados), age conversion from radiocarbon to calendar age (e.g., silicic sediment-based reconstructions; Hanebuth et al., 2000; Yokoyama et al., 2000), and robustness of depth uncertainties that rely on a particular coral (e.g., Barbados).

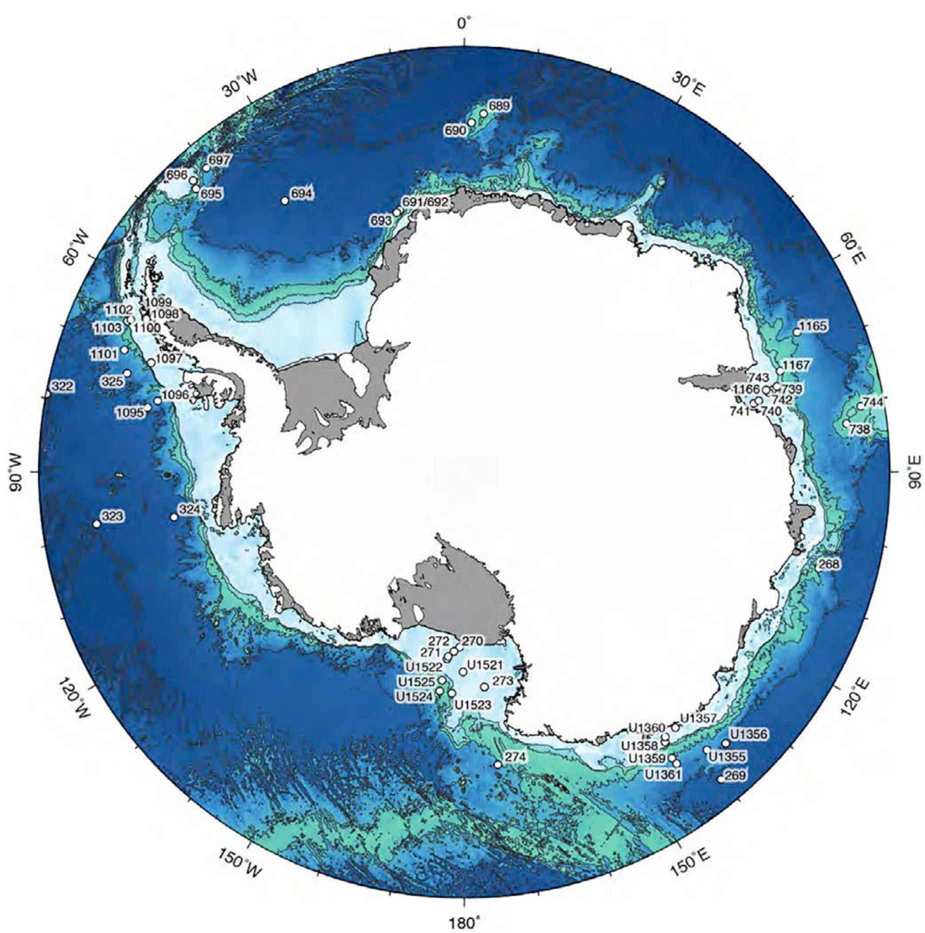

FIGURE 3. Locations of sites drilled around Antarctica during Deep Sea Drilling Project Legs 28 and 35; Ocean Drilling Program Legs 113, 119, and 178; Integrated Ocean Drilling Program Expedition 318; and International Ocean Discovery Program Expedition 374 to study meltwater sources that caused sea level to rise. Three sites (645, 646, 647) were also drilled off Greenland during Ocean Drilling Program Leg 105 for the same purpose.

SEA LEVELS DURING THE LATE PLEISTOCENE

Good localities for collecting samples are the carbonate platforms found in fringing reefs of volcanic islands and atolls as well as barrier reefs, as these structures retain long records through almost continuous reef building. Although many coral-based sea level studies have been conducted on uplifted coral terraces found on shore, at sites such as Tahiti and Huon Peninsula (Papua New Guinea), these land-based drilling projects could only sample corals back to 13,800 years ago (e.g., Edwards, et al., 1993; Bard et al., 2010; Camoin et al., 2012). Prior to the 2005 IODP Expedition 310 "Tahiti Sea Level" (Camoin et al., 2007a,b), the only corals available to the community for study of sea level during the LGM and subsequent deglaciation were from offshore of Barbados (Fairbanks, 1989). In 2010, IODP Expedition 325 (Webster et al., 2011; Yokoyama et al., 2011), using the same approach as the Tahiti drilling expedition, targeted the Great Barrier Reef in Australia (Webster et al., 2011; Yokoyama et al., 2011). The cores recovered by Expeditions 310 and 325 are providing an additional rich source of data to better understand sea level change during and after the LGM.

The three main scientific objectives of IODP Expeditions 310 to Tahiti and 325 to the Great Barrier Reef were (1) to establish the details of sea level rise, including pulses of rapid rise during the last deglaciation, such as MWP1a, MWP1b, and 19ka MWP (Figure 4; Fairbanks, 1989; Yokoyama et al., 2000), (2) to determine the nature and magnitude of seasonal to millennial-scale climate variability, and (3) to examine the biologic and geologic responses of Tahiti and the Great Barrier Reef to abrupt sea level and climate changes (Camoin et al., 2007a,b; Webster et al., 2011; Yokoyama et al., 2011).

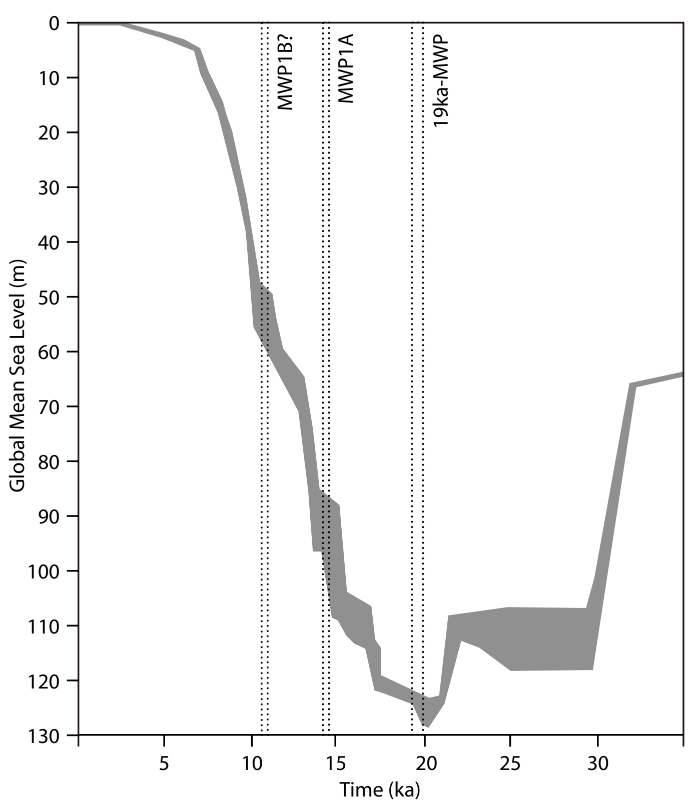

FIGURE 4. Newly obtained global mean sea level from fossil coral reef materials obtained from the Great Barrier Reef during Integrated Ocean Drilling Program Expedition 325 combined with data from a glacio hydro isostatic adjustment model. Dotted lines are previously proposed rapid melting events since the Last Glacial Maximum discussed in the text. MWP = Meltwater Pulse. *Figure modified from Yokoyama et al. (2018)*

IODP Expedition 310 marked the first IODP coring of coral reef materials from the Pleistocene. The recovered samples provided sea level records for both the Last Glacial Termination (Termination I or TI; Deschamps et al., 2012) and the deglaciation that followed the penultimate glacial maximum, Termination II in the Pleistocene (TII; Thomas et al., 2009). Termination is the term used for the relatively rapid transitions (≤10,000 years) from glacial to interglacial conditions, with T1 being the most recent termination. Analysis of uranium series nuclides from Tahitian corals that grew during TII suggests that ice volume reductions preceded atmospheric CO_2 increase, but postdate increased insolation at Northern Hemisphere high latitudes—confirming the Milankovitch hypothesis, which says that glacial terminations were initiated by changes in high-latitude insolation (Thomas et al., 2009). The large magnitude of sea level changes during TI and TII were also recorded in assemblages of large benthic foraminifera in the reef materials, suggesting that those specimens can be used to identify deglaciations and independently validate U-series ages obtained from coral samples, even though foraminifera shells may be susceptible to diagenetic changes after deposition (Fujita et al., 2010).

The sea level reconstruction for TI made possible by the Tahiti cores identified the timing and magnitude of MWP-1A, which had not been tightly constrained in previous studies. Debate continues about whether the Northern Hemisphere ice sheet is the sole source of meltwater for MWP-1A. The answer is important because it will help us understand the stability of Antarctic ice sheets against global warming as well as solve the missing ice problem. A sequence of U-series dates obtained from shallow-water corals drilled during Expedition 310 yielded a date for MWP-1A of ~14,600 years ago with a sea level change magnitude of about 16 ± 2 m at a rate of about 40 mm yr^{-1} (Deschamps et al., 2012). Using sea level fingerprinting techniques (Clark et al., 2002), these results have been compared to the Barbados sea level reconstructions of Fairbanks (1989) in an effort to identify the source of the meltwater that drove this event. This analysis found that the source of meltwater was likely not restricted to the Northern Hemisphere ice sheets, and must include a contribution from Antarctica. However, no cores older than 16,000 years old were recovered by the Tahiti drilling, so the magnitude of LGM sea level minimum and its source remained unknown.

In 2010, IODP Expedition 325 to the Great Barrier Reef recovered fossil reef materials from two transects separated by more than 500 km. Detailed investigations of the different reef facies contained in the cores, together with more than 1,000 dates obtained from radiocarbon and U-series dating of coral samples, show almost identical relative sea level histories in both transects (Yokoyama et al., 2018). These analyses were enabled by the use of new core sampling equipment, including HQ-size wireline core barrels used in the mining industry, and resulted in better recovery of reef materials (35%–40%) than previously possible, allowing construction of more accurate sea level curves.

Modeled GMSL from IODP Expedition 325 results suggests that the maximum sea level drop during the LGM was 118 m at the Great Barrier Reef. This is larger than the 102 m drop estimated for the Northern Hemisphere ice sheets during the LGM, suggesting that Antarctic excess ice volume during the LGM was at least 11 m of GMSL. After correcting for GIA, the GMSL drop during the LGM becomes −125 m to −130 m based on the Great Barrier Reef record, and accordingly, the excess LGM Antarctic ice volume must have been even higher (e.g., 23–28 m GMSL from Antarctica; Yokoyama et al., 2018). Because the GIA contributions at these and other far-field sites are dominated by hydro-isostatic effects, the uncertainties in crustal rheology have only a small impact, and the GIA signal depends mostly on the magnitude of the local water load (Figure 5). The new sea level data revealed previously unknown rapid drops and rises in sea levels during the last 30,000 years (Yokoyama et al., 2018).

In addition, almost 3°–5°C cooling was recorded in the core samples as $\delta^{18}O$ and Sr/Ca excursions during the LGM (Felis et al., 2014). These large temperature changes severely impacted the Great Barrier Reef, and together with rapid sea level changes resulted in at least five "near death events" during the last 30,000 years (Webster et al., 2018). The Great Barrier Reef's survival of these significant environmental changes may provide a key to understanding the ecological resilience of reef systems (Webster et al., 2018).

In summary, analyses of cores collected globally and in a range of settings by scientific ocean drilling have revealed unexpected behavior of the major ice sheets and their responses to climate forcing. A rapid melting, so-called MWP-1A, occurred at around 14,600 years ago according to corals obtained from IODP Expedition 310 to

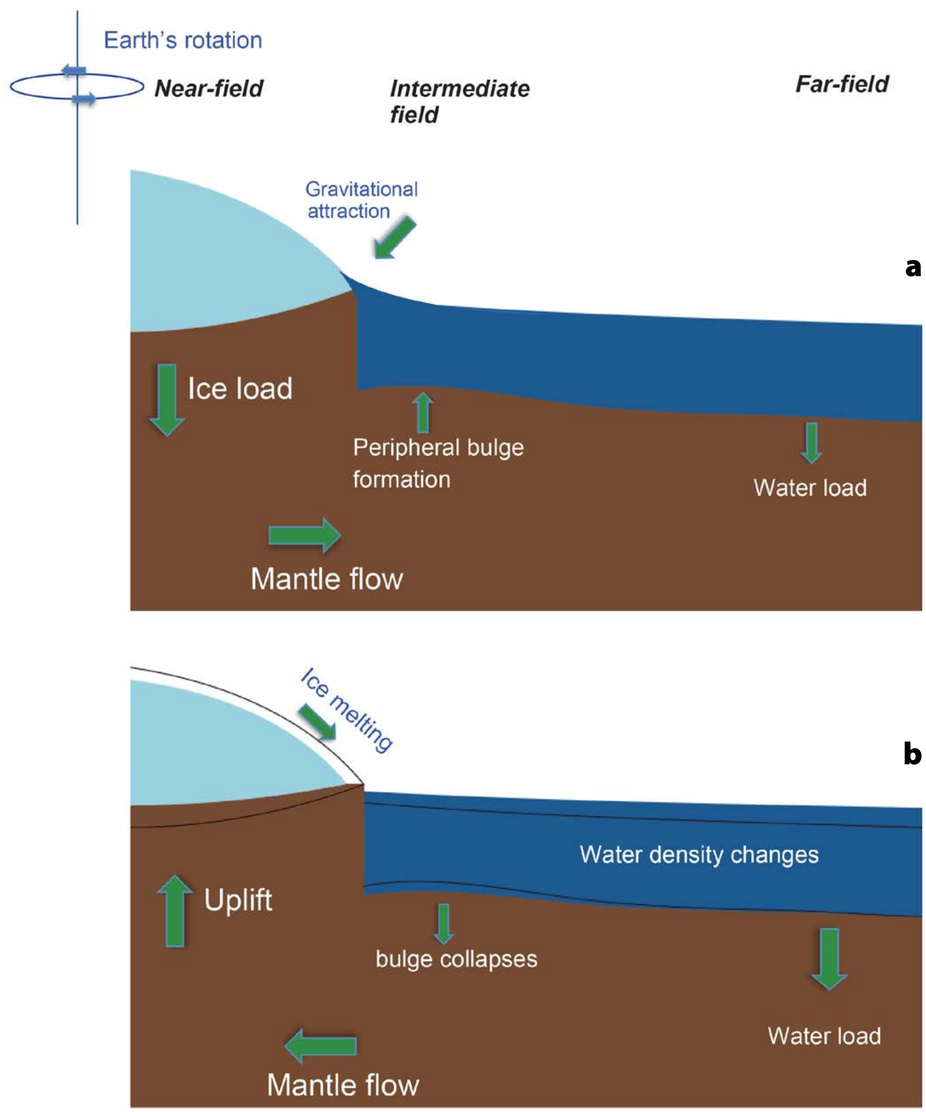

FIGURE 5. Schematic diagram of physical processes and their impacts associated with changes in ice sheets. (a) During the growth stage, these include local crustal loading and an intermediate crustal bulge due to mantle flow, gravitational attraction of seawater adjacent to and toward the ice margin, and perturbation of Earth's rotational axis. (b) During the melting stage, there is local uplift, bulge collapse, and a decrease in rotational disturbances and local gravitational effects on seawater. *From Yokoyama and Esat (2011)*

Tahiti. The conventional picture of ice sheets is that growth is slow but disintegration is rapid. However, cores from the Great Barrier Reef collected during IODP Expedition 325 clearly captured a rapid, two-step buildup of global ice sheet volume, reflected as two rapid sea level falls at about 30,000 years ago and 21,000 years ago, before culmination at the LGM. Because current glaciological models do not have the capacity to reproduce these rapid changes identified through scientific ocean drilling, it is important to incorporate this dynamic behavior into models in order to better predict future changes.

CONCLUSIONS

Scientific ocean drilling has provided the Earth and ocean sciences communities with valuable data that have allowed reconstructions of past global mean sea level and ice sheet volumes. These data provide some of the most immediate large-scale constraints on climate and ice sheet interactions, the rate and magnitude of ice sheet and climate adjustments, and local environmental conditions from previous epochs, particularly during and since the last glacial maximum.

Our understanding of the extent and magnitude of the major ice sheets since the LGM has been greatly enhanced by scientific ocean drilling core data, which have shown that sea level is highly variable and very dynamic, contradicting the results of ice sheet modeling efforts. However, this variability points out that more data are needed to fully understand sea level changes that occurred before and during the LGM at a resolution sufficient to more tightly constrain the GMSL curve.

The responses of the Antarctic Ice Sheet to past climate forcings are a critical, but poorly constrained, component of our understanding of potential contributions of the Antarctic Ice Sheet to present and future sea level changes. Given that many formerly glaciated regions of Antarctica are now submerged, seafloor surveys and scientific ocean drilling will continue to play a vital role in more tightly constraining the history of the Antarctic Ice Sheet and regional sea level change.

Our estimates of the magnitude of the fall in sea level during the Last Glacial Maximum and the late glacial period also rely heavily on IODP results. These estimates of roughly −130 m GMSL, in combination with reconstructions of the Northern Hemisphere ice sheets, allow us to infer that the Antarctic Ice Sheet was much larger than its present maximum extent (30 m GMSL) and larger than suggested by glaciological modeling. Further sampling of the Antarctic continental shelf by scientific ocean drilling is required to better constrain the evolution of the Antarctic Ice Sheet and to distinguish between different possible ice history scenarios.

On longer timescales (e.g., pre-Quaternary), the effects of other geological processes become increasingly significant. In particular, sea level changes resulting from dynamic topography can reach amplitudes of tens of meters. Robust paleo-sea level data are required to validate numerical models of this process. This makes the interpretation of sea level data from the last interglacial particularly difficult because dynamic topography and GMSL effects are of comparable magnitude in this epoch and not readily disentangled.

Although today models of GIA are more mature and have been repeatedly tested against large data sets, there remain significant uncertainties associated with the rheological parameters and the trade-off between ice and Earth models. These uncertainties have generally not been well explained by the GIA community, but must be considered when these models are applied to observational data, such as those collected during Deep Sea Drilling Project, ODP, and IODP expeditions.

Improvements in numerical models of geophysical processes and in seafloor sampling techniques and refinements in analytical methodology will produce more accurate data and a more comprehensive understanding of paleo-environments. These advancements will expand the range of scientific questions that can be addressed and lead to further refinements in our understanding of past and present sea level and climate. The value of IODP's contribution to this process cannot be overstated.

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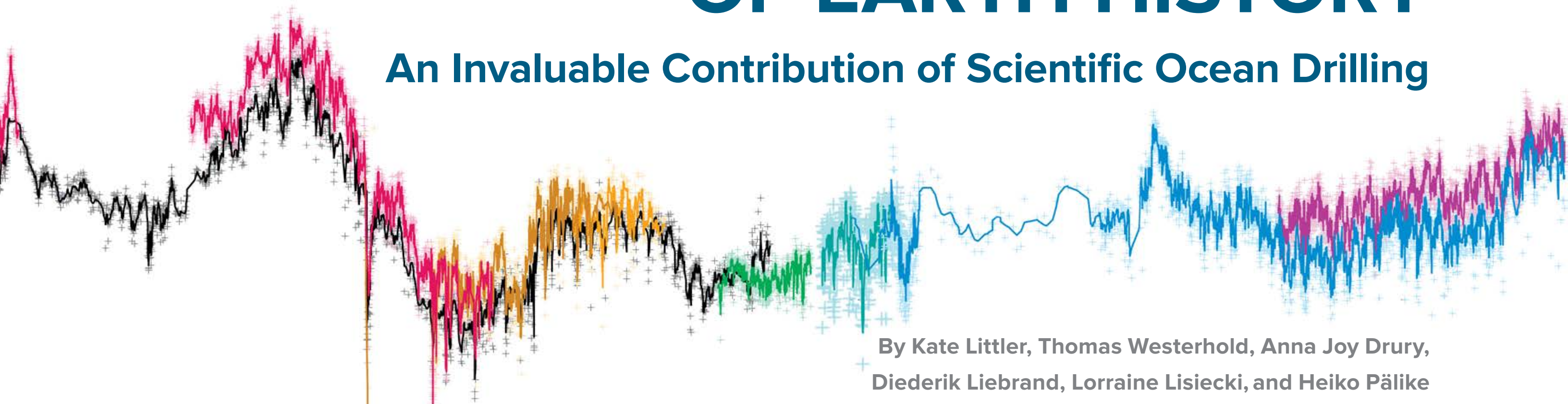
ASTRONOMICAL TIME KEEPING OF EARTH HISTORY

An Invaluable Contribution of Scientific Ocean Drilling



By Kate Littler, Thomas Westerhold, Anna Joy Drury, Diederik Liebrand, Lorraine Lisiecki, and Heiko Pälike

ABSTRACT. The mathematically predictable cyclic movements of Earth with respect to the sun provides the basis for constructing highly accurate and precise age models for Earth's past. Construction of these astronomically calibrated timescales is pivotal to placing major transitions and events in the geological record in their temporal context. Understanding the precise nature and timing of past events is of great societal relevance as we seek to apply these insights to constrain near-future climate scenarios. Scientific ocean drilling has been critical in this endeavor, as the recovery and analysis of high-quality and continuous marine sedimentary archives underpin such high-resolution age models for paleoclimate records. This article identifies key astronomically calibrated records through the past 66 million years (the Cenozoic) collected during multiple Deep Sea Drilling Project, Ocean Drilling Program, Integrated Ocean Drilling Program, and International Ocean Discovery Program expeditions, highlights major achievements, and suggests where future work is needed.

INTRODUCTION

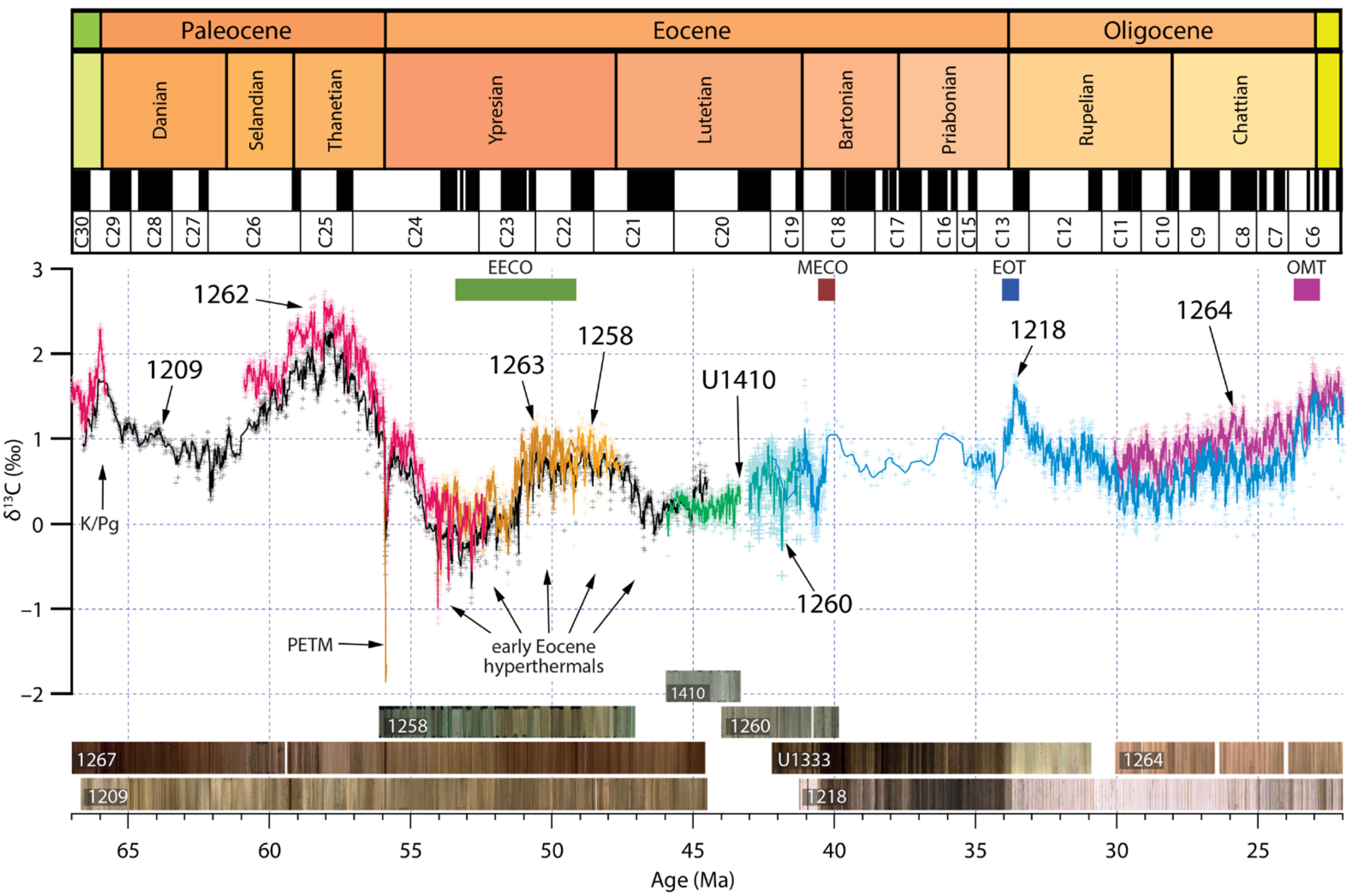
Five decades of scientific ocean drilling by the International Ocean Discovery Program (IODP) and its predecessors continue to provide unique sample material essential for developing highly accurate astronomically calibrated timescales. It has long been recognized that cyclic changes in both the absolute distance of Earth from the sun throughout the year and the angle of Earth's rotational axis influence the latitudinal distribution of incoming solar radiation (insolation) and, hence, the amplitude of the seasons (Milankovitch, 1941; Laskar et al., 2004). Through many processes within the Earth system, these quasi-cyclic changes in insolation pace global climate change (e.g., Hays et al., 1976). Time-series analysis of the high-resolution sediment archives provided by scientific ocean drilling clearly document the persistent response of the Earth system to astronomical climate forcing over the last 66 million years. In particular, records of elemental abundances in sediment derived from X-ray fluorescence (XRF) core scanning and of the stable isotope ratios of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) of bulk sediment and benthic foraminifera—which are proxies for water chemistry and combined temperature and ice volume—are dominated by variations corresponding to Earth's astronomical cycles of eccentricity (~400 kyr and ~100 kyr), obliquity (~41 kyr), and orbital precession (~23 kyr). The orbital imprint in deep ocean sediments is ubiquitous, providing an important means of time keeping as well as allowing investigation of internal Earth system feedback processes.

Here, we highlight the great contribution that scientific ocean drilling has made to constructing precise astrochronological timescales for the Paleogene (from 66 to 23 million years ago) and the Miocene to Pleistocene (from 23 million to 11,700 years ago).

THE PALEOCENE, EOCENE, AND OLIGOCENE

Paleoclimate records from the Paleogene greenhouse world provide a unique opportunity to constrain Earth's climate system behavior under similar atmospheric CO_2 concentrations projected for the year 2100, and to investigate in detail the causal relationships between astronomical forcing and climatic/cryospheric and carbon cycle responses. Within the Paleogene, the Paleocene and Eocene Epochs (~66–34 million years ago) were generally characterized by warm "greenhouse" climates, reaching peak temperatures during the Early Eocene Climatic Optimum (EECO; Zachos et al., 2008; Lauretano et al., 2018) and punctuated by orbitally paced "hyperthermals" (i.e., strong, short-lived heating events) such as the Eocene Thermal Maximum 2 (~54 million years ago; e.g., Stap et al., 2010; Figure 1). The spatial coverage and temporal resolution of records was very limited prior to recovery of high-quality, multiple-hole sedimentary successions from the Atlantic, including Ocean Drilling Program (ODP) Leg 207 (e.g., Sexton et al., 2011), ODP Leg 208 (e.g., Zachos et al., 2010; Littler et al., 2014; Lauretano et al., 2016, Westerhold et al., 2017), and IODP Expedition 342 (e.g., Boulila et al., 2018; Vahlenkamp et al., 2018). Important records were also recovered from the Pacific, including ODP Leg 198 (e.g., Westerhold et al., 2011, 2018), and IODP Expedition 320/321 (e.g., Westerhold et al., 2014). Both XRF and stable isotope records from these continuous archives provided spectacular new insights into climate dynamics of a warm world (Figure 1). In particular, eccentricity-modulated precession cycles are ubiquitous at these sites (e.g., Zachos et al., 2010; Littler et al., 2014; Lauretano et al., 2016; Westerhold et al., 2017).

Following long-term mid-late Eocene global cooling, as indicated by a gradual increase in $\delta^{13}C$ values, the largest shift in the climate state of the Cenozoic occurred during the Eocene-Oligocene climatic transition (EOT; ~34 million years ago; Figure 1), which marked the establishment of a larger and more permanent Antarctic ice cover that reached its continental margin (Coxall et al., 2005; Pälike et al., 2006b). The mid-Oligocene glacial interval (28–26 million years ago; Pälike et al., 2006b; Liebrand et al., 2017) was another major cooling episode characterized by a large but dynamic Antarctic ice sheet that varied in size on astronomical timescales. This was followed by warming and retreat of the Antarctic



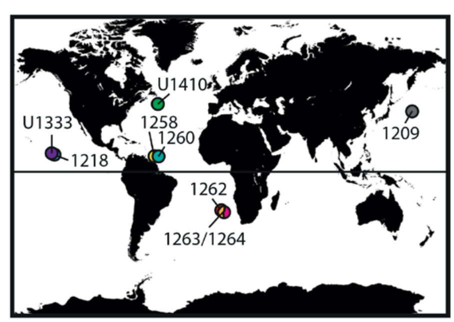


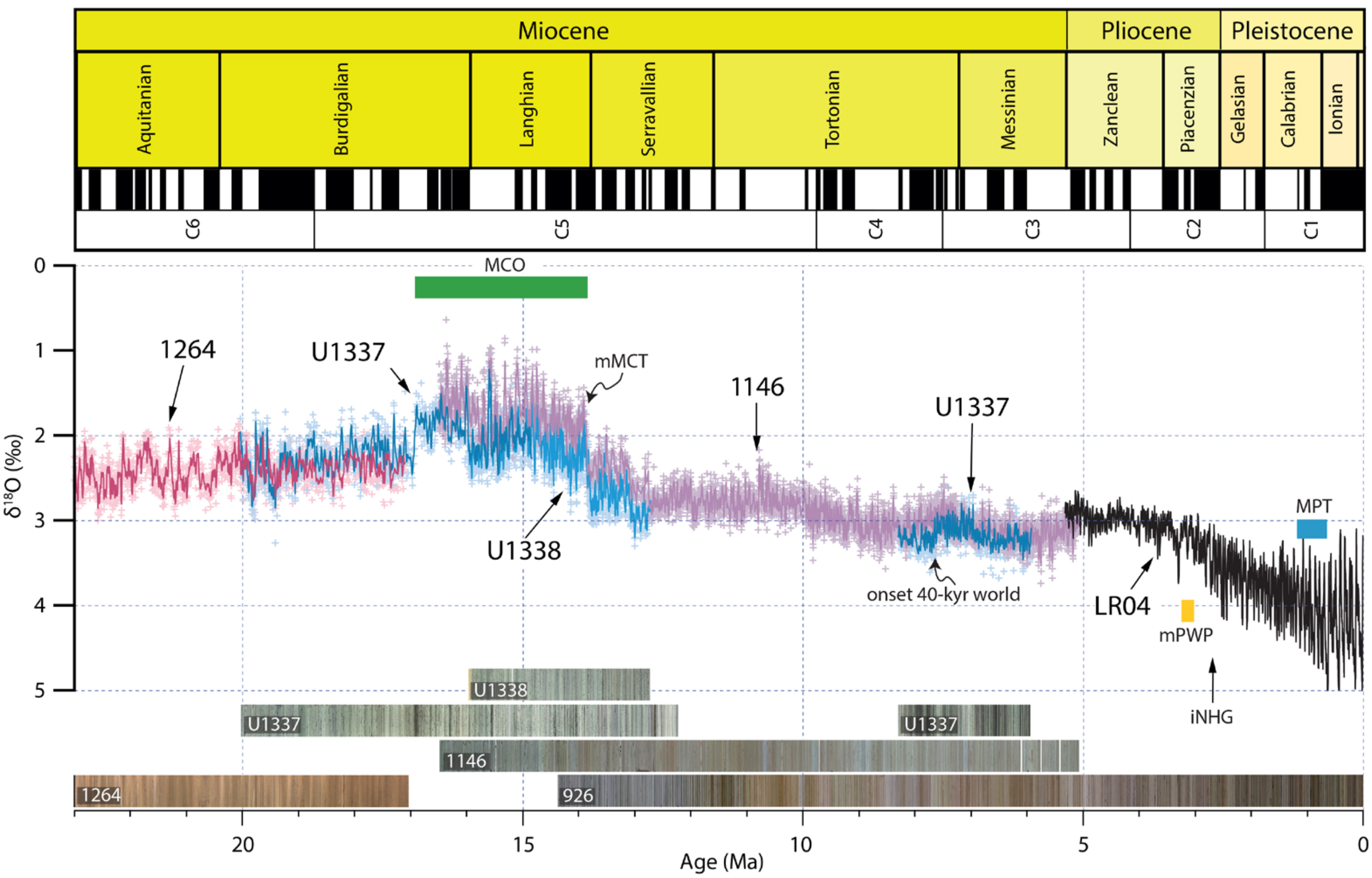
FIGURE 1. Compilation of the benthic carbon isotope data sets used in the construction of astronomically tuned age models in the Paleogene, plotted against age in millions of years (Ma). Data sources: ODP Site 1209 (Leg 198; Westerhold et al., 2011, 2018), ODP Site 1218 (Leg 199; Coxall et al., 2005; Pälike et al., 2006b; Coxall and Wilson, 2011), ODP Site 1258 (Leg 207; Sexton et al., 2011), ODP Site 1262 (Leg 208; Littler et al., 2014), ODP Site 1263 (Leg 208; Stap et al., 2010; Lauretano et al., 2015, 2016), ODP Site 1264 (Leg 208; Liebrand et al., 2016), IODP Site U1410 (Expedition 342, Vahlenkamp et al., 2018), and IODP Site U1333 (Expedition 320/321; Westerhold et al., 2014), all updated on the Westerhold et al. (2017) age model where appropriate. Variability in $\delta^{13}C$ best illustrates astronomical-scale variability in the warm, ice-free early Paleogene world. Colored lines represent three-point running means of the data. The inset map locates ODP and IODP sites for which data are presented. Representative core images from which these isotope data are generated are shown below the plot, with additional images from IODP Site U1333 spanning the middle-late Eocene, for which no published high-resolution isotope data (yet) exists. PETM = Paleocene-Eocene Thermal Maximum. MECO = Middle Eocene Climatic Optimum.

ice sheet, preceding the transient cooling and "re-glaciation" of Antarctica across the Oligocene-Miocene climatic transition (OMT; 23 million years ago; Billups et al., 2004; Pälike et al., 2006b; Liebrand et al., 2016; Beddow et al., 2018).

The Oligocene (~34–23 million years ago) was first astronomically calibrated using sediments recovered from the equatorial Atlantic (ODP Leg 154; Shackleton et al., 1999; Zachos et al., 2001) and Pacific (ODP Leg 199, Pälike et al., 2006b). This tuning has been confirmed at the ~400 kyr eccentricity level using sedimentary records from the Atlantic Ocean, including ODP Leg 177 (Billups et al., 2004), ODP Leg 154 (Pälike et al., 2006a), ODP Leg 208 (Liebrand et al., 2016), and IODP Expedition 342 (Van Peer et al., 2017). A more recent eccentricity-tuned record from the equatorial Pacific (IODP Expedition 320/321; Beddow et al., 2018) confirmed the accuracy of the numerical ages across the Oligocene–Miocene transition to the ~100 kyr eccentricity level.

THE MIOCENE, PLIOCENE, AND PLEISTOCENE

The Miocene (~23.0–5.3 million years ago) was characterized by a series of stepwise changes in global climate: warming culminating in the Miocene Climatic Optimum (MCO; 17.0–13.9 million years ago; Holbourn et al., 2014, 2015) as indicated by the lowest $\delta^{18}O$ values, cooling across the middle Miocene Climate Transition (mMCT; ~13.9 million years ago; Tian et al., 2013; Holbourn et al., 2014) portrayed by increasing $\delta^{18}O$ values, and the late Miocene onset of the "40-kyr world" (~7.7 million years ago; Drury et al., 2017, 2018b; Figure 2). The first Miocene deep-sea astronomically resolved records were recovered from ODP Leg 154 (Shackleton and Crowhurst, 1997; Shackleton et al., 1999; Zeeden et al., 2013; Wilkens et al., 2017) and ODP Leg 162 (Hodell et al., 2001)



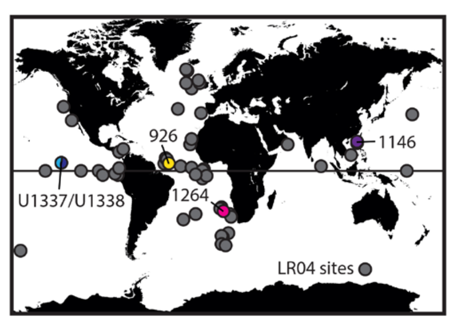


FIGURE 2. Compilation of selected benthic oxygen-isotope data sets used in the construction of astronomically tuned age models in the Miocene-Pleistocene, plotted against age in millions of years (Ma). Date sources: LR04 Stack (Lisiecki and Raymo, 2005), ODP Site 926 (Leg 154; Wilkens et al., 2017), ODP Site 1146 (Leg 184; Holbourn et al., 2007), ODP Site 1264 (Leg 208; Liebrand et al., 2016), IODP Site U1337 (Expedition 320/321; Holbourn et al. 2015; Drury et al., 2017), and IODP Site U1338 (Expedition 320/321; Holbourn et al., 2014). Benthic $\delta^{18}O$ records reflect both temperature and ice-volume variability and best represent astronomical-scale variability in the Neogene Icehouse. Colored lines represent three-point running means of the data. The inset map indicates ODP and IODP sites for which data are presented. Representative core images from which these isotope data are generated are shown below the plot, with an image from ODP Site 926, for which XRF elemental data exist but are not plotted. Note that all $\delta^{18}O$ data is offset by +0.64‰ relative to raw values, except for LR04 data, which are already corrected to equilibrium.

in the Atlantic, and ODP Legs 184 and 202 in the Pacific (e.g., Holbourn et al., 2005). Scientific ocean drilling has now provided continuous astronomical-scale stable isotope stratigraphies from 23 to 5 million years ago at key sites from ODP Legs 154, 162, 177, 184, and 208, and IODP Expedition 320/321 (Billups et al., 2004; Tian et al., 2013; Holbourn et al., 2014, 2015, 2018; Liebrand et al., 2016; Drury et al., 2017, 2018a,b). These records are underpinned by astrochronologies that are precise at the obliquity to precession levels, within the limitations of the numerical astronomical solutions. However, astronomically tuned records that combine isotope- and magnetostratigraphies are only available for the intervals spanning 24–16 million years ago (ODP Leg 177, Site 1090; Billups et al., 2004) and 8–6 million years ago (IODP Expedition 321, Site U1337; Drury et al., 2017).

The Pliocene and Pleistocene (5.3 million to 11,700 years ago) are characterized by a long-term global cooling onward from the mid-Pliocene Warm Period (mPWP, ~3 million years ago) and the intensification of Northern Hemisphere glaciation (iNHG; ~2.7 million years ago; Woodard et al., 2014). Superimposed on these long-term trends are astronomically paced oscillations between glacial and interglacial periods, which are observed in many high-resolution benthic $\delta^{18}O$ records and other climate-sensitive proxies. Overall, astronomical-band variance in benthic $\delta^{18}O$ increases exponentially during the long-term cooling trend and ice sheet expansion of the last 5 million years (Lisiecki and Raymo, 2007). Again, scientific ocean drilling has recovered astronomically resolved climate records from dozens of cores, providing the opportunity to create an average or stack of the synchronized global $\delta^{18}O$ signal ("LR04"; Lisiecki and Raymo, 2005). Stacks improve confidence in astronomically tuned age models by increasing the signal-to-noise ratio of astronomical responses (Imbrie et al., 1984), minimizing the impact of hiatuses or disturbances in individual cores, and providing an estimate of globally averaged sedimentation rates to assist with the tuning process. Within the Pleistocene, orbital tuning is associated with age uncertainties of 4 kyr (Lisiecki and Raymo, 2005). Robust astrochronologies made possible through stacked deep-sea drilling records are critical to identifying and understanding the major Plio-Pleistocene climate events, such as the mPWP (e.g., Dowsett et al., 2012) and the Mid-Pleistocene transition (MPT; ~1.2–0.6 million years ago) when the dominant mode of climate variability shifted from 41 kyr to 100 kyr cycles (e.g., Clark et al., 2006).

OUTLOOK

Despite much recent progress toward constructing a highly accurate Cenozoic stratigraphic framework using data from scientific ocean drilling cores, outstanding issues remain for several time periods. For example, there is a mid–late Eocene (~34–44 million years ago) "gap" in coverage, where until recently we lacked suitable cores to construct high-resolution geochemical proxy records (Figure 1). Continuing work on the IODP Expedition 320/321 sites, notably Site U1333 and sediments recovered from IODP Expedition 369 in 2017 in the Southeast Pacific, will hopefully close this stratigraphic gap. Multiple records spanning the same time interval will allow inter-basin and latitudinal differences in the expression of astronomically paced climate cycles to be fully explored, and will give greater confidence in the orbitally tuned age models for those intervals. A major outstanding goal is to acquire multiple astronomically tuned records from different ocean basins with which to generate a complete Cenozoic stack to match that already available for the Plio-Pleistocene. Despite the invaluable archive currently provided by ODP and IODP coring, the scarcity of suitable sediments, particularly from the high latitudes and the Indian Ocean, remains a critical challenge. Recent Indo-Pacific IODP expeditions (353–356, 363, 369, 371) and future Southern Ocean and Atlantic Ocean drilling can help resolve these issues. Ultimately, further scientific ocean drilling is essential to developing precise and accurate age models for Cenozoic climate reconstructions.

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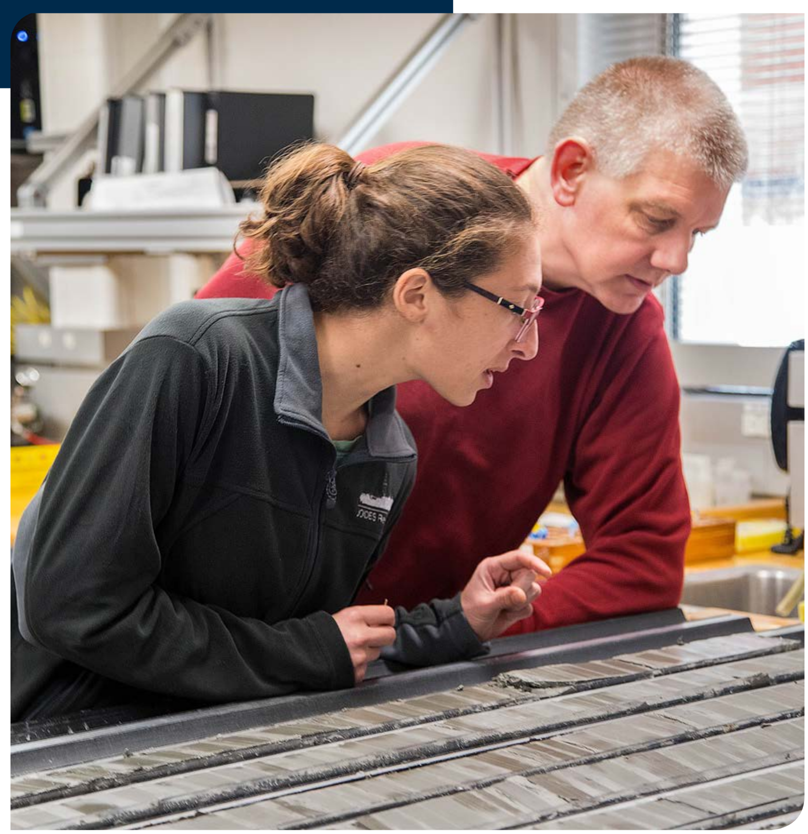
SPOTLIGHT 6.

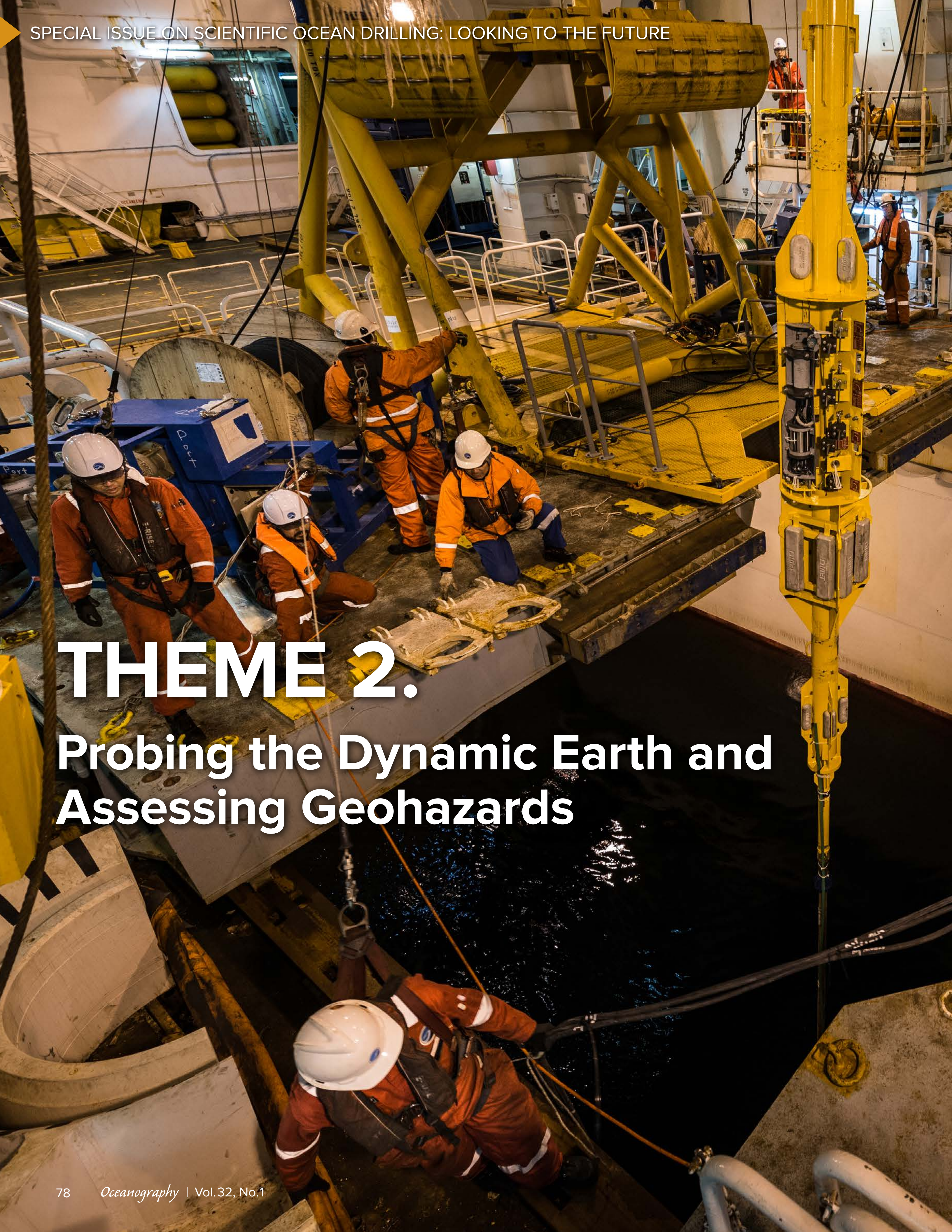
Future Opportunities in Scientific Ocean Drilling: Climate and Ocean Change

Scientific ocean drilling through the current phase of the International Ocean Discovery Program has provided invaluable geographic and temporal data that address critical climate and ocean issues, yet significant gaps remain for future drilling to target. For example, by using the program's highly successful regional and transect drilling strategies, there is the potential to transform our understanding of the El Niño-Southern Oscillation and the monsoonal systems in North America and Africa. Accessing seafloor in the northern high latitudes would provide a critical complement to ongoing regional drilling in the Southern Ocean, where seven expeditions will be conducted between 2017 and 2021 around the Antarctic continent. Understanding tropical climate systems and their effects on the global Earth system also requires future scientific ocean drilling. Synthesis of regional drilling results, combined with recovery of sediments from key time periods, particularly the pre-Pliocene, will vastly improve our understanding of all aspects of climate dynamics under the $p\mathrm{CO_2}$ levels predicted for Earth's climate in the near-term. Linking marine paleoclimate records with terrestrial counterparts at all spatial and temporal scales will enhance understanding of the entire Earth system and its response to change.

– Debbie Thomas



Sedimentologists Anna Halberstadt (University of Massachusetts Amherst, USA) and Claus-Dieter Hillenbrand (British Antarctic Survey, UK) look at a freshly split core aboard *JOIDES Resolution* during IODP Expedition 379, Amundsen Sea. *Photo credit: Tim Fulton, IODP JRSO*



THEME 2.

Probing the Dynamic Earth and Assessing Geohazards

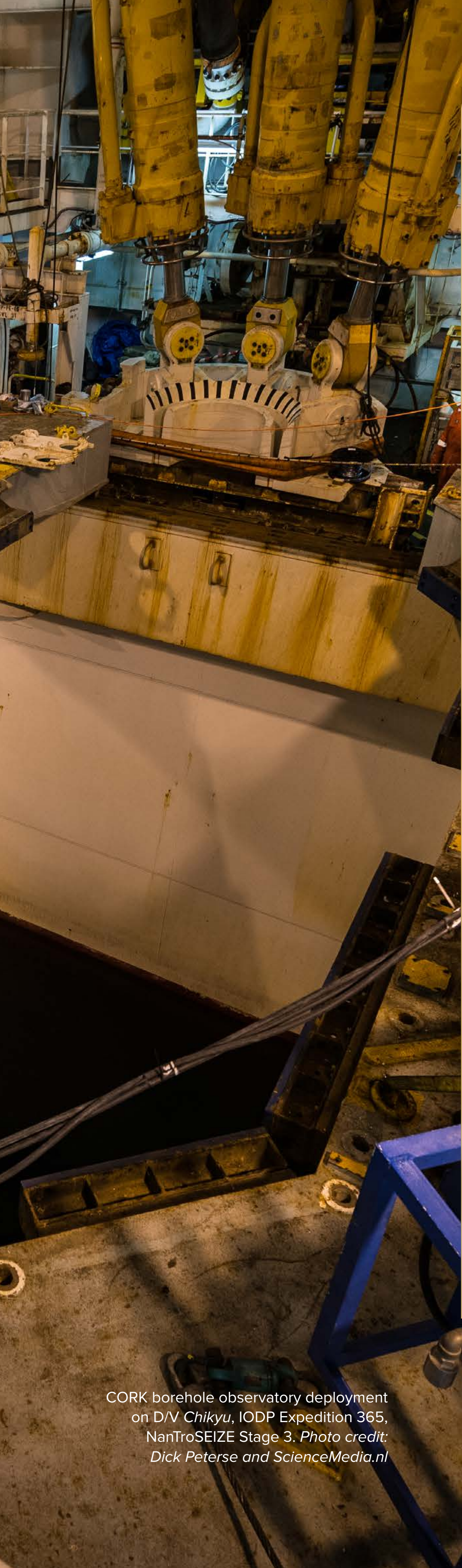
Scientific ocean drilling lies at the center of fundamental advances in understanding the dynamics of Earth's mid-ocean ridges and continental margins, including some of the earliest underpinnings of the nascent theory of plate tectonics in the 1960s. Over the past five decades, the Deep Sea Drilling Project (DSDP), the Ocean Drilling Program (ODP), and the Integrated Ocean Drilling and International Ocean Discovery Programs (IODP) have provided unique access to the subseafloor that has driven continued refinement of these ideas, led to the discovery of new geological phenomena, and motivated revolutionary borehole sensor and instrument development. Through sampling and continuous in situ monitoring of Earth's most active geological systems, scientific ocean drilling has led to profound insights into the dynamics of earthquakes and associated strain accumulation and release, landslides, hydrothermal circulation, and gas hydrate systems.

These efforts include drilling to sample and log boreholes in order to characterize fluid and rock composition, rock physical properties, and in situ fluid flow, temperature, and stress state in Earth's most active geologic systems. Deep riser-based drilling on *Chikyu* as part of the multi-expedition and multiyear Nankai Trough Seismogenic Zone Experiment, in addition to numerous investigations by *JOIDES Resolution* along the Ring of Fire in the Pacific, have provided access to the deep interior of subduction zones that in the recent past have generated (repeated) historical great earthquakes and tsunamis. This has yielded the most comprehensive view of any such geohazard process in the world.

In addition, borehole observatories emplaced across the spectrum of geological and tectonic settings, from ocean ridges to trenches, are providing a sustained presence in the subseafloor, enabling both continuous monitoring and active in situ experimentation designed to probe the subsurface. These investigations have provided an increasingly clearer understanding of the mechanisms that underlie subduction zone earthquakes and tsunamis. This approach also has provided novel insights into coupled fluid, thermal, geochemical, and biological processes that shape the evolution of newly formed oceanic crust and the nature of episodic, transient flows of methane and fluid in hydrate systems.

In this special issue of *Oceanography*, we highlight foundational DSDP, ODP, and IODP contributions to understanding our planet's dynamic processes over a range of timescales, as well as the exciting new questions that have emerged from these efforts, which lie at the heart of the current program's Earth in Motion theme. These include studies of great subduction earthquake processes, the discovery and underlying mechanisms for slow earthquake phenomena, the use of drilling to probe the energetics and dynamics of both recent and ancient earthquakes, the advances made in our understanding of expansive and vigorous fluid, heat, and chemical cycling in mid-ocean ridge hydrothermal systems, and the collection of a broad suite of observations enabled by borehole observatories.

– Demian M. Saffer



CORK borehole observatory deployment on D/V *Chikyu*, IODP Expedition 365, NanTroSEIZE Stage 3. *Photo credit: Dick Peterse and ScienceMedia.nl*

PROCESSES GOVERNING GIANT SUBDUCTION EARTHQUAKES

IODP Drilling to Sample and Instrument Subduction Zone Megathrusts

By Harold J. Tobin, Gaku Kimura, and Shuichi Kodaira

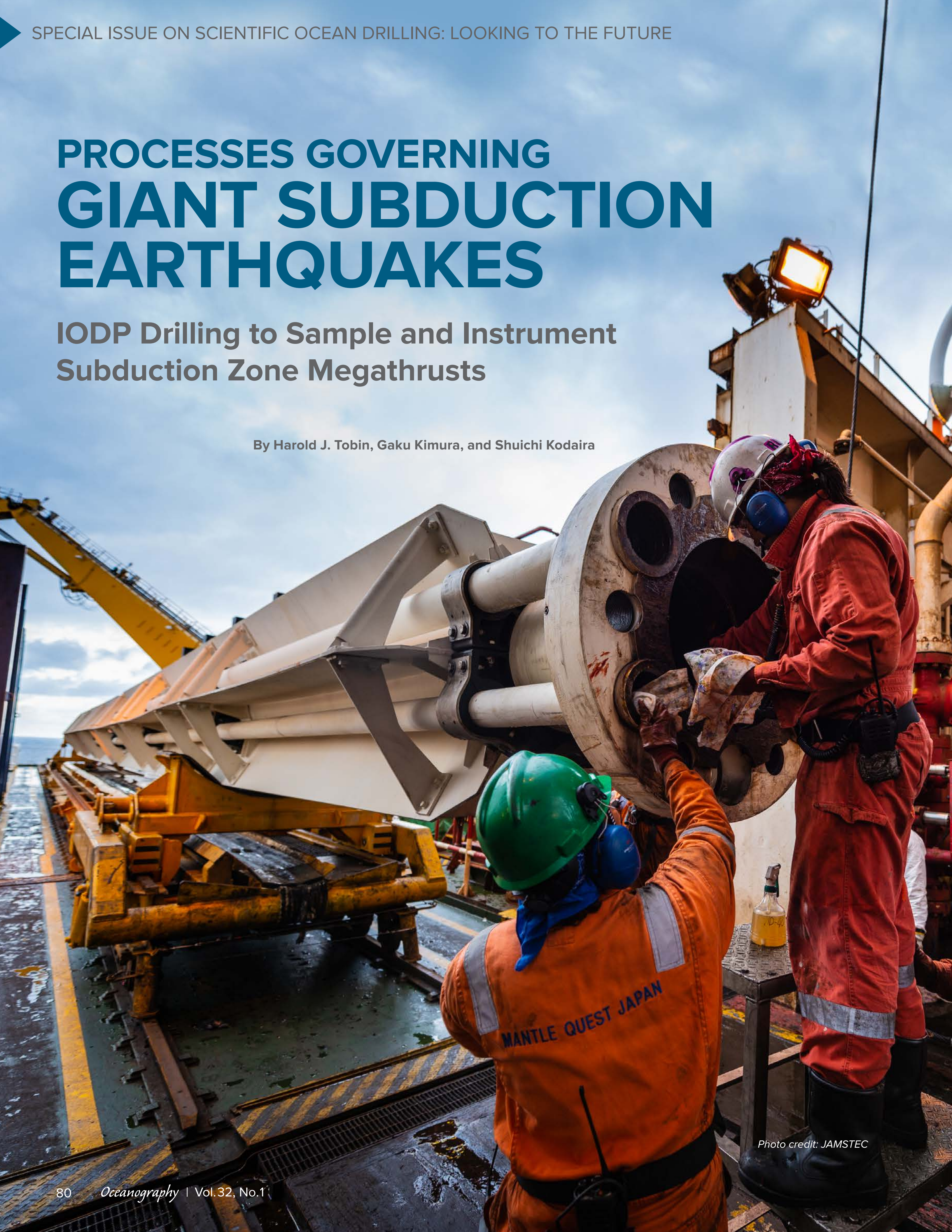


Photo credit: JAMSTEC

ABSTRACT. Scientific ocean drilling from 2007 through 2018 has played a major role in an ongoing revolution in the understanding of plate boundary fault zone mechanics, structure, and associated megathrust earthquake processes and the tsunamis they create. Major efforts at the Nankai, Costa Rica, Sumatra, and Japan Trench subduction zones that have employed both the riser Japanese drillship *Chikyu* and the riserless US drillship *JOIDES Resolution* have sampled main plate boundary faults (décollements), associated splay faults, and incoming plate sediments and basement rocks that develop into the fault system. Research on these rocks and in the boreholes shows that great earthquake ruptures not only can slip all the way to the tip of the megathrust at the seafloor in some events but may well do so typically. One location on a plate boundary fault can apparently also exhibit a range of behaviors over the course of a seismic cycle, from slow slip and tremor to rapid coseismic slip, depending on state of stress, pore pressure, and acceleration interacting with intrinsic lithologic properties. Scientific ocean drilling has provided data and samples for laboratory tests of frictional mechanics, for numerical modeling of fault processes, and for testing new hypotheses on megathrust fault processes, thus playing a central role in the modern pursuit of the grand challenge of understanding how faults that are capable of generating giant subduction earthquakes work.

INTRODUCTION

Drilling to understand megathrust earthquake processes and fault zone properties has been a major focus of both the Integrated Ocean Drilling Program and the International Ocean Discovery Program (IODP), and was a primary justification for the construction of the riser drilling vessel *Chikyu*. In 2004, not long after publication of the Integrated Ocean Drilling Program Initial Science Plan, in which that objective was identified as a central strategic scientific goal of the program (Coffin et al., 2001), the Sumatra-Andaman earthquake and devastating tsunami occurred. It was Earth's first magnitude 9 earthquake *and* first ocean-basin spanning tsunami in over 40 years, since the 1964 Alaska earthquake. By the time it happened, plans were well under way for scientific ocean drilling in the Nankai Trough during the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), and drilling proposals had been submitted for the Costa Rica Seismogenesis Project (CRISP) as well. Since 2004, several other giant subduction earthquakes and tsunamis have occurred, most notably the Tōhoku event of March 2011 in the Japan Trench.

During the IODP era of scientific ocean drilling, there has been a sustained effort to access the geologic record of megathrust processes as well as the active deformational signals (strain and pore pressure transients, seismic activity, and fluid and heat transport) from the accessible portions of these subduction plate boundary fault systems. Both riserless and riser expeditions have been undertaken to study fault processes at the Sumatra, Costa Rica, Nankai, and Japan Trench subduction zones, as well as a very recent Hikurangi Trough effort (see Wallace et al., 2019, in this issue).

Collectively, these drilling-based projects contributed significantly to a revolution in understanding of how fault locking, slip, and friction work. For example, based on samples of shallow (<1 km below the seafloor) thrust faults recovered during NanTroSEIZE IODP Expedition 316, Sakaguchi et al. (2011) and Yamaguchi et al. (2011) discovered evidence for frictional heating during past fault slip, indicative of seismic rupture reaching the trench. Prior to this work, the typical view was that rapid slip was unlikely to propagate shallowly, and such a claim was controversial when published. Just three days later, the Tōhoku earthquake occurred hundreds of kilometers away in the Japan Trench. Geomorphic, geodetic, and seismologic evidence soon showed that 50 m or more of rapid frictional slip clearly reached the tip of the plate boundary fault during that earthquake, vividly confirming the new view suggested by the Nankai results. IODP drilling on Expedition 343 (JFAST) provided in situ temperature measurements, confirming frictional heating during fault slip and collecting fault zone samples that documented the signature of past high temperature friction.

Another key related advance from IODP Expedition 362 (Sumatra trench) in 2016 documents that diagenetic alteration of thick sedimentary accumulations entering the subduction trench—for example, the formation of cements—can also create frictional conditions conducive to seismic slip right to the tip of the fault (Hüpers et al., 2017). Furthermore, investigation of lithologically diverse sediments where the plate boundary fault initially forms in the sedimentary sequence off Costa Rica (Expeditions 334 and 344 in 2011 and 2012, respectively) points to differences in favorability of clay-rich vs. carbonate-rich sediments in promoting rapid and seismic vs. slow and/or aseismic slip to the trench at that subduction margin. At larger spatial and temporal scales, three-dimensional seismic imaging and drilling results from the Costa Rica margin have led to reevaluation of the subduction erosion hypothesis in favor of episodic bursts of vertical uplift and collapse of the margin without necessarily requiring net tectonic removal of the forearc from below (Edwards et al., 2018).

Taken together, the intensive study of the Sumatra, Costa Rica, Nankai, and Japan Trench subduction systems has played a major role in the development of a new view of the mechanics and behavior of the upper portions of subduction zone plate boundary faults. Here, we review some of the major findings of IODP drilling from these four subduction systems and allied research in each of them to highlight common themes that have emerged. All of the IODP expeditions have produced a wide range of additional results that are relevant to IODP themes, particularly the tectonic evolution of accretionary and non-accretionary margins, but these topics are beyond the scope of this review.

NanTroSEIZE: SAMPLING FAULTS AND OBSERVING TRANSIENT SLIP AT THE SHALLOW END OF THE PLATE BOUNDARY

The Nankai Trough is formed by subduction of the Philippine Sea Plate to the northwest beneath the Eurasian Plate at a local calculated rate of 5.8 cm yr^{-1} (Figure 1; DeMets et al., 2010). With its ~1,300 year historic record of great (M_w > 8.0) earthquakes that are typically tsunamigenic (Ando, 1975; Hori et al., 2004), this margin was deemed especially favorable for study of a seismogenic zone through drilling. The plate boundary here is nearly fully locked (lacking aseismic or slow slip on the main megathrust) and is in the mid to late interseismic stage (i.e., close in time to the next expected major earthquake). However, a recent offshore acoustic GPS geodetic study suggests that the Kumano region (southeast of the Kii peninsula), where the NanTroSEIZE transect is located, may be locked to a lesser degree than other parts of this subduction zone (Yokota et al., 2016), consistent with observations of slow transient slip and very low-frequency local earthquakes (Sugioka et al., 2012; Araki et al., 2017; also see below for discussion).

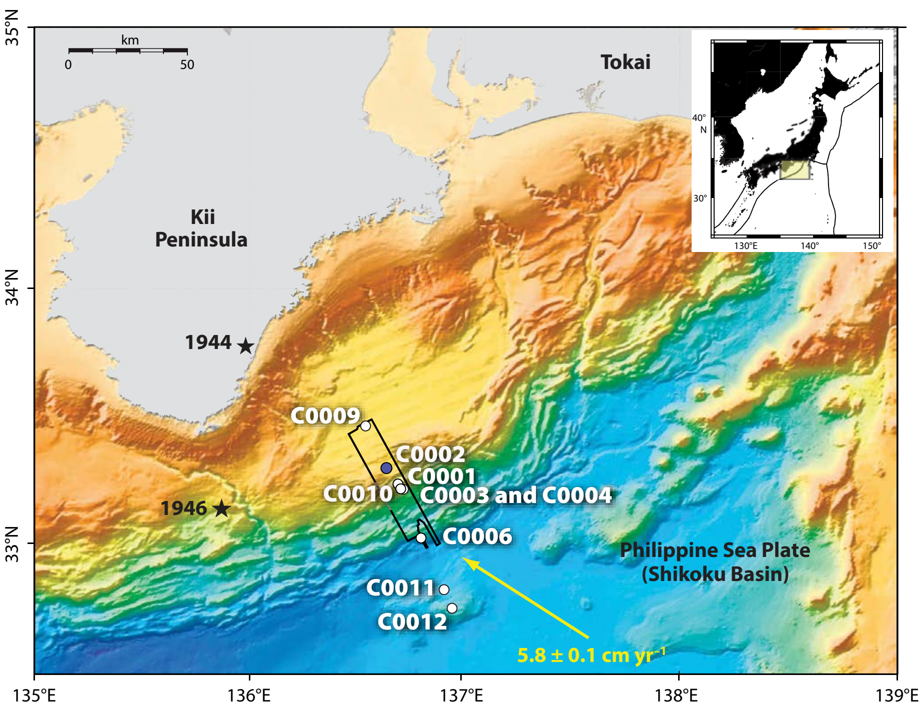


FIGURE 1. Location map of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) drilling transect area in the central-eastern Nankai Trough off the Kumano region, Japan. Numbered IODP sites are shown, as is the three-dimensional seismic footprint (box). Stars indicate the epicentral positions of the 1944 and 1946 great megathrust earthquakes. The yellow arrow shows the direction of relative plate convergence across the Nankai Trough of DeMets et al. (2010). *After Tobin et al. (2014)*

The NanTroSEIZE Complex Drilling Project (CDP), the largest project in the history of scientific ocean drilling, has included 11 IODP expeditions and more than 200 scientists. It began in 2007 and continues today, with IODP Expedition 358, which began in October 2018 and is scheduled to continue through March 2019. It. Its transect includes full drilling of the incoming plate section and upper igneous basement through the frontal thrust and out-of-sequence or "megasplay fault" region, as well as ultradeep drilling at two sites (C0002 and C0009) in the Kumano forearc basin (Figure 2). Site C0002 includes the deepest scientific ocean drilling hole ever

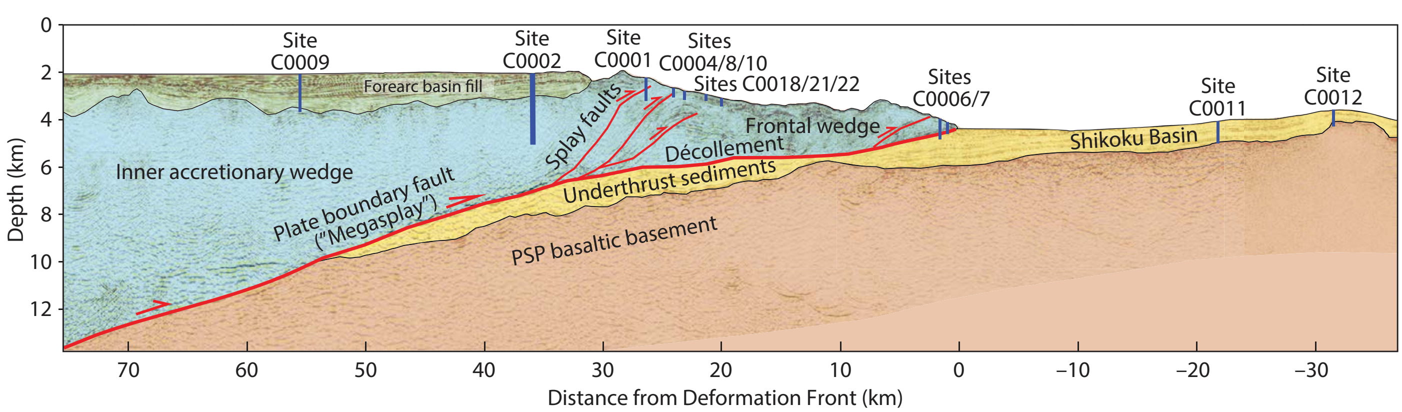


FIGURE 2. Interpreted seismic depth section through the NanTroSEIZE drilling area, after Park et al. (2002) and Moore et al. (2009). *Adapted from Tobin et al. (2014)*

undertaken, extending to 3,056 meters below the seafloor (mbsf), with plans for deepening to 5,200 mbsf during Expedition 358. NanTroSEIZE scientists also installed an advanced real-time borehole observatory for geodesy, pore pressure, and seismic observations at more than 800 mbsf. Overviews of the tectonic and geologic results of this transect were published in Tobin et al. (2014) and in Underwood and Moore (2012); here, we review the specific results regarding past and present dynamic fault activity.

Among the most remarkable results of NanTroSEIZE drilling to date is the discovery that fault slip at the frontal thrust (Site C0007) and megasplay (Site C0004) is apparently extremely localized in millimeters-thick faults that exhibit evidence of shear-related heating believed to result from slip at tsunamigenic to (potentially) earthquake speeds (centimeters per second to meters per second). As synthesized by Ujiie and Kimura (2014), at both fault drill penetrations, very fine-grained fault gouge several millimeters to 1 cm thick were found embedded in wider zones of fractured and brecciated rocks (Figure 3). The dark gouge zone at 438 mbsf at the frontal thrust (Site C0007) is 2 mm thick and bounded by sharp planar surfaces; it marks a biostratigraphically determined 1.67 million year age reversal. Along with several additional thin dark gouge zones in the same interval, it has accommodated ~6 km of slip (Screaton et al., 2009). These observations indicate that this is the main plate boundary thrust, and it shows strong localization of faulting over hundreds of earthquake cycles.

Studying these gouge zones in detail, Sakaguchi et al. (2011) found anomalies in vitrinite (organic matter) reflectance values from which they estimated that the fault gouges had been subject to 330°–390° ± 50°C temperatures, compared to an ambient background of only ~20°C, probably consistent with frictional heating that only occurs during rapid slip (Fulton and Harris, 2012). This result was further corroborated by X-ray fluorescence and X-ray diffraction data from the core taken across the gouge zones, which revealed geochemical variation consistent with the preferential occurrence of illite in the fault gouge clays as compared to the surrounding breccia (Yamaguchi et al., 2011), also a possible result of frictional heating.

Taken together, these detailed studies of the gouge deformational fabrics, strong localization, and geochemical proxies for frictional heating suggest that past Nankai earthquake-speed fault rupture propagated all the way to the trench, at least in one or more past events, and also all the way to the seafloor at the drilled megasplay fault.

Low-angle thrust slip has long been considered to be possible only in the presence of strongly elevated pore fluid pressure (Hubbert and Rubey, 1959), and evidence for high pore pressure in accretionary wedge settings has been much discussed and sought (see Saffer and Tobin, 2011, for a review). However, there is little direct evidence of anything more than very modest pore pressure above hydrostatic ("normal") levels in the fault zones drilled so far. Direct downhole pressure monitoring within the megasplay fault at ~410 mbsf at Site C0010 documented pore pressure slightly in excess

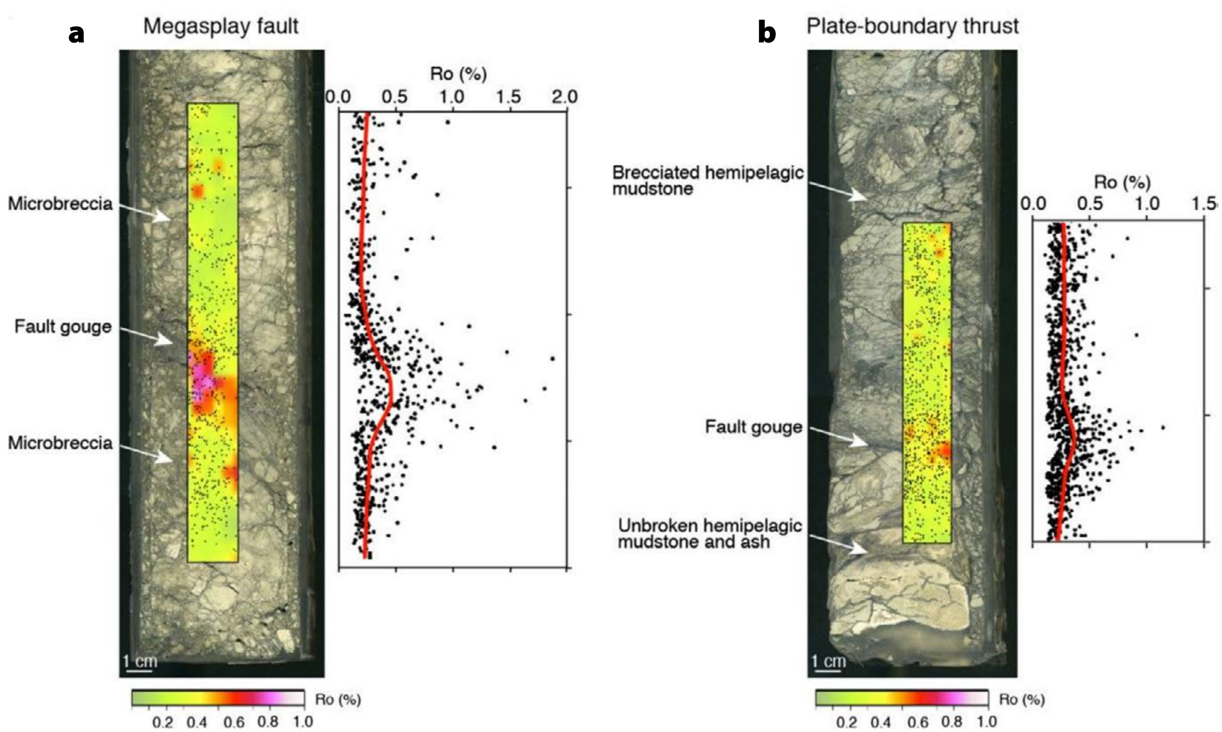


FIGURE 3. Vitrinite reflectance data from Sakaguchi et al. (2011), superimposed on images of the fault zone core from (a) the Site C0004 splay fault, and (b) the Site C0007 frontal thrust fault. *After Ujiie and Kimura (2014).*

of hydrostatic (Hammerschmidt et al., 2013). This result is consistent with shipboard porosity data that show no indication of excess porosity (hence high pore pressure) beneath the shallow megasplay (Screaton et al., 2009). There is similarly no direct physical property evidence nor indirect geochemical signs of elevated pore pressure in the frontal thrust region. Seismic velocity inferences suggest, however, that pore pressures may be high at levels deeper than drilling has reached so far (Park et al., 2010; Kitajima and Saffer, 2012).

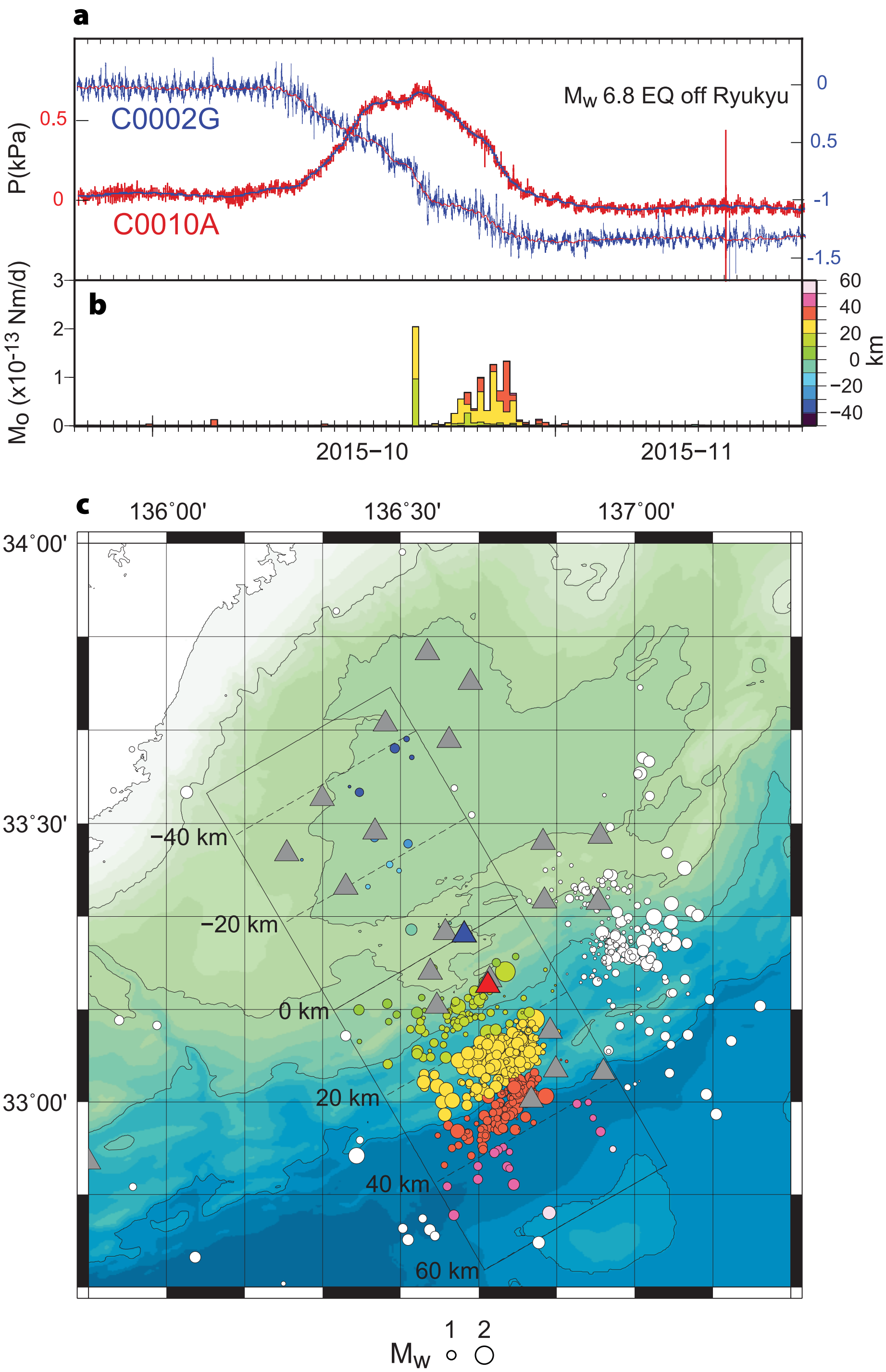


FIGURE 4. Observations of one example of a slow slip transient event. (a) Pore fluid pressure observations in the screened interval at the two borehole observatories installed as part of NanTroSEIZE and connected to the Japanese Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) real-time seafloor cable observatory. (b) Time series of the moment release by low-frequency tremor during the same interval as recorded on the seafloor network and binned in color by distance from the C0002G observatory. (c) Same low-frequency tremor data set shown spatially, along with locations of ocean bottom seismometer stations (triangles). *After Araki et al. (2017)*

Perhaps the most groundbreaking result of the NanTroSEIZE project to date is the insight gained from installation of deep borehole observatories that stream data in real time to shore via the Japanese DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) cable system. At Sites C0010A and C0002G, IODP has installed borehole instrument packages at around 450 mbsf and 850 mbsf, respectively, in which seismic activity, strain, pore fluid pressure, and temperature are continuously monitored (Kopf et al., 2016; Araki et al., 2017). The two sites are 11 km apart in the dip direction, spanning the outer limits of the zone believed to be locked and seismogenic. These are the first real-time deep ocean subduction zone observatories of their kind.

Along with the dense seafloor array of broadband seismometers in the NanTroSEIZE/DONET region, these borehole observatories have permitted direct and real-time observation of transient slow slip events on the shallow, updip edge of the locked plate boundary fault. In particular, pore fluid pressure observations made in a sealed, low-permeability interval of the sedimentary formation that overlies the plate boundary in the upper plate wedge (Figure 4) have proven to be effective proxies for volumetric strain. Araki et al. (2017) identified eight recurring transient strain events accompanied by low-frequency tremor and very low-frequency earthquakes in the period between 2012 and 2016, each representing several centimeters of slip, most likely on the plate boundary, and lasting days to weeks. The first such transient events captured offshore Nankai were calculated to account for 30%–55% of the total plate motion (Araki et al., 2017). Along with previous pioneering detections of shallow transient slip events that occurred offshore Costa Rica (Brown et al., 2005; Davis et al., 2011, 2015) and Nankai in the

Muroto region southwest of Japan (Davis et al., 2013), they represent an entirely new window into real-time deformation beneath the ocean floor.

The twin discoveries that (1) fast seismic slip has taken place at even shallow levels of the main frontal thrust and the major splay faults, and (2) slow slip, tremor, and very low-frequency earthquakes occur on the regional plate boundary fault directly beneath the observatories implies that *the same fault system hosts both fast and slow slip in the same place at different times through an earthquake cycle*, upending the idea that faults are intrinsically of seismic or aseismic type. This is strong evidence for the emerging view of rate-state frictional behavior as conditional, as opposed to an intrinsic property of a particular fault zone lithology.

The borehole observatories are capturing the spectrum of fault locking and strain release on short timescales, apparently right where the fault is transitioning from its shallow and conditionally stable regime to the zone of seismogenic frictional locking and instability, as envisioned by Saffer and Tobin (2011) and others in recent years. This is an unprecedented real-time view of the faulting process. Recent observations of slow slip transient behavior and swarms of foreshocks before the Tōhoku and Iquique (Chile) megathrust earthquakes have been hypothesized as precursory phenomena that could one day be used as an early warning tool (Kato, 2012; Brodsky and Lay, 2014), but that require just the sort of observations that the NanTroSEIZE observatories are now providing.

SUMATRA: DRILLING THE INCOMING PLATE AND POTENTIAL DÉCOLLEMENT HORIZON

The M_w 9.2 Sumatra-Andaman earthquake on December 26, 2004, which generated a disastrous tsunami (Stein and Okal, 2005), was one of the three largest recorded earthquakes in history. The rupture propagated ~1,300 km along strike from offshore northern Sumatra to the Andaman Islands located on the Burma-Sunda Plate. Three months later, on March 28, 2005, it was followed by an M_w 8.7 earthquake ~400 km to the south of the 2004 hypocenter off Nias island (e.g., Briggs et al., 2006) and then a series of plate boundary ruptures in 2007 and 2010 (Figure 5).

Ocean drilling sites in the Indian Ocean prior to the 2004 Sumatra-Andaman earthquake were mainly located on the Bengal-Nicobar Fan and the Ninety East Ridge, where drilling was designed to reveal the links between Himalayan tectonics and the climate of Asian monsoon (Deep Sea Drilling Project Leg 22, Ocean Drilling Program [ODP] Legs 116 and 121, and IODP Expedition 353 and 354). IODP Expedition 362 targeted two drilling sites on the incoming plate in order to reveal what factors controlled the 2004 great earthquake and tsunami in relation to the development of the Bengal-Nicobar Fan and the huge accretionary prism characteristic of the hanging wall of the rupture area of the 2004 earthquake (Dugan et al., 2017).

Geophysical and geological data sets acquired immediately after the 2004 earthquake showed that trench-filling sediments overlie ~1.5 km of Nicobar Fan deposits such that a total thickness of more than 4 km are present in the Sumatra trench (Figure 6; Henstock et al., 2006; Singh et al., 2008; Dean et al., 2010). In addition, structural features show that the 2004 tsunami-generating rupture area is characterized by landward-vergent thrusts (i.e., "backthrusts" relative to the underlying plate boundary megathrust) around the deformation front, whereas the 2005 deformation front off Nias island is a seaward-vergent fold-and-thrust system, as is more common in accretionary prisms (Henstock et al., 2006; Dean et al.,

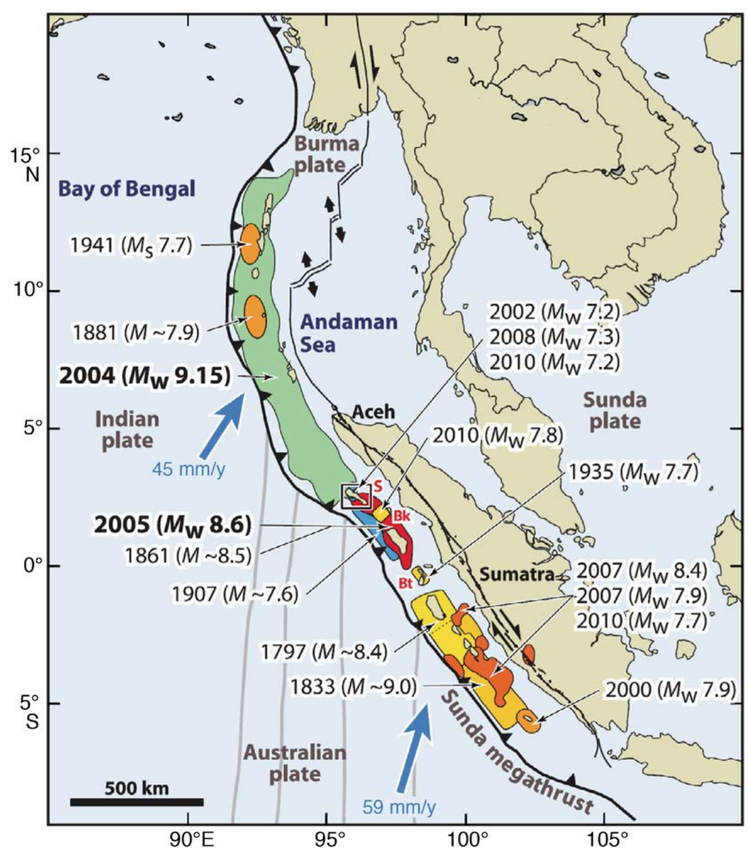


FIGURE 5. Tectonics and seismic history of the Sumatra margin and Sunda megathrust region. Rupture areas of historical megathrust earthquakes (M > 7) are shown. Plate convergence vectors are in blue. Black lines are faults, and gray lines are fracture zones. *After Dugan et al. (2017)*

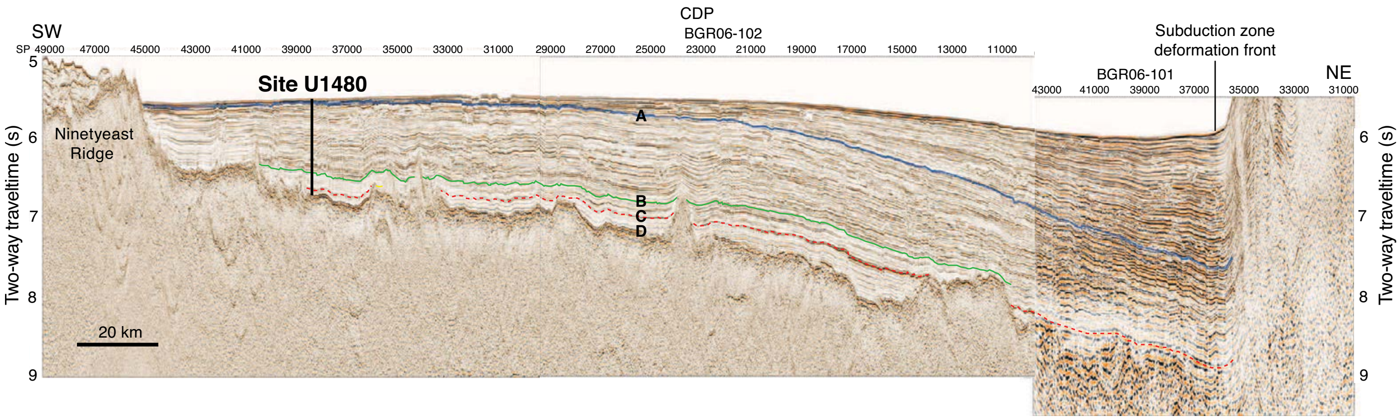


FIGURE 6. Composite seismic reflection profile of IODP Expedition 362 area targeting the incoming plate sedimentary section and upper igneous basement rocks at Site U1480. Letters A to D denote seismic horizons, where A (blue line) is the base of the trench wedge, C (dashed red line) is the potential décollement horizon, and D is the top of igneous oceanic basement. *After Dugan et al. (2017, references therein)*

2010; Moeremans et al., 2014). A sudden uplift of the accretionary prism likely generated the tsunami when slip propagated to (or near to) the trench. High seismic velocity in the large, thick accretionary wedge led to hypotheses that the wedge is unusually strong in bulk properties, promoting large slip and seafloor uplift (Gulick et al., 2011). Scientific questions for Expedition 362 drilling were therefore: What were the physical properties and conditions of the plate boundary décollement and frontal thrust beneath the thick sediments, and what was the specific geological effect of development of Nicobar Fan on the development of the accretionary prism and the occurrence of the great earthquake and tsunami?

Drill Site U1480 (and similar Site U1481) of IODP Expedition 362 are located in the Nicobar Fan east of the Ninety East Ridge offshore north Sumatra (Figure 5). The very thick trench wedge (everything above horizon A in Figure 6) precluded drilling to the décollement at the deformation front, so the strategy was to drill the lower part of the incoming plate section distal to the thrust front, where the lower section—laterally equivalent to the plate boundary fault décollement horizon—is accessible. A complete sedimentary section of the interval and basement rocks was recovered. Sediments between horizons A and C represent the Nicobar turbiditic fan, underlain by pelagic sediments that in turn overlie igneous basement (horizon D). Compositional analysis of the Nicobar Fan section documents that the sediment supply increased dramatically in the ~9.5 Ma to ~2 Ma interval from the Eastern Himalaya and Indo-Burmese wedge on land to the north (McNeill et al., 2017). Tectonic and climate linkage producing a punctuated sediment supply is clearly documented. As the Late Cenozoic main sediment source of the accretionary wedge of the Sumatra forearc is likely to be the Bengal- and Nicobar Fan, this history is quite significant to understanding the onset of the forearc of the Sumatra Trench.

Two prominent structural features of the 2004 rupture area are sediments more than ~3-4 km thick in the trench and landward vergent thrusts at the deformation front (Henstock et al., 2006; Singh et al., 2008; Dean et al., 2010). Therefore, understanding the relationship of these features to the large rupture propagation is a key to understanding fault slip conditions and tsunami generation. Hüpers et al. (2017) focused on the geologic significance of the pelagic sediments beneath the Nicobar Fan and above the basement recovered by IODP Expedition 362. This interval contains horizon C (Figure 6), which represents the interpreted potential future décollement level, so its properties are of special interest for understanding the mechanical characteristics of the megathrust faulting process.

These pelagic sediments are dominantly composed of hydrous amorphous silica and altered volcanic ash-origin palagonite, including hydrous smectite. They lay with little burial on the ocean floor for more than 30 million years, then were overlain by the Nicobar Fan since ~9 million years ago, followed more recently by thousands of meters of trench filling sediments. This thick burial and loading would have increased the temperature, and complete dehydration from amorphous silica to quartz would have progressed in the now-deep sediments. Observed freshening of the interstitial fluid in this interval is a signal of this dehydration (Hüpers et al., 2017). Such rapid dehydration would increase pore fluid pressure and result in decrease of effective strength. Hüpers et al. (2017) further suggest that the seismic reflector that develops laterally landward in this horizon is due to such a reaction. The horizon extends to the décollement beneath the accretionary prism beyond the deformation front. As Hüpers et al. (2017) discuss, the dehydration would have reached completion by the time subduction delivers this section to the tip of the plate boundary fault zone, and therefore the frictional property of the décollement would likely have already transformed to an unstable (velocity weakening) state, due to precipitation of quartz, before entering the subduction fault system.

As with the Nankai margin discussion

above, the prevailing wisdom prior to this discovery held that the unstable-stable (or aseismic to seismogenic) transition along the plate boundary megathrust is located beneath the forearc wedge, but these new results from Sumatra strongly suggest that the transition is instead located beneath the thick trench filling wedge, that is, *seaward* of the wedge tip. Therefore, the entire low-angle megathrust may be in the frictionally unstable zone, with no shallow stable-sliding portion. Combined with a strong accretionary wedge (Gulick et al., 2011), this unstable fault facilitates large seismic slip and concomitant tsunamigenic uplift of the outer wedge, as suggested by seismic and geodetic inversion studies (Ammon et al., 2005; Bletery et al., 2016). Hüpers et al. (2017) suggest that this scenario could be applicable to Cascadia and other places where trench filling sediments are thick and the thrust at the deformation front shows landward vergence.

MIDDLE AMERICA TRENCH: CRISP DRILLING OF THE OSA PENINSULA TRANSECT

At the Middle America Trench, subduction erosion has long been hypothesized to take place during convergence of the Caribbean and Cocos Plates (Figure 7). The processes associated with subduction erosion were investigated during IODP Expeditions 334 and 344, as well as with a 2011 three-dimensional seismic reflection survey (Bangs et al., 2014; Edwards et al., 2018). The history and persistence of subduction erosion vs. accretion have long been debated for the Costa Rica margin, in particular, as well as the prevalence of these processes globally. At the ODP Leg 170 Nicoya Peninsula transect along strike to the northwest, subsidence of the forearc was suggested to result from long-term subduction erosion at this margin (Vannucchi et al., 2001). Based on this older work, the Costa Rica margin has come to be seen as a prime example of long-term subduction erosion processes.

IODP Expeditions 334 and 344 targeted the Middle America Trench off the Osa Peninsula of southern Costa Rica (Vannucchi et al., 2013; Harris et al., 2013, respectively) as the first stage of the Costa Rica Seismogenesis Project (CRISP; Figure 8). The setting for these expeditions is a region of the trench where the Cocos Ridge collides with and subducts beneath the Osa Peninsula of the Caribbean Plate.

Seismic imaging showed that the main forearc inner wedge is composed of layered sedimentary material rather than old crystalline forearc crust as believed

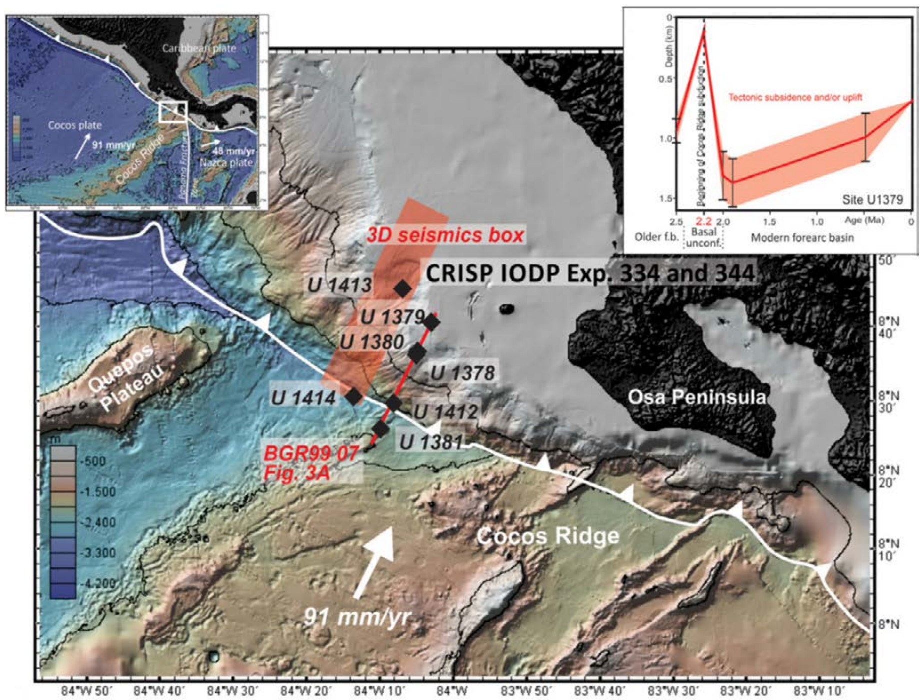


FIGURE 7. Costa Rica Seismogenesis Project (CRISP) IODP drilling area and tectonic setting. Location of seismic line BGR99-07 (Figure 8) marked in red. *After Vannucchi et al. (2016)*

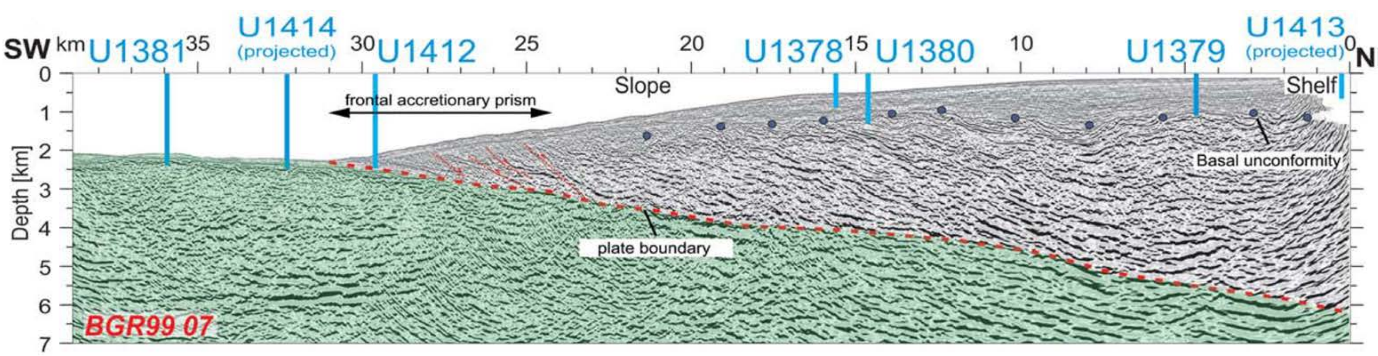


FIGURE 8. BGR99 07 depth-processed seismic line with IODP Expedition 334 and 344 drill sites. Line location is shown in Figure 7. Subducting lower plate is masked in green. The high-amplitude reflector at the base of the slope sediments is marked by blue dots, and underlain by older forearc basin fill. *After Vannucchi et al. (2016)*

for the ODP Nicoya transect (Bangs et al., 2014). Interpreting drilling results in light of that seismic evidence, Vannucchi et al. (2016) proposed a new paradigm they call a "depositionary margin," defined as a subduction zone where extreme basal tectonic erosion removes the entire forearc crust concurrently with rapid forearc basin filling by terrigenous input from the continent, leaving a deep basinal section underlain directly by the downgoing plate and plate interface fault.

In a new analysis of the drilling results and seismic imaging, Edwards et al. (2018) re-interpreted the tectonic history recorded by the basin and wedge of the Osa region. By tying basinal sequence analysis to stratal ages obtained from analysis of drill cores, they showed that this region has undergone rapid, geologically brief periods of uplift and subaerial erosion plus collapse and basin deposition throughout the Pleistocene, as lower plate topographic features have entered and passed through the subduction zone. They show that basal tectonic erosion and landward retreat of the margin are neither required nor likely, contrary to previous models that propose wholesale tectonic erosion here. These results may prove to have implications for the tectonic erosion model more generally.

The results of IODP scientific ocean drilling in the Middle America Trench have also contributed insights into seismogenesis in subduction zones. The Middle America Trench is characterized by active seismicity (e.g., Protti et al., 1995; Deshon et al., 2003, 2006; Arroyo et al., 2014), but historically does not generate M8 and larger great earthquakes. A key element here is the relationship between the subduction of topographic highs—seamounts, which typify this margin—and the nucleation and propagation of earthquakes. Prevailing wisdom has held that a seamount is an asperity (an area where the fault is locked) in the seismogenic zone (Cloos, 1992; Scholz and Small, 1997); when this locked asperity fails, rupture would then propagate away from the seamount region, resulting in a large-magnitude earthquake. Wang and Bilek (2011) put forth an alternative hypothesis, suggesting that seamount subduction instead promotes aseismic creep and relatively small earthquakes, not large ruptures. These hypotheses are compatible if it is recognized that magnitude 6.5–7.5 earthquakes are, in fact, small events from the megathrust perspective and scale.

As with Nankai, Sumatra, and the Japan Trench, the materials in the plate boundary fault zone and their frictional properties have been studied in detail to shed light on the fault rupture process. Ikari et al. (2013) proposed another, mineralogically grounded, hypothesis on the question of whether subducted seamounts are asperities or whether they promote weak, quasi-aseismic zones. On the basis of friction experiments using IODP samples, these authors argue that the carbonate sediment cap typical above seamounts facilitates seismic slip because chalk is frictionally strong and velocity weakening (a term that connotes that the material loses shear strength with increasing slip speed). Based on these experimental results, Vannucchi et al. (2017) suggested carbonate sediments in the plate boundary fault might promote slip to the trench, in contrast to clay-rich sediments. Both sediment types exhibit velocity weakening under fast (seismic) rupture (~m s^{-1}) experimental conditions, but carbonate ooze is much weaker than clayey sediments. During slow slip, on the other hand, clayey sediments show velocity strengthening while carbonate ooze still shows velocity weakening (Ikari et al., 2013). Note that under those slow slip conditions, their strength is opposite: the clay is weaker than the carbonates. Combining the results of friction experiments with analysis of three-dimensional seismic profiles that show the plate boundary décollement is located within the carbonate horizon and extends to the deformation front, Vannucchi et al. (2017) suggest that in the Osa region, rapid slip would propagate to the trench, similar to observations of the 2011 Tōhoku earthquake.

JFAST: THE JAPAN TRENCH FAST DRILLING PROJECT

A striking observation from the 2011 Tōhoku-oki earthquake was the very large fault slip that reached the shallowest part of the subduction zone in the Japan Trench (e.g., Lay et al., 2011). Comparison of bathymetry measured before and after the earthquake showed ~50 m of trenchward seafloor displacement (Fujiwara et al., 2011) caused by coseismic slip along a seafloor-breaching fault at the trench axis (Kodaira et al., 2012). The large shallow fault slip generated the more than 10 m average height of the devastating tsunami (maximum >40 m) that struck the entire coastline of northeastern Japan (e.g., Fujii et al., 2011; Mori et al., 2012).

IODP Expedition 343 and 343T, the Japan Trench Fast Drilling Project (JFAST), was carried out beginning in April 2012, 13 months after the earthquake, in the large slip zone of the earthquake as IODP's first-ever "rapid response" drilling (Figure 9). In order to understand how the extremely large fault slip reached the tip of the subduction zone, JFAST drilling was planned to reach the fault at less than 1,000 mbsf with three main objectives: (1) estimate the stress state in the fault zone, (2) obtain cores from the coseismically slipped fault to examine the plate boundary structure and measure physical-chemical properties of the fault, and (3) measure in situ residual temperature anomalies across the fault zone to estimate frictional heating during the earthquake and thereby infer actual frictional properties of the fault zone during rapid slip.

The expedition had to be done as soon as possible after the earthquake and required drilling in extremely deep water (~7,000 m depth). A site was selected ~6 km from the trench axis where seismic data imaged the plate boundary at ~900 mbsf (Figure 9b). During Expedition 343, *Chikyu* successfully drilled to the fault zone. Then, a string of 50 thermistors was hung in the fault zone borehole between 650 mbsf and 820 mbsf

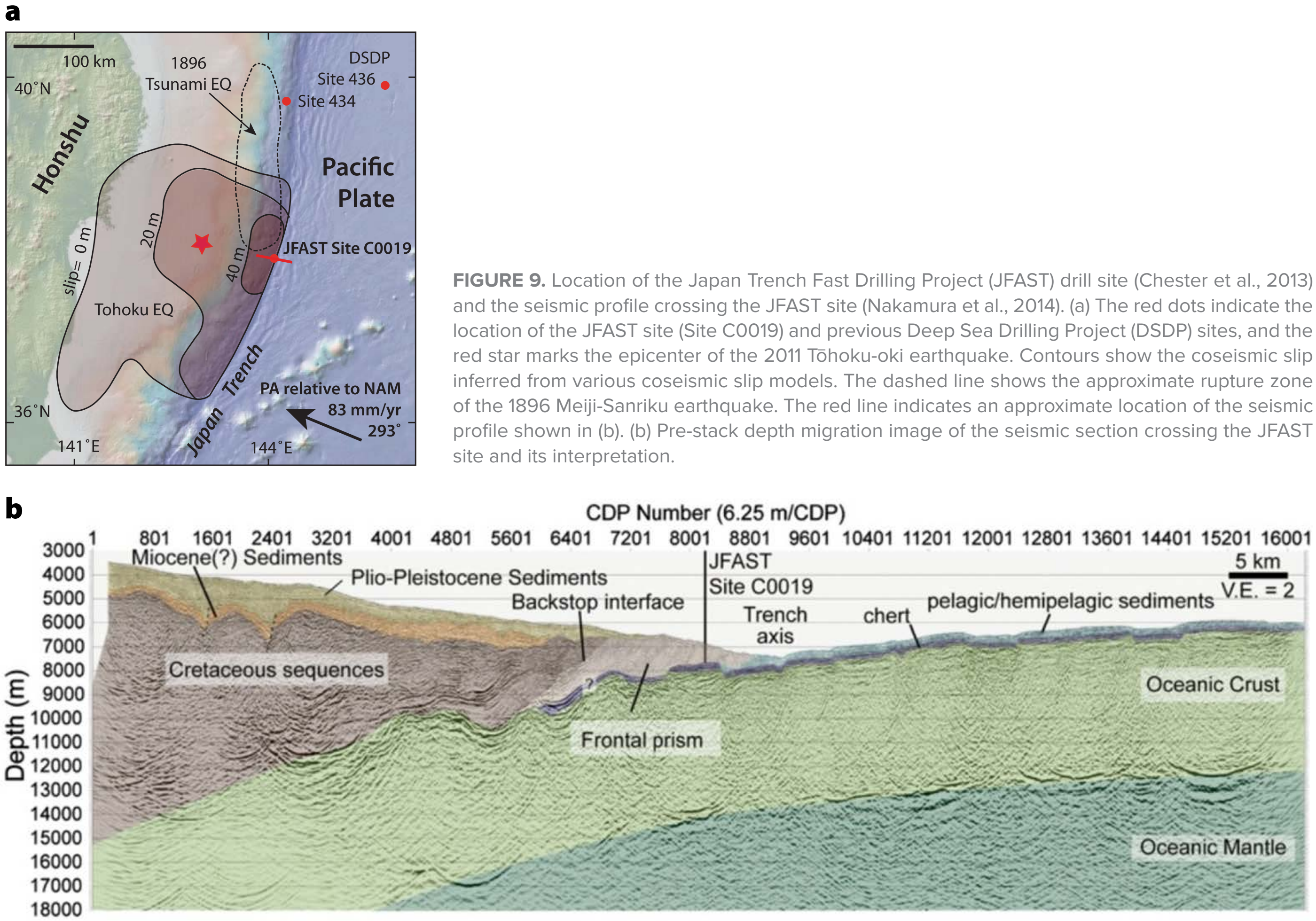


FIGURE 9. Location of the Japan Trench Fast Drilling Project (JFAST) drill site (Chester et al., 2013) and the seismic profile crossing the JFAST site (Nakamura et al., 2014). (a) The red dots indicate the location of the JFAST site (Site C0019) and previous Deep Sea Drilling Project (DSDP) sites, and the red star marks the epicenter of the 2011 Tōhoku-oki earthquake. Contours show the coseismic slip inferred from various coseismic slip models. The dashed line shows the approximate rupture zone of the 1896 Meiji-Sanriku earthquake. The red line indicates an approximate location of the seismic profile shown in (b). (b) Pre-stack depth migration image of the seismic section crossing the JFAST site and its interpretation.

on Expedition 343T in July 2012. In April 2013, after nine months of continuous temperature monitoring, the remotely operated vehicle *Kaiko* retrieved the observatory.

Geophysical logging at Site C0019 collected resistivity images of the borehole wall, including images of borehole "breakouts" (failures of the borehole wall from which stress conditions can be deduced). Based on their directions and sizes, Lin et al. (2013) concluded that the stress state in the shallow portion of the hanging wall of the rupture zone had changed from a thrust-faulting stress regime to a normal-faulting or near-normal-faulting stress regime during the earthquake. This suggested coseismic fault weakening and nearly total stress drop at the shallow portion of the large slip zone, consistent with earthquake observations (Hasegawa et al., 2011) and geodetic observations (Sato et al., 2011).

Core samples were collected from a key interval where seismic data show a strong reflector that is interpreted as the main plate boundary fault. In the cores, the fault zone was identified at ~820 mbsf by changes in geological properties, such as lithology, age, and orientation of bedding (Chester et al., 2013). The fault zone sediment consists of pelagic brown clay with a scaly fabric (Figure 10), not observed in other cores collected from the surrounding area. Although a complete section of the plate boundary fault zone was not recovered, the total thickness of the fault zone (i.e., the scaly clay layer) was estimated as less than 5 m based on analysis of the recovered core and the thickness of the un-recovered gaps. The thin nature of

FIGURE 10. Photo of the core recovered from the plate boundary fault zone showing a highly deformed scaly clay layer. *From Mori et al. (2014)*

the fault zone suggests that localization of the coseismic slip caused or contributed to the very large slip along the fault.

In order to investigate frictional properties that control slip in the shallow part of the rupture zone, Ujiie et al. (2013) carried out high velocity friction experiments on core samples collected from the scaly clay layer. They used a high-velocity, large-slip rotary shear device to conduct experiments under permeable and impermeable conditions. They set experimental parameters to be comparable to the conditions of fault motion during the earthquake (i.e., slip rate of 1.3 m s^{-1}, displacements of ~15 m to 60 m). Resultant observed steady-state shear stress under a normal stress of 2.0 MPa shows ~0.4 MPa and ~0.2 MPa for the permeable and impermeable cases, respectively (Figure 11). Under the effective normal stress of 7 MPa at a depth of 820 mbsf on the décollement at Site C0019, these results yielded 1.32 MPa and 0.22 MPa, which corresponds to apparent coefficient of friction of 0.19 and 0.03 for the permeable and impermeable cases, respectively. Ujiie et al. (2013) concluded that the measured shear strengths of samples from the plate boundary fault in the large slip zone of the Japan Trench are lower than those obtained from the fault material at Nankai Trough. Examination of the microstructures in the gouge samples following the high velocity friction experiments shows that the very low shear stress can be attributed to the smectite-rich weak clay and the expansion of pore fluids by frictional heating, known as thermal pressurization.

Finally, the JFAST project included estimation of frictional heating due to coseismic slip of the fault using long-term temperature measurements collected by an array of borehole instruments. The frictional shear stress—and therefore the effective coefficient of friction—can be estimated from the temperatures measured along the fault if the coseismic fault slip is known. Because the temperature increase along the fault during the earthquake was very large (hundreds of degrees), it was expected that residual (albeit small) temperature anomalies would be observed even one or two years later.

Depth versus time and temperature was plotted, revealing a small temperature anomaly at the plate boundary fault (Figure 12; Fulton et al., 2013). After removal of the background geothermal gradient, the plot shows values 0.3°C higher at 814–820 mbsf than temperatures at shallower depths. It took about two months for the temperatures to equilibrate in the borehole after disturbance by drilling (as indicated in the figure by the cold colors for two months after the deployment). From the observed

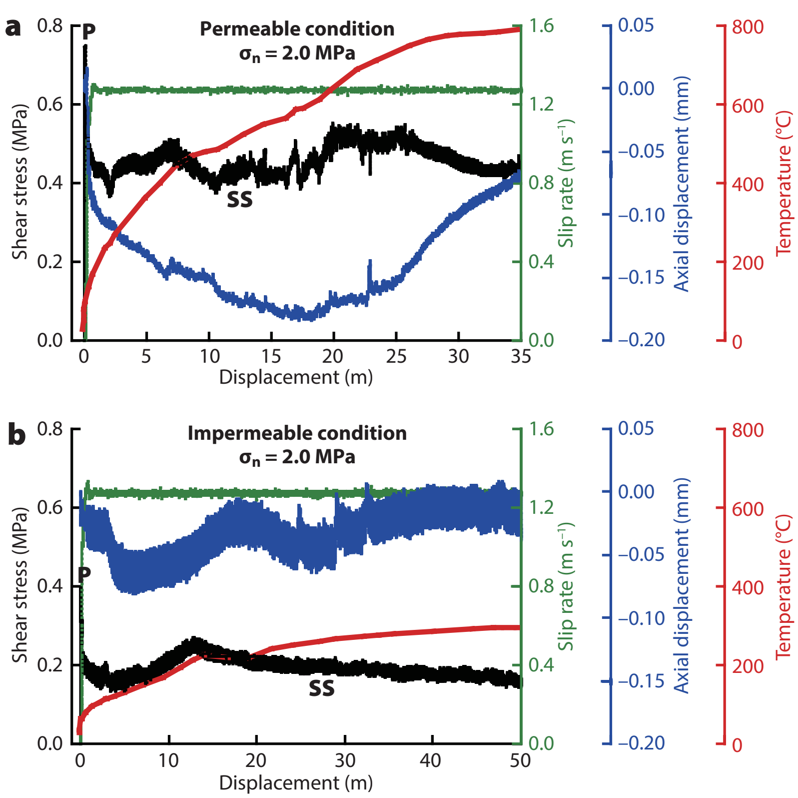


FIGURE 11. Results of high-velocity friction experiment using cores from the plate boundary zone. Shear stress (black line), slip rate (green line), axial displacement (blue line), and temperatures (red line) during the experiment under (a) permeable and (b) impermeable conditions under the normal stress of 2.0 MPa are plotted as a function of displacement. P and SS indicate the initial peak shear stress and the steady-state shear stress (Ujiie et al., 2013).

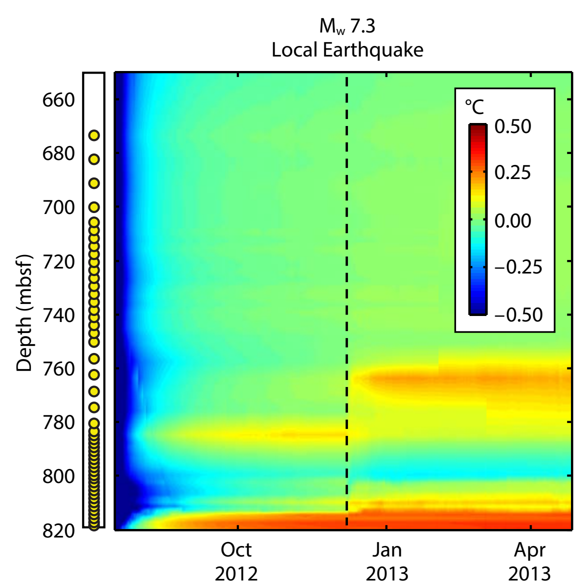


FIGURE 12. Time-depth temperature map in the JFAST borehole. Yellow dots indicate locations of temperature sensors below ~650 mbsf. Colors indicate residual temperatures after the background geotherm is removed. *Adapted from Fulton and Brodsky, 2016*

temperature anomaly of 0.3°C, an average shear stress during the fault slip was estimated to be 0.54 MPa, which corresponds to an apparent frictional coefficient of 0.08. These extremely low values (as compared to standard "Byerlee" rock friction values of 0.65 to 0.8 observed in decades of laboratory experiments at low speed and inferred from small faults globally) are consistent with those estimated by the laboratory experiment described above, in between the permeable and impermeable laboratory results, but closer to the results from the impermeable case (Ujiie et al., 2013). The implication is that the fault slipped with extremely little frictional resistance, akin to the coefficient of friction for a banana peel underfoot (Mabuchi et al., 2012).

These direct measurements, the first of their kind for a major earthquake, contributed greatly to understanding of how rapid, coseismic slip can and does propagate to the seafloor, triggering tsunamis. Taken together with the results from NanTroSEIZE, CRISP, and Sumatra drilling, the discovery of conditional and state-dependent frictional properties of the shallow fault zone revolutionized our understanding of seismic slip in subduction megathrust fault zones. Furthermore, JFAST was the first rapid response IODP expedition of any kind, demonstrating that this approach is feasible and can pay rich rewards.

SYNTHESIS AND CONCLUSIONS

In the IODP era, scientific ocean drilling has permitted rapid advances in the understanding of subduction megathrust properties and processes. It has done so by being the field laboratory, observatory, and data-based ground truth for a wide range of hypotheses based on remote geophysical observations. Over the past three decades, we have seen the advent of broadband seismology and continuous, high-precision geodesy, both on land and now offshore. Borehole observatories have provided key data sets, illuminating interseismic and coseismic processes. Advances in laboratory friction studies and many other types of geological, microstructural, and geochemical measurements have been possible only because of the availability of samples obtained through scientific ocean drilling, and many paradigms have fallen by the wayside as new ones have emerged. The consensus view now is that, rather than faults neatly dividing into seismogenic vs. aseismic, a spectrum of fault behaviors is governed by specific lithology, pore fluid pressure, ambient stress conditions, and propagation of rupture from depth. Observatories are revealing fault processes in real time, permitting tests of new, more sophisticated and nuanced hypotheses on what controls fault locking and release during slow and fast rupture.

Important avenues for future research include understanding the reasons why some megathrust earthquakes do not slip all the way to the surface, as well as understanding what governs locking vs. creeping fault systems. With recent observations suggesting that faults near the tip of a subduction system can be locked, quantifying the spatial extent of and controls on shallow locking has emerged as an urgent question for seafloor geodesy and future drilling, sampling, and observatory installation (see Wallace et al., 2019, in this issue for the first major foray into addressing this topic). Exploring how lithology controls frictional stability and slip behavior, particularly in the marine carbonates that typify deep pelagic sediments in many places, is another high-priority goal.

The factors governing tsunamigenesis remain poorly understood—for example, are faults that do not directly displace the surface capable of creating sufficient seafloor deformation to spawn tsunamis? If so, under what conditions? Studies of the role of large-scale wedge structures in promoting slip on splay faults as a source of tsunamis and submarine slope failure (e.g., Haeussler et al., 2015) will shed light on global geohazards related to tsunamigenic subduction earthquakes.

As this article goes to press, IODP Expedition 358 is conducting riser drilling at Site C0002 in the NanTroSEIZE transect. The expedition's main objective is to deepen the hole to more than 5,000 mbsf by April 2019, thereby sampling the main plate boundary fault zone at the depth of slow slip, tremor, and likely partial locking as well. This hole would complete the NanTroSEIZE transect and set the stage for final deployment of the first real-time megathrust plate boundary observatory inside a deep seafloor borehole.

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SPOTLIGHT 7. D/V *Chikyu*

In 1990, construction of a new scientific drilling vessel informally called "Godzilla Maru" was proposed to the Japanese government by the Aviation Electronics Council in Japan. Advanced ocean drilling using riser techniques would expand horizons in Earth, ocean, and life sciences and provide unique capabilities in support of international scientific ocean drilling, complementing the riserless US *JOIDES Resolution* drillship and European-supported mission-specific platforms.

The Japanese government decided to move forward with the construction of D/V *Chikyu* in 2001.The Center for Deep Earth Exploration (CDEX) was established within the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in October 2002 to oversee construction and operation of the ship, and *Chikyu* was delivered in July 2005. A shakedown cruise was conducted off the Tōhoku Pacific coastline near Honshu Island prior to Expedition 314, which started in September 2007, the very first *Chikyu* expedition under the umbrella of the 2003–2013 Integrated Ocean Drilling Program.

The *Chikyu* riser drilling capability was designed to reach deeper (>3.0 km) subseafloor targets than any other scientific drilling platform to date. In addition, *Chikyu*'s large hull accommodated extensive and well-equipped onboard laboratories with space for large analytical instruments such as an X-ray CT scanner and an X-ray fluorescence core scanner as well as a shielded geomagnetic laboratory. The stability of the vessel also allowed for high-precision analyses using the onboard inductively coupled plasma mass spectrometer.

As of September 2018, 17 Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) expeditions have been carried out, with a total of 938 expeditions days, a cumulative drilling depth exceeding 40 km, and 5.6 km of core recovered. *Chikyu* expeditions have been focused on two of the four main IODP science themes, with repeated efforts to significantly improve our understanding of the seismogenic zone and the subseafloor biosphere. These include the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) to drill into the thrust faults of the M8+ seismogenic zone in the Nankai accretionary prism (12 expeditions), subsurface biosphere studies in the Okinawa Trough (IODP Expedition 331) and off the Shimokita Peninsula (IODP Expedition 337), the Japan Trench Fast Drilling Project (JFAST) to study the immediate aftereffects of the 2011 Tōhoku earthquake (IODP Expedition 343), and investigation of the temperature limit of the hot, deep biosphere off Japan's Cape Muroto (IODP Expedition 370).

IODP Expedition 358, initiated on October 7, 2018, and scheduled to end on March 31, 2019, concludes the decadal NanTroSEIZE project. The goal of this expedition is to drill down to the plate boundary fault, about 5 km below the ocean floor, where M8+ class earthquakes occur every 100–150 years. Its successful completion would represent the deepest borehole in the history of scientific ocean drilling. More importantly, it would be a pinnacle in global earthquake research, vastly improving our understanding of this immense geohazard for society, not only in Japan but around the world in other heavily populated seismogenic zones. Finally, as a key aspiration and future target, *Chikyu* aims to drill through the entire ~6–7 km of mature oceanic crust and retrieve core samples from Earth's mantle, below the globally recognized Mohorovičić seismic discontinuity (Moho), a major objective outlined by visionary scientists nearly 60 years ago but not yet achieved in 50 years of scientific ocean drilling.

– Shin'ichi Kuramoto, Nobu Eguchi, and Sean Toczko

Photo credit: JAMSTEC

RISER DRILLING

Access to Deep Subseafloor Science

By Yasuhiro Yamada, Brandon Dugan, Takehiro Hirose, and Saneatsu Saito

ABSTRACT. Riser-based drilling became available to scientists for the first time when the Japanese drilling vessel (D/V) *Chikyu* began operations in 2005. The introduction of a vessel that could take advantage of riser drilling technology was a key advancement as scientific ocean drilling transitioned from the Ocean Drilling Program to the Integrated Ocean Drilling Program. Because riser drilling enables control of downhole pressure, *Chikyu* opened a new frontier for scientists, allowing for deeper drilling and sampling of the subseafloor to at least 7 km depths. Riserless drilling uses seawater as drilling fluid, and technical difficulties may arise when the borehole becomes unstable. In contrast, riser drilling uses riser pipes that connect the ship to the wellhead at the seafloor (Figure 1). Circulation of weighted drill mud through the riser pipe stabilizes the borehole during deep drilling operations, allowing continuous sampling and data collection, including from cuttings, mud gas, and downhole logging. These samples and data allow characterization of in situ physical properties (e.g., stress, fluid pressure) and gas and fluid chemistry. Riser drilling operations in the Nankai Trough and off Shimokita Peninsula in Japan demonstrate the value of this technology to achieving new understanding of the processes occurring deep in seismogenic zones.

DEEP DRILLING CAPABILITY

Circulation of weighted drill mud through riser pipes (Figure 1) balances wellbore and formation pressures to prevent formation fluid from flowing into the borehole or caving in of the borehole. In addition, it helps clean the borehole by transporting drill cuttings to the surface, and it lubricates and cools the drill string, transmits hydraulic horsepower to the drill bit, and stabilizes the walls of the borehole until casing can be set and/or observatory equipment can be installed. These functions allow *Chikyu* to drill to previously unreachable depths, into the seismogenic zone or the upper mantle—current drilling capability is 7,000 meters below the seafloor (mbsf) in 2,500 m water depth. One drawback of using riser technology is that continuous coring is not feasible for ultra-deep drilling projects due to limited ship time; however, spot or sidewall coring allows collection of cores at selected, important depth intervals that are often identified in logging data. The gaps between the cored and non-cored intervals can be examined in geophysical borehole logs as well as in cuttings and mud gas samples.

GEOPHYSICAL LOGGING

Geophysical logging is a technique to measure formation characteristics in situ. Instruments with a variety of sensors are sent down the borehole on a cable either after the hole is drilled (wireline logging) or they are built into the drill collars and collect data as the hole is being drilled (known as logging while drilling, or LWD). Logging has been routinely used in scientific ocean drilling where core recovery is insufficient. The tools that can be used in riserless drilling are limited to the standard measurements (e.g., natural gamma ray, sonic velocity, resistivity, density, porosity) because of limitations in the diameter of the hole vs. the sizes of available logging tools.

Because of the larger diameter pipe, riser drilling can take advantage of a broader suite of logging tools available from industry and collect data such as high-resolution borehole images, nuclear magnetic resonance (NMR) measurements, formation tests, fluid samples, sidewall cores, and geochemical measurements. Stable borehole conditions provided by riser drilling also result in improved quality of geophysical logging data collected from the deep subseafloor.

Deep riser drilling (e.g., seismogenic zone drilling) is commonly completed with extensive LWD operations in addition to limited coring. LWD and mud logging, combined with limited core data, are invaluable for characterizing the entire drilled section. Deep scientific targets of riser drilling, which are traditionally interpreted using multichannel seismic reflection data, can be refined by check-shot surveys and look-ahead vertical seismic profiling while drilling. With such a breadth of tools available, conducting downhole logging while using the deep riser drilling technology on *Chikyu* will be a vital component of future scientific ocean drilling at great depths.

MUD CIRCULATION SYSTEM

In addition to improving borehole stability, mud circulation during riser drilling provides access to data that are not available for riserless drilling. Two main areas where riser systems have provided new data streams are cuttings and gas geochemistry. Cuttings produced by drilling are delivered to the drillship via the mud circulation system (Figure 1). These formation samples are extremely valuable for calibrating petrophysical interpretations based on geophysical logs, documenting the lithology and composition

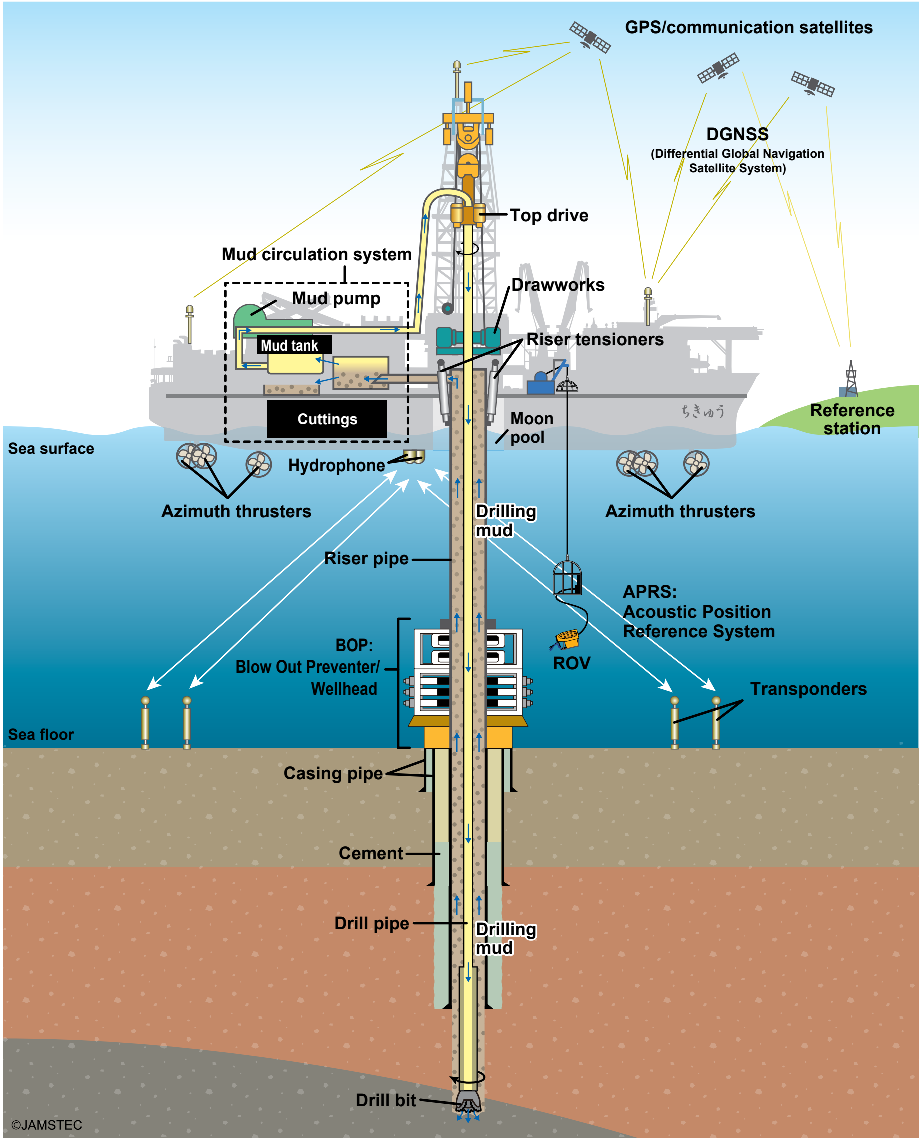

FIGURE 1. The riser drilling system.

of the formation, and providing fossils for age dating of the formation. These cuttings-based data allow routine geological assessment even in intervals where scientific cores are not collected.

Instead of or in addition to gas samples collected in situ using wireline pressure cores or advanced logging-based fluid samplers, wellhead gas samples can inform multiple studies that include thermal history, microbial activity, and fluid flow. Wireline sampling technologies require additional ship time and only provide a few point measurements, whereas mud gas analysis during riser drilling provides a means of gathering data on formation gases continuously. Gases released from the formation during drilling are delivered to the surface via a closed-loop system, and are continuously monitored and sampled with mud degassing instrumentation.

Shipboard gas analysis and sampling are used for continuous safety monitoring by assessing the composition of hydrocarbon gases (e.g., C_1–C_5), a crucial component for any drilling operation. Gases can also be analyzed shipboard for non-hydrocarbons and isotopes (e.g., δ^{13}C-methane), providing near-real-time data on board. Analyses of these data aid contamination, fluid flow, and fluid source studies. Gas samples can also be sealed and sent to shore for more detailed elemental or isotopic studies. As continuous gas and cuttings analyses are relatively new to scientific ocean drilling, it is expected that the data they produce and their future scientific impact will expand as more scientists participate in studies that use riser drilling.

Mud circulation can enhance core recovery and quality from the deep subseafloor, even from gas/fluid-rich or highly fractured formations. In combination with cuttings, recovered cores are available for scientific examination and interpretation, including lithology, physical and geomechanical properties, and geochemical characteristics.

ACHIEVEMENTS OF SCIENTIFIC RISER DRILLING IN THE NANKAI TROUGH AND OFF SHIMOKITA

Riser drilling was a key component of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), a series of 13 Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) expeditions that began in 2007 and will conclude in 2019. NanTroSEIZE employed both riserless and riser drilling to collect sediments and fluid/gas in the Nankai trough subduction zone off the Kii Peninsula, Japan. The program was designed to investigate fault mechanics and seismogenesis along a subduction plate boundary fault system through direct sampling, in situ measurements, and long-term monitoring in conjunction with allied laboratory and numerical modeling studies. The seismogenic zone targeted at ~5,200 mbsf at Site C0002 was the deep target centerpiece of NanTroSEIZE. This unprecedented deep ocean borehole could only have been achieved using riser-based drilling and a carefully planned casing program.

Through combined riserless and riser drilling and associated scientific operations, significant knowledge of the Nankai seismogenic zone has been gained. Borehole logging and core data were used to estimate in situ stress orientations and magnitudes (e.g., Lin et al., 2016; Huffman et al., 2016; Kitajima et al., 2017; Oohashi et al., 2017). Isotopic analyses of mud gas during riser drilling in the Nankai Trough allowed near-real-time assessment of the transition from biogenic to thermogenic methane, providing insights into the thermal state of the formation and the extent of methanogenic microbial activity (Strasser et al., 2014; Tobin et al., 2015). Mud gas concentration analyses showed increased methane concentrations near the base of the Kumano forearc basin sediments, which may be the result of upward fluid migration (Strasser et al., 2014; Ijiri et al., 2018). The culmination of 10 years of IODP NanTroSEIZE deep drilling efforts, Expedition 358 in October 2018 was designed to characterize the megasplay fault/plate boundary fault at seismogenic/slow slip depths (~5.2 km below the seafloor).

Earlier, the primary targets of IODP Expedition 337 drilling, off Shimokita Peninsula, Northeast Japan, were coal and shale beds in a forearc basin in order to examine the limits of life in the deep biosphere and the ecological roles of deep life in biogeochemical carbon cycling. Riser drilling with a blowout preventer (BOP) and drilling mud adjusted to balance the formation pressure were essential for drilling in this hydrocarbon-bearing basin. Expedition 337 achieved the world record for the deepest subseafloor depth from which core samples have been retrieved, 2,466 mbsf.

Based on rigorous contamination assessment efforts during Expedition 337, multiple lines of geochemical and microbiological evidence demonstrated that a heterotrophic microbial ecosystem exists even at subseafloor depths down to ~2.5 km and that it contributes to biological carbon cycling within the lignite-associated sedimentary habitat (Inagaki et al., 2015). Formation fluid and gas samples were collected in situ using a wireline logging tool following an extensive suite of geophysical logging runs that included all fundamental logging tools, detailed borehole imaging, NMR measurement, and in situ analysis of the formation fluids. The samples and data sets collected resulted in significant scientific discoveries, including determining the energy limits for active microbial life in deep subseafloor sedimentary habitats (Inagaki et al., 2015; Tanikawa et al., 2018). IODP Expedition 337 greatly expanded our knowledge of the deep subseafloor biosphere, a theme central to IODP.

SUMMARY AND FUTURE PERSPECTIVES

By providing access to continuous sampling (fluids, gases, and rocks) and data sets (e.g., advanced logging), riser drilling has opened the door not only to drilling deeper into the subseafloor but to a new era of drilling science. In the coming decades, riser drilling will give scientists access to more data, in situ tests, and samples from deep inside Earth. By using robotics and information technologies, samples and data collected continuously will be acquired and processed automatically. In situ borehole experiments such as the (Extended) Leak-Off Test (XLOT) will also be conducted more frequently. XLOT is a technique to measure the in situ stress field (based on the least compressive stress value) by shutting off the wellhead and pumping fluid into the borehole to increase the pressure until fluid enters permeable formations or a fracture is formed. These approaches will enhance the volume of data acquired during drilling, and using advanced telecommunication technology many of them will be delivered quickly to onshore scientists for further processing, analysis, evaluation, and interpretation. Riser drilling coupled with long-term borehole observatories may be a crucial step toward such data-driven, automated, real-time science in the future.

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Listening Down the Pipe

By Evan A. Solomon, Keir Becker, Achim J. Kopf, and Earl E. Davis

ABSTRACT. Since 1991, over 30 borehole observatories have been installed by the Ocean Drilling Program (ODP), the Integrated Ocean Drilling Program, and the International Ocean Discovery Program (IODP), mostly in young oceanic crust and in subduction zones. These installations have provided a sustained presence in the subseafloor environment, enabling collection of a new generation of long-term, time-series data sets of temperature, pressure, and deformation, as well as continuous fluid sampling and in situ active experimentation. These multidisciplinary observations have pushed the frontiers of knowledge about Earth's linked geodynamic, hydrological, geochemical, and biological processes.

ODP/IODP BOREHOLE OBSERVATORY DESIGNS AND INSTRUMENTATION

Nearly all of the designs for ODP/IODP subseafloor observatories[1] require some sort of reentry cone and casing to stabilize the upper part of the hole, and a plug to seal the inside of the borehole against hydraulic interference from the overlying ocean and to allow reestablishment of equilibrium in situ conditions post-drilling. The original observatory design (Figure 1a) was called the Circulation Obviation Retrofit Kit (CORK), and the term "CORK" is often loosely used to refer to all subsequent designs. Since 2001, CORK observatories have become more sophisticated, with multiple subseafloor seals that isolate intervals of interest, and they can now host a range of increasingly advanced instrumentation for geophysical, geochemical, and microbiological experiments (Figure 1b–e). For example, many of the CORKs deployed by IODP in the last two decades included OsmoSamplers that continuously collect formation fluid for several years and can be configured for fluid flow rate monitoring, microbiological sampling, and microbial colonization experiments (Figure 2; e.g., Wheat et al., 2003, 2011; Jannasch et al., 2004; Solomon et al., 2009; Orcutt et al., 2011; Cowen et al., 2012).

With the deployment of cabled ocean observatory systems in the United States, Japan, and Canada in the last decade, providing power to some of the installations is no longer a limitation, and a new generation of CORK observatories are transmitting subseafloor geophysical data to land-based laboratories in real time (e.g., Araki et al., 2017; Saffer et al., 2017; McGuire et al., 2018). "CORK-Lite" models that can be deployed by remotely operated vehicles allow installation of instrumentation in existing reentry boreholes without the aid of a drillship (e.g., Wheat et al., 2012), and some designs include the simple Smart and Genius plugs that permit temporary monitoring of a zone of interest (Kopf et al., 2011). With portable rock drills now used as mission-specific platforms in IODP, deployment of subseafloor observatories will also be possible from ships of opportunity (e.g., Kopf et al., 2015) and in regions where the drillships *JOIDES Resolution* and *Chikyu* cannot operate.

SELECTED SCIENTIFIC HIGHLIGHTS

Some of the most exciting achievements enabled by ODP/IODP observatories to date are listed below. They showcase the diversity of research endeavors and the breadth of the community involved in investigations of IODP's "Earth in Motion" theme, including the processes and natural hazards occurring on human timescales.

- Long-term sealed-hole pressure and temperature records have demonstrated that the uppermost young oceanic basement is highly hydraulically transmissive over regional (tens of kilometers or more) scales, supports extensive lateral fluid flow associated with small pressure differentials, and thus functions as an immense subseafloor aquifer (e.g., Becker and Davis, 2004; Davis and Becker, 2004; Fisher and Wheat, 2010).
- Cross-hole tracer experiments indicate significant structural control of ridge-parallel fluid flow and very low effective porosity in the upper oceanic crust (e.g., Neira et al., 2016).
- In situ monitoring of the radiocarbon content of dissolved inorganic carbon at the Mid-Atlantic Ridge flank revealed that seawater residence times in the oceanic crust can be 10 to 100 times longer than regional heat flow-based estimates, reflecting the heterogenous nature of fluid flow paths (Shah Walter et al., 2018).
- In situ monitoring of fluid composition and flow rates in young oceanic

[1] It is beyond the scope of this short article to describe the evolution of ODP/IODP observatory designs and subseafloor instrumentation in detail; for technical reviews, we refer the reader to Becker and Davis (2005) and Davis et al. (2018).

crust has enabled evaluation of the role of off-axis hydrothermal circulation in global geochemical cycles (e.g., Wheat et al., 2003; Fisher and Wheat, 2010).

- CORK fluid sampling has shown that dissolved organic carbon is removed from cool circulating fluids at the Mid-Atlantic Ridge flank, driven by microbially mediated oxidation, and that this removal mechanism may account for at least 5% of the global loss of dissolved organic carbon in the deep ocean (Shah Walter et al., 2018).
- In situ collection of microbial samples and cultivation experiments in CORKs installed in young oceanic crust show significant changes in microbial community structure between hydrothermal systems and through time (e.g., Cowen et al., 2003; Orcutt and Edwards, 2014; Jungbluth et al., 2016). Results from North Pond on the Mid-Atlantic Ridge show a diverse bacterial community engaged in both heterotrophy and autotrophy at potential rates that may exceed those in ocean bottom water (Meyer et al., 2016).
- Recent improvements in CORK design and CORK-compatible in situ fluid sampling equipment have enabled collection of large volumes of pristine basement fluid whose analysis shows that basalt-hosted ridge-flank fluids harbor a distinct assemblage of novel viruses, including many that infect archaea, pushing the known geographical limits of the virosphere into the oceanic basement (Nigro et al., 2017).
- Active and passive experiments at different spatial scales using CORKs have documented variation in fault permeability with fluid pressure in subduction zones (e.g., Screaton et al., 2000; Kinoshita and Saffer, 2018).
- Sealed-hole pressure records of the response of a surrounding rock formation to tidal loading yields information on the formation's in situ hydrologic and elastic properties, which inform hydromechanical models of a range of processes, such as pore pressure response to coseismic ground motion (e.g., Becker and Davis, 2004; Davis and Becker, 2004).
- Subseafloor pressure recorded in well-sealed borehole observatories provides an extraordinarily sensitive proxy for plate-scale strain on timescales ranging from years to coseismic slip, with the most sensitive strain monitoring done in hydrologically isolated low-porosity formations (e.g., Davis et al., 2004, 2013; Araki et al., 2017). These measurements have led to the discovery of a range of deformation events, from small earthquakes and dike intrusions, to shallow slow slip events that may accommodate a large fraction of the plate motions in subduction zones (see Wallace et al., 2019, in this issue).
- CORK pressure records show that fault slip in shallow portions of subduction zones can occur spontaneously, be triggered by dynamic stress changes (e.g., earthquakes), and can occur with little or no seismic expression (e.g., Davis et al., 2013; Araki et al., 2017; Wallace et al., 2019, in this issue).

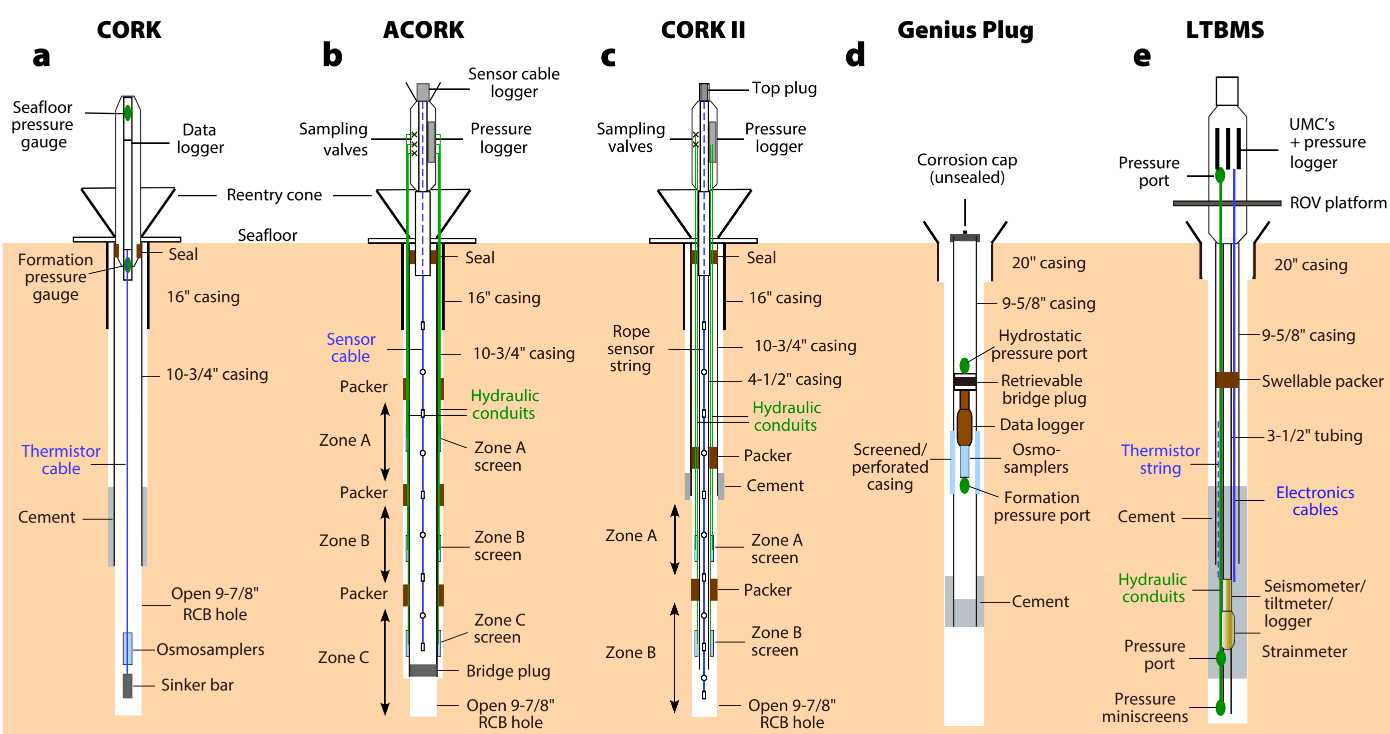

FIGURE 1. Schematic of the evolution of ODP/IODP borehole observatory designs. (a) The original CORK. (b) Advanced CORK (ACORK). (c) CORK II. (d) Genius Plug (Kopf et al., 2011). (e) Long-Term Borehole Monitoring System (LTBMS; Saffer et al., 2017). UMC = underwater mateable connector. See Davis et al. (2018) for a recent technical summary.

- High-resolution borehole temperature monitoring after the 2011 Tōhoku-oki earthquake at the Japan Trench enabled near-real-time estimation of the frictional shear stress and apparent friction coefficient, showing very low shear resistance to fault slip at shallow depth (Fulton et al., 2013, and 2019, in this issue)
- CORKs provided the first in situ measurements of fluid flow rates along a subduction zone megathrust at depth (Figure 2), documenting enhanced fluid flow in response to fault slip (e.g., Solomon et al., 2009; Fulton and Brodsky, 2016). Results also show that dewatering in the forearc of subduction zones occurs not only through the upper plate but also within the subducting igneous crust, with implications for pore pressure development and effective stress along the plate boundary (e.g., Solomon et al., 2009).
- Broadband seismic borehole observatories in the Western Pacific obtained direct and unexpected seismological evidence of the age-dependent lithosphere-asthenosphere boundary (Kawatsu et al., 2009).

CONCLUDING REMARKS

CORK borehole observatories track Earth's "pulse" at spatial and temporal scales that are not possible with traditional IODP coring techniques. Progressive improvements in CORK design and performance and in situ geochemical and microbiological sampling equipment have made probing the biogeochemistry of the crustal deep biosphere a more consistent and pristine research avenue in scientific ocean drilling (e.g., Jungbluth et al., 2016). Recent cross-hole experiments have provided direct measurements of formation properties at scales larger than can be obtained with conventional core-based analyses, and have illuminated how these properties may vary in time. Continuous monitoring with CORK observatories has improved the quantification of natural forces driving off-axis hydrothermal circulation and transformed our understanding of the role this circulation plays in marine biogeochemical cycles and in sustaining the deep biosphere. The ability to directly monitor the subseafloor environment removed from the influences of ocean phenomena at the seafloor has led to robust records of regional crustal strain associated with tectonic events both at mid-ocean ridges and in subduction zones. More recently, CORKs installed to document and understand the patterns of strain accumulation and release along subduction thrusts have the sensitivity and bandwidth to detect very small deformation at timescales from seconds to months. This has led to the detection of shallow slow slip events and illuminated their relationship to larger, more destructive subduction zone earthquakes.

The multidisciplinary progression in CORK design and instrumentation over the last few decades has given us a more holistic understanding of the subseafloor environment. Because CORKs can accommodate a wide range of experiments and instrumentation and respond to the rapid pace at which these technologies evolve, CORK-based monitoring and active experimentation should continue to play an important role in scientific ocean drilling over the next few decades. These multidisciplinary observations will continue to transform our understanding of Earth and how it evolves.

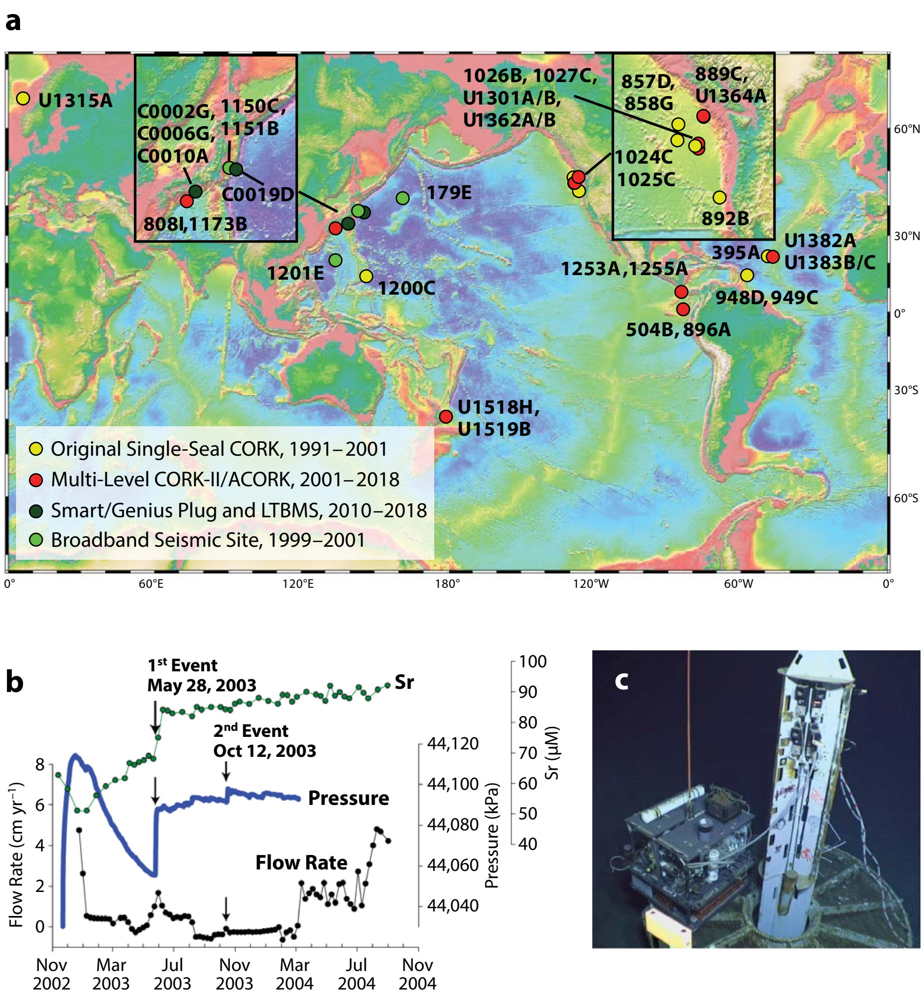

FIGURE 2. (a) Map of CORK locations. (b) CORK observatory record of pore pressure, fluid flow rate, and fluid composition changes along the shallow plate boundary during two slow slip events at the Costa Rica subduction zone (Reprinted from Solomon et al., 2009, with permission from Elsevier). (c) CORK-II wellhead deployed at the Mid-Atlantic Ridge during IODP Expedition 336. A Geomicrobe sampling system (Cowen et al., 2012) is sitting on the remotely operated vehicle platform and attached to the microbiology bay. Fluids are sampled from a screened interval within the igneous oceanic crust at depth.

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TŌHOKU-OKI FAULT ZONE FRICTIONAL HEAT MEASURED

During IODP Expeditions 343 and 343T

By Patrick M. Fulton, Emily Brodsky, James J. Mori, and Frederick M. Chester

ABSTRACT. During the March 11, 2011, M_w 9.1 Tōhoku-oki earthquake, the plate boundary fault slipped an astonishing 50 m or more, with the slip extending all the way to the seafloor within the Japan Trench. The result was a much larger earthquake and tsunami than expected as well as considerable devastation on land. The earthquake challenged our understanding of subduction zone mechanics but also presented an opportunity to resolve long-standing questions regarding the amount of frictional resistance faults exhibit during earthquakes, resistance that influences the amount of fault slip and associated tsunami hazards. Here we report on how scientific ocean drilling successfully allowed the measurement of frictional heating within the fault zone that ruptured during the Tōhoku-oki earthquake.

THE TŌHOKU-OKI EVENT AND IODP RAPID RESPONSE

The amount of frictional heat generated per unit fault area during an earthquake is the direct product of the average shear stress during slip and displacement. By drilling through a fault and measuring the frictional heat signal within the fault zone after a great earthquake, such as the Tōhoku-oki event, frictional resistance can be evaluated. However, the measurement must be made within a year or two of the earthquake before the thermal signal dissipates.

Through the rapid-response efforts of Integrated Ocean Drilling Program (IODP) Expeditions 343 and 343T, the Japan Trench Fast Drilling Project (JFAST) was implemented aboard D/V *Chikyu* within one year after the M_w 9.1 Tōhoku-oki earthquake (Chester et al., 2013a). The objectives of JFAST were to drill across the plate boundary fault, characterize the fault with geophysical logging, collect core samples, and install a temperature observatory to monitor the frictional heat signal (Chester et al., 2013a). These two expeditions presented considerable challenges, including rapid development of an appropriate observatory system and then drilling and installing it across the plate boundary fault ~820 meters below seafloor (mbsf) in a water depth of ~7 km.

OBSERVATORY INSTALLATIONS TO MEASURE THERMAL RESPONSE

The observatory, consisting of 55 autonomous titanium-encased temperature-sensing dataloggers with an accuracy of ~0.001°C and 10-minute sampling intervals, was installed July 15, 2012 (Figure 1). The observatory was recovered successfully on April 26, 2013. The resulting data reveal a 0.31°C anomaly with a maximum centered at 819 mbsf, coincident with the primary geologic plate boundary fault inferred from core and logging data (Fulton et al., 2013; Figure 2). These results are the clearest direct measurement of frictional heat ever made after an earthquake. The anomaly is interpreted to reflect an average coseismic friction coefficient (the ratio of shear to normal stress) of 0.08 (Fulton et al., 2013). This value is much less than typical static friction values of 0.6–0.85 (Byerlee, 1978) and implies that the fault at this location had very little resistance during slip. This very low frictional resistance is consistent with high-speed laboratory friction measurements on fault core material from the same Tōhoku-oki plate boundary fault (Ujiie et al., 2013), and with stress determinations from analysis of stress-induced fracturing along the borehole walls during drilling. The borehole stress analysis reveals no residual shear stress on the fault after the earthquake, implying that the stress drop was complete at the site (Lin et al., 2011; Brodsky et al., 2017).

FAULT ZONE CORE MATERIALS

In addition to the direct temperature measurements, new advances in quantifying geologic signatures of frictional heating have been applied to the limited amount of recovered core. At 821.5–822.65 mbsf, a core section of highly sheared scaly clay was interpreted to come from the main plate boundary fault; based on core recovery, it is estimated to have a thickness of <4.86 m (Chester et al., 2013b). Given the prevalence of smectite, particularly within samples from a highly sheared slip zone about 16 cm from the top of the core, Schleicher et al. (2015) suggest that these scaly clays have not been heated above 200°C. Using combined real-time XRD and rapid heating experiments, Schleicher et al. (2015) illustrate that smectite becomes permanently altered at temperatures >200°C. Experiments have also shown that heating of smectite above 250°C can result in the authigenesis of fine-grained ferromagnetic minerals (Hirt et al., 1993; Yang et al, 2016). Although Scheicher et al. (2015) do not find evidence of thermogenic alteration in their XRD measurements, analysis of other samples within the same fault zone core by Yang et al. (2016) find magnetic susceptibility changes indicative of very fine-grained thermally generated minerals. Yang et al. (2016) interpret their results to suggest that the samples were heated to temperatures of 300°–800°C. Theoretical modeling indicates that on a fault with friction as low as 0.08, such high temperatures would be achieved at these depths only in millimeter-thick slip zones (Fulton and Harris, 2012). Whether the conflicting peak temperature estimates can be reconciled by the locations of samples relative to possible sources of frictional heat or otherwise remains unclear and motivates future theoretical and experimental investigation of fault zone materials collected via scientific ocean drilling.

Rabinowitz et al. (2015) identified several other major faults within recovered core between 817 and 833 mbsf based on chemostratigraphic evidence of large total displacements. Subsequent analysis of biomarker thermal maturity across these mudstone and pelagic clay faults reveals localized anomalies within slip zones interpreted to be the result of frictional heating above 120°C (Hannah Rabinowitz and colleagues, unpublished

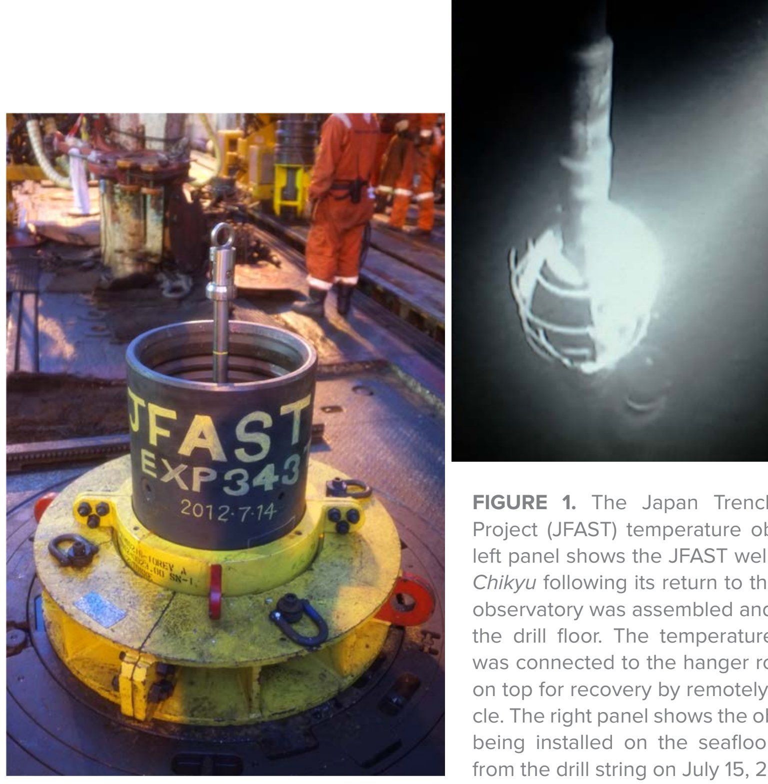

FIGURE 1. The Japan Trench Fast Drilling Project (JFAST) temperature observatory. The left panel shows the JFAST wellhead on board *Chikyu* following its return to the ship after the observatory was assembled and hung beneath the drill floor. The temperature sensor string was connected to the hanger rod with the ring on top for recovery by remotely operated vehicle. The right panel shows the observatory after being installed on the seafloor and released from the drill string on July 15, 2012.

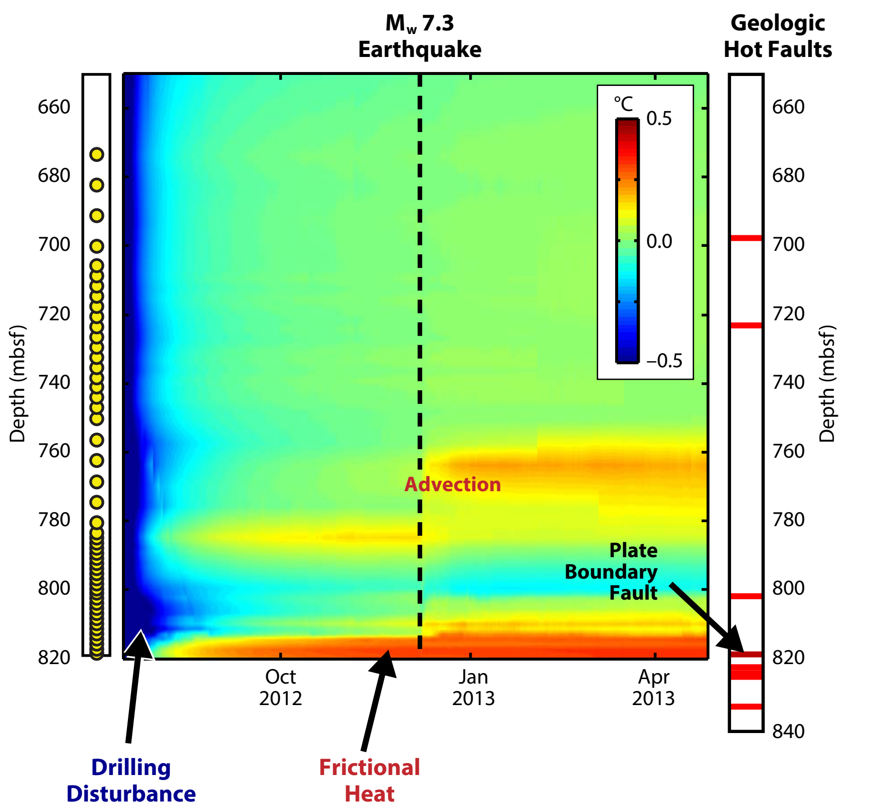

FIGURE 2. Residual borehole temperature data, after the background geotherm was removed, as a function of time from Integrated Ocean Drilling Program Hole C0019D (Expedition 343) in the Japan Trench. Yellow dots (left) mark sensor positions in the observatory and red lines (right) indicate faults identified from geologic signatures of frictional heating in core samples from Hole C0019E. Note that due to bathymetric differences between the separate coring and observatory holes, fault locations identified in the core are expected to be a few meters deeper relative to the seafloor than in the observatory (Chester et al., 2013b). Fluid advection is not seen within the plate boundary fault but is observed within the temperature data at shallower depths in response to a December 7, 2012, M_w 7.3 earthquake and other aftershocks (Fulton and Brodsky, 2016). The differences in hydrologic and thermal response to earthquakes and drilling disturbance at different depths is indicative of the dominance of conductive heat transfer within the plate boundary fault (Fulton et al., 2013; Fulton and Brodsky, 2016). *Adapted from Fulton and Brodsky (2016)*

data). The data do not constrain whether or not these particular faults slipped during the Tōhoku-oki earthquake, but they do support the possibility of multiple fault surfaces slipping during a single event. Note that the directly observed temperature signal measures the total energy over a region that includes all of these potential fault strands and thus does not resolve which (if any) were active during this particular earthquake.

Additional evidence of frictional heating in the JFAST core samples comes from other faults identified at depths around 697, 720, and 801 mbsf. Using mineral magnetic methods, electron microscopy, and X-ray spectroscopy, Yang et al. (2018) identified the presence of pyrrholite, a mildly magnetic iron sulfide mineral, exclusively within these faults zones. Ruling out other potential mechanisms for pyrrholite formation at this site, such as prolonged diagenetic reaction of magnetite or thermochemical sulfate reduction, they interpret their analyses as evidence of thermally driven pyrite-to-pyrrholite reactions at temperatures between 640°C and 800°C. There is no evidence of any frictional heat associated with these faults in the borehole temperature data, which implies that the pyrrholite occurrences in the borehole record the effects of previous earthquakes where fault slip was large.

CONCLUSION

Together, these studies made possible by IODP Expeditions 343 and 343T illustrate how both the direct and the indirect measurements of frictional heat at the Japan Trench are providing important insights into paleoseismicity and constraints on the resistive forces influencing earthquake and tsunami hazards. The JFAST project was motivated by scientific objectives that required drilling shortly after a disaster in order to obtain time-sensitive measurements. The amazing success of JFAST relied heavily on the IODP scientific infrastructure, engineering and technical expertise, and program management structures, without which such a rapid response scientific ocean drilling project would not have been possible.

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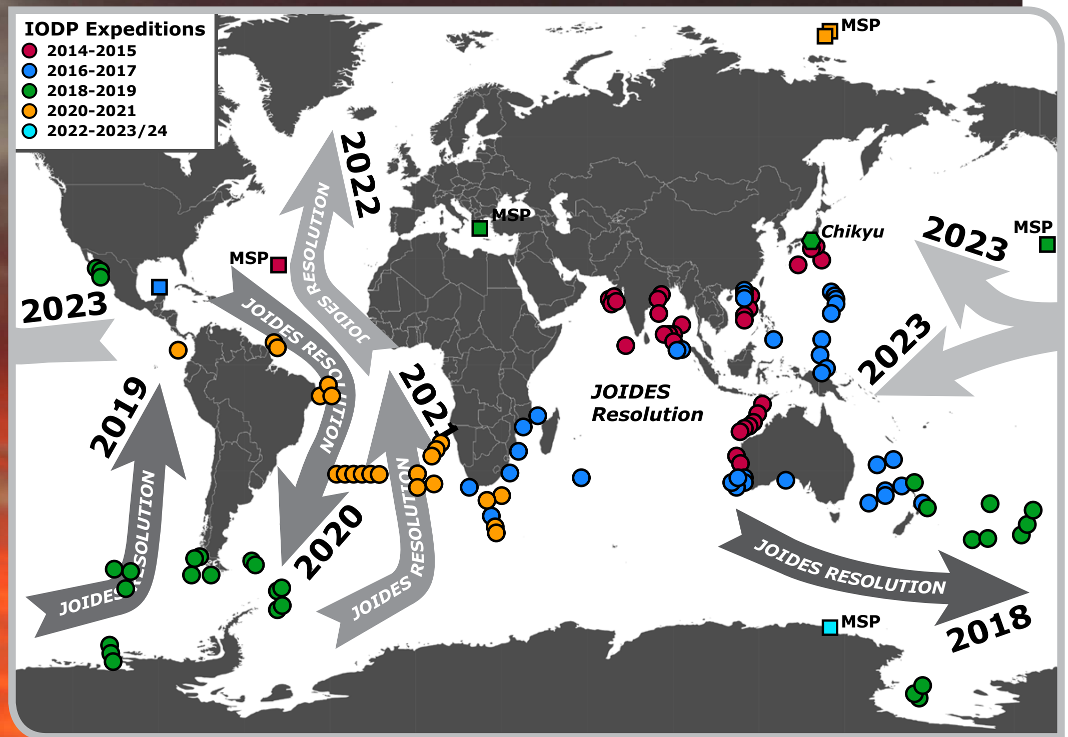


SPOTLIGHT 8. Regional Science Planning

Although not new to scientific ocean drilling, International Ocean Discovery Program science planning has become regionally focused for two of its ship platforms, *JOIDES Resolution* and *Chikyu*. While the non-riser drilling vessel *JOIDES Resolution* follows a globe-encircling track that is regionally planned, riser vessel *Chikyu* operations focus on deep targets in regions around Japan, and the *mission-specific platforms* have been operating around the world.

The *JOIDES Resolution* ship track is determined up to five years in advance of drilling in order to identify operational regions for this platform and to allow scientists to develop proposals for work within its target regions. This regional planning brings *JOIDES Resolution* to all ocean basins, and it will circumnavigate Earth at least once over the course of 10 years. For example, *JOIDES Resolution* started out in the South China Sea and the Western Pacific in 2014–2015, and the plan is to have the ship return in the general Indo-Pacific region in 2023–2024. The long-term planning of ship tracks keeps all proponent teams worldwide engaged and, so far, has created substantial proposal pressure in the regions surrounding the proposed track of *JOIDES Resolution*.

– Anthony A.P. Koppers and Clive R. Neal

BACKGROUND. Sunrise from *JOIDES Resolution*, Expedition 340, Lesser Antilles. *Credit: Etienne Claassen, IODP USIO*

SLOW MOTION EARTHQUAKES

Taking the Pulse of Slow Slip with Scientific Ocean Drilling

By Laura M. Wallace, Matt J. Ikari, Demian M. Saffer, and Hiroko Kitajima

Scientists prepare fluid samplers for installation in a borehole observatory at the Hikurangi subduction zone on IODP Expedition 375. *Photo credit: Aliki Westrate, Expedition 375 Outreach and Education Officer*

ABSTRACT. The discovery of a spectrum of slow earthquakes and slow slip events on many of Earth's major tectonic faults has sparked a revolution in the fields of seismology, geodesy, and fault mechanics. Until about 15 years ago, it was believed that faults either failed rapidly in damaging earthquakes or by creeping at rates of plate tectonic motion. However, the widespread observation of episodic, slow fault slip events at plate boundaries around the world, including at subduction zones, has revealed that fault slip behavior spans a continuum of modes, from steady creep to fast, earthquake-inducing slip. Understanding the processes that control these various failure modes is one key to unlocking the physics of earthquake nucleation and slip on faults. Scientific ocean drilling holds a unique place at the forefront of these efforts by allowing direct access to fault zones and sediment in the subsurface where slow slip events occur, by enabling near-field monitoring in borehole observatories, and by providing samples of incoming sedimentary succession that comprises the protolith for material in slow slip source regions at subduction zones. Here, we summarize fundamental contributions from scientific ocean drilling at subduction zones to this emerging field.

INTRODUCTION

Slow slip events (SSEs) involve transient aseismic slip along a fault, lasting days to years, at a rate intermediate between plate tectonic displacement rates (centimeters per year) and the slip velocity required to generate seismic waves (centimeters to meters per second). Installation of dense, plate-boundary-scale geodetic networks in the last two decades has enabled detection of these events, revealing their importance as a significant mode of fault slip. The observation of SSEs and associated seismic phenomena at subduction megathrusts worldwide has created one of the most dynamic fields of research in seismology and geodesy today (e.g., Ide et al., 2007; Schwartz and Rokosky, 2007; Peng and Gomberg, 2010). Although SSEs appear to bridge the gap between typical earthquake behavior and steady, aseismic slip on faults, the physical mechanisms that lead to SSEs and their relationship to the destructive, seismic slip on subduction thrusts remain poorly known.

Evidence for transient creep events on continental faults—such as the San Andreas—has been noted in a few cases for some time (e.g., Goulty and Gilman, 1978; Sacks et al., 1982; Linde et al., 1996), but such events were not well characterized until continuously operating GPS networks began to reveal episodic, aseismic fault slip events at several subduction zone plate boundaries. The first well-documented subduction zone slow slip events were discovered in southwest Japan (Hirose et al., 1999) and Cascadia (Dragert et al., 2001) at locations downdip of areas that are thought to store strain and then slip catastrophically in great earthquakes (so-called "locked zones"). These discoveries were quickly followed by a succession of observations of SSEs at other circum-Pacific subduction zones (e.g., Kostoglodov et al., 2003; Douglas et al., 2004; Sagiya, 2004; Hirose and Obara, 2005; Ohta et al., 2006; Wallace and Beavan, 2006; Outerbridge et al., 2010; Valee et al., 2013; Ruiz et al., 2014). In tandem with the geodetic observations, seismologists recognized the occurrence of tremor at subduction zones, an emergent seismic signal previously associated mainly with volcanic processes (Obara, 2002). This was soon linked spatially and temporally to many geodetically detected slow slip events, and was termed "non-volcanic tremor" (NVT) at first (Rogers and Dragert, 2003; Hirose and Obara, 2005). Coincident tremor and slow slip episodes are now commonly observed at the Cascadia and Nankai Trough subduction zones, and are often called "episodic tremor and slip" (ETS) events. Observations of tremor were followed by recognition of a range of slow seismological expressions of slow slip, including low frequency and very low frequency earthquakes (Shelly et al., 2006; Ito et al., 2007), thought to represent shear slip on the plate boundary (Shelly et al., 2007). These tremor and low frequency earthquakes are typically considered to be part of the spectrum of slow slip event behavior.

SSEs involve a few to tens of centimeters of slip over periods of weeks to years, in some cases releasing accumulated tectonic stress equivalent to that of magnitude 6.0–7.0 earthquakes. The observation that these kinds of slow slip events likely preceded (and perhaps triggered) the 2011 M_w 9.0 Tōhoku-oki (Japan Trench) and the 2014 M_w 8.1 Iquique (Peru-Chile Trench) subduction plate boundary earthquakes (Kato et al., 2012; Ito et al., 2013; Ruiz et al., 2014) provided an impetus to clarify the poorly understood relationship between SSEs and damaging megathrust earthquakes (Obara and Kato, 2016). Most well-studied SSEs occur along the deep end of the earthquake generation zone, for example, below the "seismogenic" zone and at depths greater than 20–30 km (Dragert et al., 2001; Obara et al., 2004; Hirose and Obara, 2005; Ohta et al., 2006; Wallace and Beavan, 2010; Radiguet et al., 2012). However, recent observations indicate that slow slip events are also common to the shallow portions of offshore subduction plate boundaries, at less than 15 km depth (Saffer and Wallace, 2015), and continue to within a few kilometers of the seafloor, possibly all the way to the trench (Wallace et al., 2016; Araki et al., 2017).

Despite the fact that SSEs are now widely recognized to play an important role in the accommodation of plate motion at tectonic boundaries, our understanding of why they occur is largely incomplete. A variety of theories regarding the origin of SSEs have been proposed; most of these consider episodic slow slip as a consequence of low effective stress (due to elevated fluid pressures) within a conditionally stable frictional regime (see reviews in Saffer and Wallace, 2015, and Bürgmann, 2018). These hypothesized mechanisms for SSEs arise from theoretical and modeling studies (e.g., Liu and Rice, 2007) and indirect interpretations of physical properties from seismic imaging of faults known to host slow slip (Kodaira et al., 2004; Audet et al., 2009; Song et al., 2009; Kitajima and Saffer, 2012). Most well-studied subduction zone SSEs occur too deep (>20 km depth) for the high-resolution imaging, direct sampling, and in situ measurements within the SSE source region that are needed to test these ideas. This lack of access has placed inherent limits on our ability to resolve the physical processes and in situ conditions responsible for slow fault slip behavior.

However, shallow SSE regions, where slow slip events occur much closer to Earth's surface (<15 km), may provide the best chance to resolve outstanding questions about slow slip. For example, at the northern Hikurangi subduction zone offshore New Zealand, a recent seafloor geodetic experiment has shown that SSEs can occur to within 2 km of the seafloor, and possibly all the way to the trench (Wallace et al., 2016). The close proximity of SSEs to the seafloor there presents a remarkable opportunity to use scientific ocean drilling to drill into and sample, collect downhole logs, and conduct monitoring in the very near field of the SSE source area. To that end, International Ocean Discovery Program (IODP) drilling took place in 2017 and 2018 at north Hikurangi on Expeditions 372 (Pecher et al., 2018) and 375 (Saffer et al., 2018) (Figure 1a), representing the first IODP effort specifically targeted at resolving

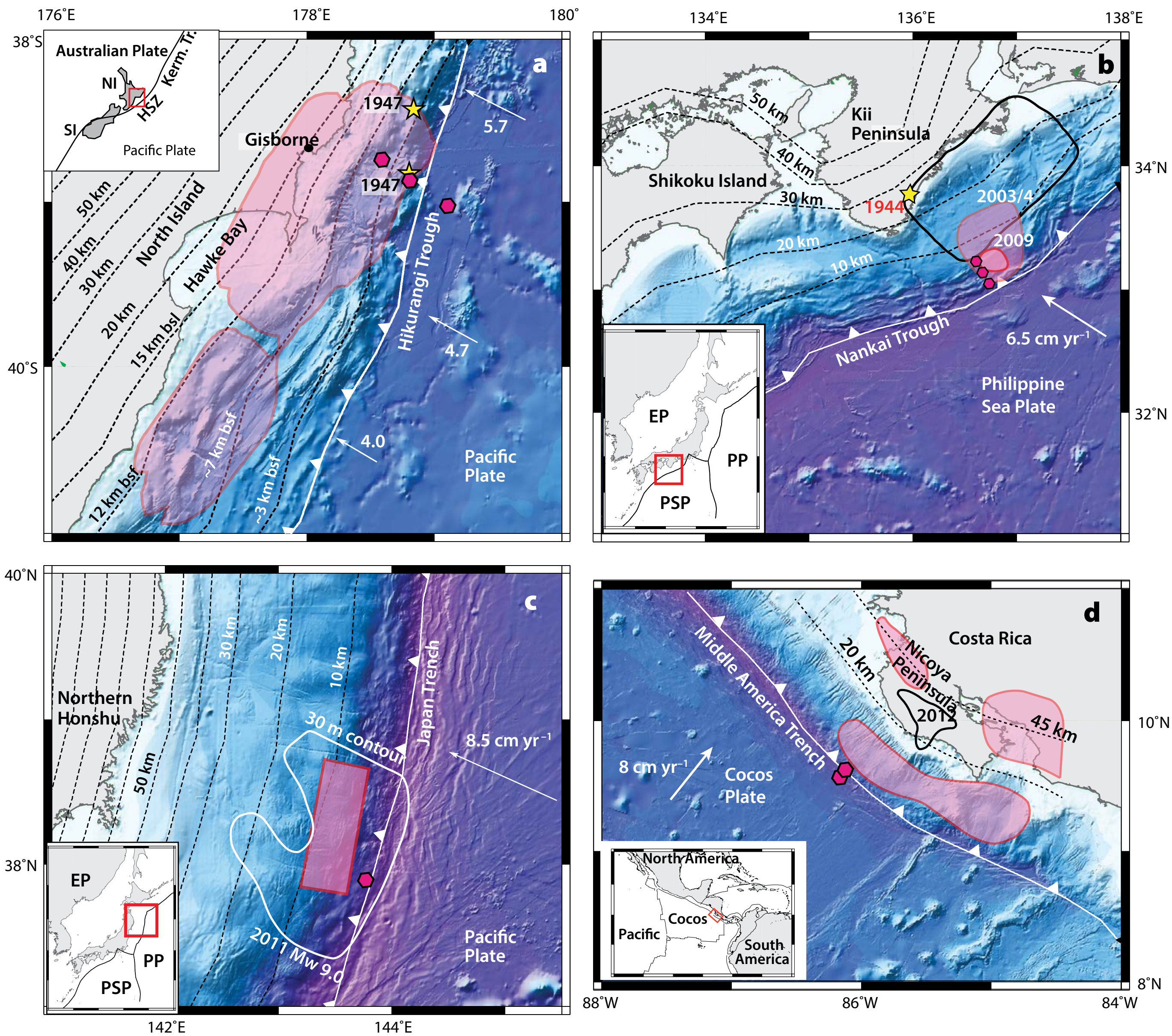


FIGURE 1. Four subduction margins with well-characterized shallow slow slip events (SSEs) and slow earthquakes, where IODP drilling has also taken place: (a) Hikurangi, (b) Nankai, (c) Japan Trench, and (d) Costa Rica. Black dashed contours are depths to the interface (in kilometers below Earth's surface); pink shaded areas show the locations of SSEs and slow (very low frequency) earthquake clusters (Ito and Obara, 2006; Wallace et al., 2012; Dixon et al., 2014; Sugioka et al., 2012; Ito et al., 2013). Black/white solid contours outline slip in previous large plate interface earthquakes at Nankai, Costa Rica, and Northern Japan. Yellow stars show epicenters of historical large subduction interface earthquakes at Hikurangi and Nankai. Pink dots show locations of previous IODP drilling. *Modified from Saffer and Wallace (2015)*

the origins of SSEs. However, shallow SSEs have also been observed at southwest Japan's Nankai Trough (Araki et al., 2017), the Japan Trench (Kato et al., 2012; Ito et al., 2013), and Costa Rica's Middle America Trench (Brown et al., 2005; Davis et al., 2015), where several IODP expeditions have been undertaken over the last 20 years (Figure 1). Although the Nankai Trough, Japan Trench, and Costa Rica scientific drilling efforts were targeted at understanding seismogenic (earthquake generating) processes, IODP drilling data from these regions have provided unexpected new insights into SSE processes. We expect scientific ocean drilling to contribute even more important findings to the field of slow earthquakes, as results emerge from the recently completed Hikurangi subduction zone drilling during IODP Expeditions 372 and 375.

LONG-TERM BOREHOLE OBSERVATORIES: DETECTION AND CHARACTERIZATION OF SHALLOW SSES IN THE NEAR FIELD

Borehole monitoring systems at IODP drill sites offshore have provided some of the most robust observations to date of crustal strain during shallow subduction zone SSEs and associated hydrologic phenomena. These observatories involve a variety of configurations designed to monitor pore fluid pressure, temperature, strain, and tilt in the borehole rock formations, and to collect time series of formation fluids and flow rates using osmotically driven pumps (or so-called osmosamplers; e.g., Jannasch et al., 2003). In particular, changes in pore fluid pressure recorded in these observatories provide a highly sensitive measure of volumetric strain (Wang, 2004; Araki et al., 2017) in offshore regions near a trench that involve slip as small as only a few centimeters and where other geodetic methods lack resolution to detect or locate SSEs. Results from these instruments, most notably in the near-trench region of the Nankai (Araki et al., 2017) and Costa Rican (Davis and Villinger, 2006; Solomon et al., 2009; Davis et al., 2015) subduction zones (Figure 1), have yielded detailed observations of slow slip events that provide new constraints on location, timing, size, relationship to tremor, and potential associated changes in fault hydrogeology.

As one of the primary objectives of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), IODP Expeditions 319, 332, and 365 installed borehole observatories at two sites located ~24 km and 35 km landward of the subduction trench (Figures 1b and 2a). Site C0010 was drilled into the megasplay, one of the major active thrust faults splaying from the plate boundary, approximately 24 km from the trench. The borehole intersects the fault at 407 meters below seafloor (mbsf); the hole was initially drilled in 2009, and temporary instrument systems were deployed to monitor temperature and pore fluid pressure within the borehole (Saffer et al., 2010; Kopf et al., 2011). In 2016, a permanent observatory was installed that includes pore pressure sensors, a tiltmeter, an accelerometer, a broadband seismometer, and a volumetric strainmeter (Saffer et al., 2017). In addition, Site C0002 was drilled in the Kumano forearc basin (Figure 2a), about 11 km landward of Site C0010. A permanent observatory with the same configuration as that at Site C0010 was installed here in 2012. Together, the observatories provide a multiyear time series of formation pore pressure at two locations that define a "miniature array" with an ~11 km aperture. Formation fluid pressure changes serve as a sensitive proxy for volumetric strain during transient slow slip events, with the ability to resolve signals as small as ~10–20 nanostrain, equivalent to a crustal volume strain of approximately 10–20 parts per billion (Wang, 2004; Davis et al., 2009; Araki et al., 2017).

Since the 2012 installation of the observatory by IODP, the 5.3-year pressure time series reveal eight "strain events" that recur quasi-regularly at ~8–15 month intervals and with durations of a few days to several weeks (Figure 2b; Araki et al., 2017). These strain events are synchronous at the two boreholes, and some (though not all) are accompanied by swarms of low frequency tremors in a 40 km region of the forearc closest to the trench (Figure 1b) as detected by Japan's DONET (Dense Oceanfloor Network System) cabled seafloor network of seismometers (Kaneda et al., 2015). Similar low frequency earthquakes were observed previously in this region using shore-based networks (Ito and Obara, 2006). The sets of synchronous strain signals fall into three categories: (1) dilatation (extension) at both sites, (2) mixed signals with compression at Site C0010 and dilatation at Site C0002, and (3) compression at both sites. The magnitudes of these signals are best explained as slips of ~1–4 cm on the plate interface beneath the drill sites (Figure 2b), occurring over a period of days for the shortest events, to weeks for the longest. The sign of the strain signal allows delineation of the slipping regions, and suggests that most of the events are centered either landward, between the two boreholes (located ~30 km from the trench), or seaward of both sites, with slip possibly extending all the way to the trench.

These observations, enabled by offshore borehole observatories installed as part of IODP drilling, also indicate that repeating SSEs occur at shallow depths along the Nankai margin updip of the locked seismogenic zone and possibly extend to the trench. A third observatory, recently installed in the accretionary prism within 2 km of the trench axis during IODP Expedition 380, will provide key constraints on the seaward (trenchward) extent of slip in these SSEs (Kinoshita et al., 2018). The amount of slip deduced from the observatory signals suggests that SSEs accommodate ~30%–50% of the total amount of plate convergence, broadly consistent with partial seismic coupling (on order of 50%) in this area, as reported on the basis of a regional offshore GPS-A network (Yokota et al., 2016). This finding is especially noteworthy because the SSEs occur at a margin characterized by repeating great (M_w ~8) earthquakes that are thought to rupture at or close to seafloor depths (Satake, 1993; Sakaguchi et al., 2011), in a place where slow slip events were not necessarily expected.

Along the Costa Rican subduction margin, two borehole observatories were installed in 2002 during Ocean Drilling Program (ODP) Leg 205, offshore the Nicoya Peninsula in Costa Rica (Morris et al., 2003; Davis and Villinger, 2006; Figure 1d). One of the observatories (in Hole 1253A) was installed in the subducting Cocos Plate (~175 m seaward of the trench), penetrating the subducting sediments and underlying basement to ~600 mbsf. The second observatory (in Hole 1255A) penetrated the subduction thrust ~500 m landward of the trench at a depth of ~144 mbsf, to a total depth of 153 mbsf. Both observatories involve formation pore pressure monitoring, as well as geochemical fluid sampling and flow rate monitoring capabilities, using osmosamplers and osmoflowmeters (Jannasch et al., 2003; Solomon et al., 2009). These observatories were originally intended to assess the influence of the igneous basement on fluid flow, as well as to quantify the fluid pressure state on the plate boundary thrust

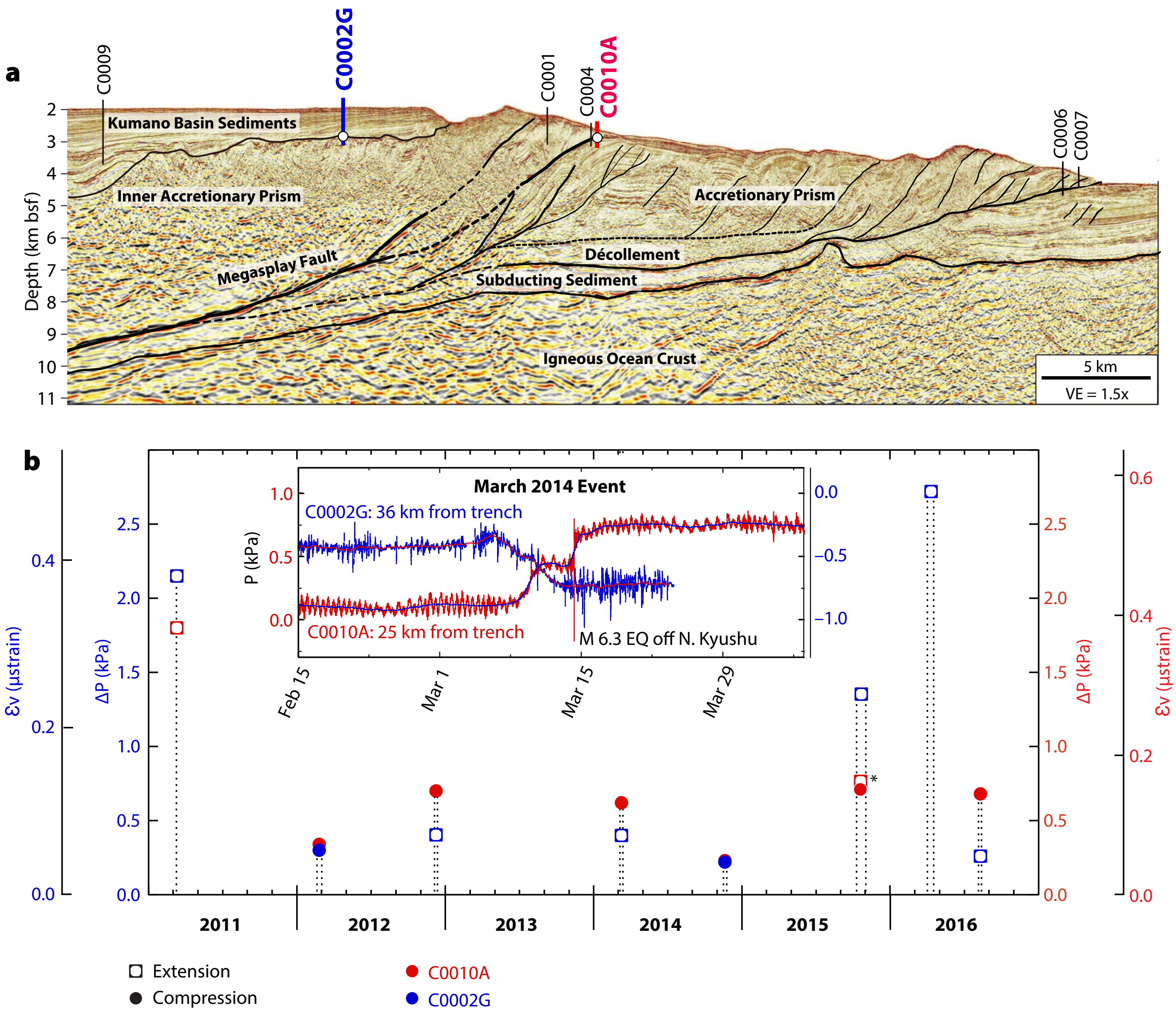


FIGURE 2. (a) Seismic line showing the locations of several Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) drill sites. Open white circles show the depths of pore pressure monitoring intervals at observatory boreholes C0002G (931–980 m) and C0010A (389-407 m). (b) Summary of SSE recurrence, shown by pressure and strain transients at Holes C0002G (blue) and C0010A (red). Dashed vertical lines indicate the duration of each event. A mixture of pressure increases (compressional strain; solid circles) and decreases (dilatational strain; open squares) are observed, and the sign of the strain provides constraints on the location of the slipping region in each event (after Araki et al., 2017). The Oct. 2015 event (denoted by asterisk) exhibited extension only at Hole C0002G, and initial compression followed by dilatation at Hole C0010A. The inset shows formation pore pressure records with oceanographic signals removed for an example SSE in March 2014. The thin line shows smoothed data using a 12 hr window.

and within the hanging wall of the fault system. However, they were also fortuitously located in a region of shallow slow slip events offshore the Nicoya Peninsula, as detected by a shore-based continuous GPS network (Dixon et al., 2014).

There is now mounting evidence for transient changes in pore pressure, and though less clear, accompanying shifts in fluid geochemistry and flow rates within the Costa Rica observatories that coincide with SSEs detected by onshore GPS sites. Solomon et al. (2009) identified two changes in fluid flow rates and fluid geochemistry (e.g., in the measured $^{87}Sr/^{86}Sr$ isotope ratios) that coincide with pore pressure shifts, which in turn are consistent with deformation due to a migrating slow slip event. This was the first evidence from an IODP borehole observatory that slow slip events impact hydrological processes and fluid geochemistry on the shallow subduction interface. Additional pore pressure transients have been observed following geodetically detected SSEs, which are interpreted as a delayed updip migration of SSEs to the trench (Davis et al., 2015). For example, in the weeks following a geodetically detected SSE in 2007, the observed pore pressure increases at Hole 1255A, combined with a pore pressure decrease at Hole 1253A as well as 1.4 cm of uplift suggested from the wellhead pressure data at Hole 1255A, led Davis et al. (2015) to suggest that the 2007 SSE involved up to 11 cm of slip to the trench.

DRILLING TO SAMPLE SSE FAULTS: FAULT ROCK PROPERTIES AND IN SITU CONDITIONS

Fault Friction and Effective Stress States: A Framework to Understand Unstable Slip and SSEs

Laboratory-based shearing experiments that simulate fault slip are one common approach to characterizing the strength and slip behavior of fault zones. In particular, rate-and-state friction—a theory that describes variations in frictional strength as functions of driving velocity (rate) and time (state)—provides a widely used and valuable theoretical framework for understanding fault sliding stability as it relates to earthquake nucleation and propagation, as well as other phenomena including fault healing, afterslip, and aseismic creep (e.g., Dieterich, 1979, 1981; Ruina, 1983; Marone, 1998). In the context of this theory, an increase in fault strength (or its resistance to sliding) as slip speed increases is known as velocity-strengthening behavior. Faults with this property are expected to slip aseismically, manifested as creep or earthquake afterslip. In contrast, velocity-weakening behavior, in which friction or resistance to sliding decreases with increasing sliding velocity, is a prerequisite for the nucleation of unstable, rapid slip that results in earthquakes (e.g., Marone, 1998; Scholz, 2002). Slow slip events are thought to occur where rock frictional properties are "conditionally stable," or near the transition from velocity-weakening to velocity-strengthening behavior. Although some previous laboratory studies have provided important insights that apply to slow slip phenomena, detailed investigations of natural material from major fault zones, particularly those that host slow slip, remain rare, and in situ sampling of these active faults generally requires drilling.

> "In total, the powerful combination of these borehole observatories and IODP drilling, logging, and sampling of fault zones—where slow slip may occur—enables us to draw connections between fault slip behavior and fault architecture, frictional behavior, lithology, fluid composition, and physical properties."

Although seismic fault slip requires velocity-weakening friction, the degree of instability also depends on other factors such as effective stress on the fault and elastic response properties of the surrounding fault rocks (e.g., Dieterich, 1986; Scholz, 1998). Under certain conditions, for example, if the rock frictional properties straddle the transition between velocity-weakening and velocity-strengthening behavior, faults may be quasi-unstable and exhibit oscillatory or slow failure (e.g., Baumberger et al., 1999; Leeman et al., 2016), such as observed during slow slip events. Another condition by which faults may exhibit transitional stability is low effective normal stress acting across the fault, either as a result of small total stresses related to shallow burial depth, or due to the presence of high pore fluid pressure (e.g., Scholz, 1998; Saffer and Tobin, 2011).

On the basis of these ideas, prevailing hypotheses for the occurrence of emergent slow slip events have focused on the roles of low effective stress, mediated by elevated pore fluid pressure, and/or frictional properties near the transition from velocity weakening to velocity strengthening (e.g., Kodaira et al., 2004; Saffer and Wallace, 2015). These ideas have been demonstrated in numerical models (Liu and Rice, 2007) and laboratory experiments (Leeman et al., 2016; Scuderi et al., 2016), and are consistent with the inferred presence of elevated in situ pore pressure in SSE and slow earthquake source regions (e.g., Song et al., 2009; Kitajima and Saffer, 2012). The testing of natural samples is a key for experimental studies of friction targeting slow slip, because they preserve in situ composition and rock properties. IODP drilling has provided unique access to these materials from within shallow fault zones implicated in SSEs at several margins (e.g., Nankai, Costa Rica), as well as sediments on the incoming (subducting) plate that comprise the protolith for SSE fault zones at depth (e.g., Sumatra, Hikurangi). Samples and geophysical logs obtained via IODP drilling have also enabled a range of deformation experiments that allow estimation of in situ pore fluid pressure, porosity, and stress state at the drill sites and by inference within the surrounding volume of the crust (e.g., Tobin and Saffer, 2009; Kitajima and Saffer, 2012).

Insights from Experimental Studies on IODP Drill Cores

Friction Studies

In the Nankai Trough, SSEs, low frequency earthquakes (LFE), and very low frequency earthquakes (VLFEs) occur within the accretionary prism at shallow depths, likely on splay faults (e.g., Ito and Obara, 2006; Obana and Kodiara, 2009) and on the plate boundary thrust (Sugioka et al., 2012; Araki et al., 2017). Laboratory friction experiments have been conducted on samples recovered by ODP and IODP drilling across three major fault zones: (1) a major out-of-sequence splay fault (the megasplay; IODP Site C0004), (2) the frontal thrust zone near the trench (Site C0007) along the NanTroSEIZE transect (Figure 2a), and (3) the décollement zone near the trench (ODP Site 1174) on the Muroto transect ~200 km to the southwest (Shipboard Scientific Party, 2001). These results primarily document velocity-strengthening friction but also show that the degree of velocity-strengthening vs. velocity-weakening behavior can vary with sliding velocity (Ikari et al., 2009; Ikari and Saffer, 2011; Figure 3). Examples where frictional parameters straddle the velocity-strengthening/velocity-weakening transition occur consistently around slip velocities (~1 μm s^{-1}) similar to those of very low frequency earthquakes in the Nankai accretionary prism (Ito and Obara, 2006; Saffer and Wallace, 2015). Furthermore, data from samples at Sites C0004 and 1174 reveal that weakening due to accumulating slip could be an additional mechanism promoting the generation of low-velocity instabilities (Figure 3; Ikari et al., 2013).

In regions where fault zones have not been sampled, scientific ocean drilling still provides critical information on fault slip behavior through access to sediments on the incoming plate. These "subduction inputs" eventually host or line the plate interface, and laboratory testing of these sediments reveals they have characteristics relevant to the shallow plate boundary (e.g. Underwood, 2007; Hüpers et al., 2017; Ikari et al., 2018). An example is the Hikurangi margin offshore New Zealand, where geodetic observations provide a robust record of repeating slow slip events (Wallace et al., 2012, 2016; Wallace and Beavan, 2010). Laboratory experiments have been conducted on a sample of carbonate-rich sediment collected at ODP Site 1124, located seaward of the deformation front, that is expected to host the plate boundary (Rabinowitz et al., 2018). These experiments document a gradual shift from velocity-weakening to velocity-strengthening friction as a function of sliding velocity, with the transition occurring at <1 μm s^{-1}, which is broadly similar to slip rates of SSEs at the Hikurangi margin determined from geodetic studies.

The variation in frictional behavior with sliding velocity observed in experiments on very fine-grained natural fault zone materials, so-called fault gouges, incoming sediments to subduction zones, and synthetic clay-rich fault gouges (e.g., Ikari et al., 2009; Saito et al., 2013; Saffer and Wallace, 2015) highlights the

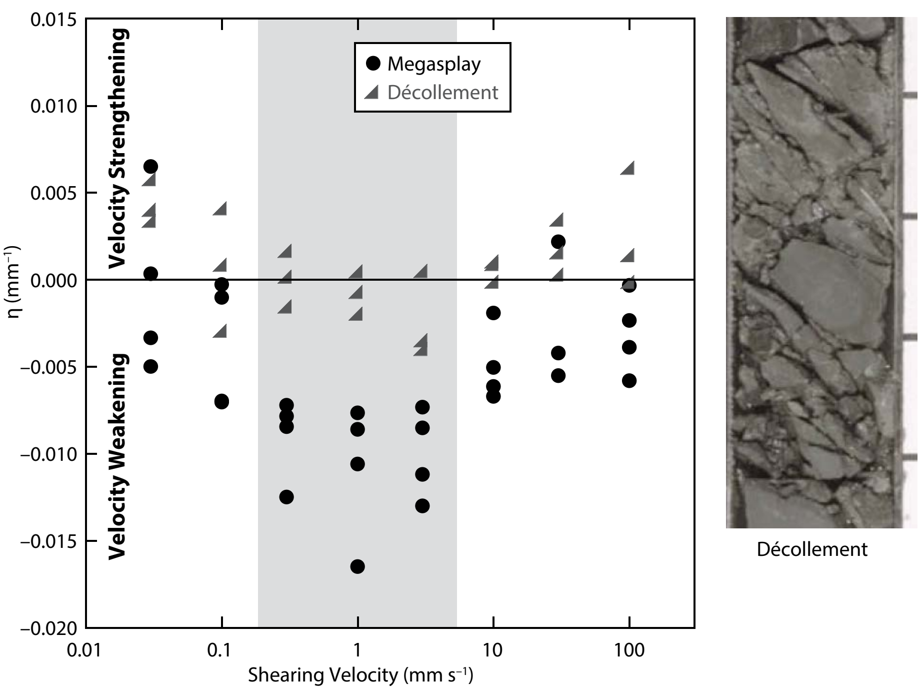


FIGURE 3. (left) Results of laboratory friction tests on core samples from the Nankai Trough megasplay and décollement zones showing slip-dependence of friction η as a function of shearing velocity (from Ikari et al., 2013). (right) The photo shows an example of a core sample from the décollement fault zone collected during ODP Leg 190 from Site 1174B, core section 72R-2. Tick marks on photo indicate 5 cm spacing.

importance of characterizing frictional behavior across a wide range of slip rates. The behavior of natural fault materials at very low sliding velocities, spanning slip rates from plate tectonic to slow earthquake to SSE, has emerged as particularly important to understanding the nucleation and generation of SSEs. A suite of experiments was recently conducted on fault zone samples at slip rates much lower than those typically explored in experimental rate-and-state friction studies but comparable to plate convergence rates of a few centimeters per year. The first of these "slow" experiments was performed on a sample from the shallow plate boundary fault zone within the region of the 2011 Tōhoku-oki earthquake where the coseismic slip was >50 m; this sample was recovered from IODP Site C0019 during the Japan Trench Fast Drilling Project (JFAST; Chester et al., 2013). These experiments revealed that when driven at plate tectonic motion rates, the fault samples exhibited velocity-weakening friction, generating laboratory SSEs characterized by strength perturbations with stress drops and peak slip velocities similar to those observed geodetically during the actual Tōhoku-oki earthquake (Ikari et al., 2015; Figure 4). Tests on IODP drill core samples from other subduction zones where shallow SSEs are known to occur, such as the Nankai Trough, Japan Trench, and Costa Rica, yield similar results (Ikari and Kopf, 2017).

The identification of frictional behavior conducive to shallow slow slip also carries important implications for earthquake hazards. If slow slip reflects the potential for velocity-weakening (and thus seismic) behavior, these regions could also be susceptible to shallow coseismic slip or tsunami earthquakes, depending on different loading conditions. Therefore, compared to purely creeping fault conditions, these regions may be at greater risk than previously thought (e.g., Polet and Kanamori, 2000; Lay and Kanamori, 2011). Thus far, laboratory experiments on natural fault zone samples collected via IODP drilling have provided important insights into the mechanisms of slow fault slip in several active subduction zones. Continued refinement of our understanding of shallow fault slip and characterizations of other regions will depend critically on the continued recovery of core material by scientific ocean drilling.

Constraints on Fluid and Stress States

An additional key to understanding the origin of transient slow slip events requires quantification of in situ effective stress states and pore fluid pressures within SSE source regions. The shallow portion of the Nankai Trough, where low frequency earthquakes and SSEs occur (Ito and Obara, 2006; Sugioka et al., 2012; Araki et al., 2017), coincides with low seismic velocity zones revealed in seismic reflection and refraction studies (Park et al., 2010; Kamei et al., 2012). Kitajima and Saffer (2012) conducted deformation

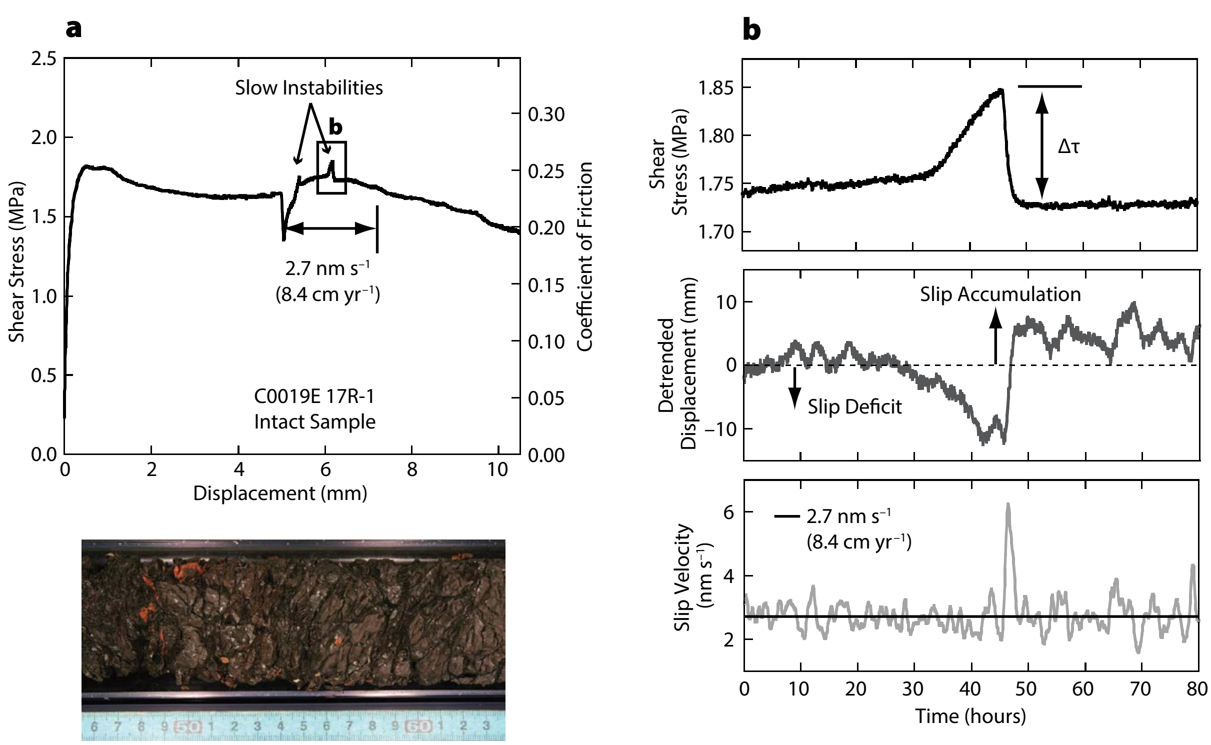


FIGURE 4. Results of laboratory friction tests on a sample of the Japan Trench plate-boundary fault zone. (a) Frictional strength as a function of displacement showing the portion of the test conducted at the plate convergence rate. Note the two perturbations, the second of which is shown in more detail in (b). (b) Shear stress, detrended slip displacement, and sample slip velocity during the second slip instability as a function of time. Slip deficit accumulates during the loading phase, and during the stress drop, slip rapidly re-accumulates and the slip velocity more than doubles, but remains slow. The photo shows an example of a core sample from the fault zone collected during IODP Expedition 343 from Site C0019E, core section 17R-1. Scale is in cm.

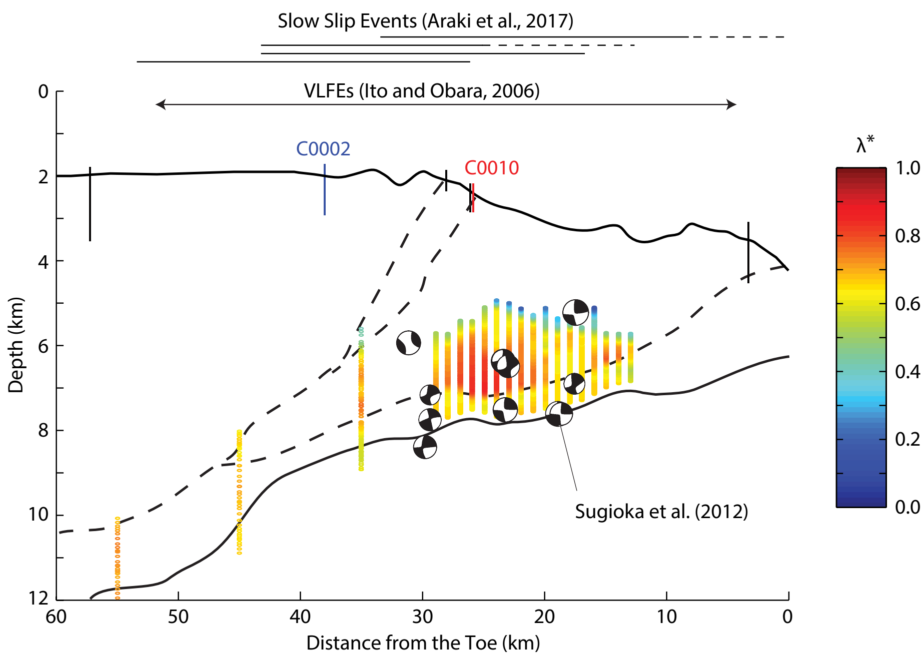


FIGURE 5. Pore pressure ratio, λ*, in the low seismic velocity zone observed along the IODP NanTroSEIZE Kumano transect at the Nankai Trough (Figure 2; Kitajima and Saffer, 2012). λ* is the ratio of excess pore pressure to effective overburden stress at hydrostatic pressure; λ* ranges 0 (hydrostatic pore pressure) and 1 (lithostatic pore pressure). The beach balls represent moment tensor solutions for low frequency earthquakes reported by Sugioka et al. (2012). The regions of observed low frequency earthquakes (Ito and Obara, 2006) and slow slip events (Araki et al., 2017) are also shown on top.

experiments on IODP cores recovered during the NanTroSEIZE project to constrain relations between P-wave velocity, porosity, and effective mean stress under simulated tectonic loading conditions. Combined with P-wave velocity values from seismic reflection and refraction data, their analysis reveals that pore pressure exceeds 90% of lithostatic pressure in the region of low Vp and is coincident with the locations of observed VLFEs and SSEs (Figure 5). The elevated pore pressure is interpreted to result from enhanced mechanical loading by lateral tectonic stresses in the wider subduction zone area. The integration of core and seismic data to estimate pore pressure in the near-trench region at the Nankai Trough is arguably the most robust inference of pore fluid pressure available for a region where slow slip and tremor occur.

Other studies have also focused on quantifying in situ stress and pore pressure in shallow subduction zones by integrating laboratory deformation experiments on IODP cores, seismic reflection surveys, drilling and logging data, and numerical modeling (Spinelli et al., 2006; Tobin and Saffer, 2009; Huffman et al., 2016; Brodsky et al., 2017; Han et al., 2017; Li et al., 2018). Elevated pore pressure has been estimated from seismic reflection and drilling data within the underthrust sediments in regions that are ~20 km from the trenches along the Muroto transect of the Nankai Trough (Tobin and Saffer, 2009), the Central Aleutian margin (Li et al., 2018), and the Cascadia margin (Han et al., 2017). Hydrologic models that simulate fluid production and flow based on IODP drilling data and laboratory measurements on core samples also suggest that pore pressure at the Costa Rica subduction zone is nearly lithostatic (as a function of the rock overburden) beneath the shallow plate interface where SSEs may propagate to the trench, whereas it is hydrostatic (with fluid pressures at equilibrium at depth) to slightly overpressured in the overriding plate (Spinelli et al., 2006). Detailed analyses of borehole stress indicators combined with rock strength data on core samples further reveals that the in situ stress state may vary spatially and temporally and that differential stresses in the near field of the near-trench region of the subduction thrust may be very low, suggesting that shallow SSE source regions are sites of high pore pressure, low effective stresses, and low strength (e.g., Huffman and Saffer, 2016; Brodsky et al., 2017). Inferences of fluid pressure conditions and stress states from drilling and seismic data, laboratory experiments, and modeling studies require increased integration with seismological and geodetic observations of SSEs, tremor, and low frequency earthquakes to even further advance our understanding of transient slow slip phenomena.

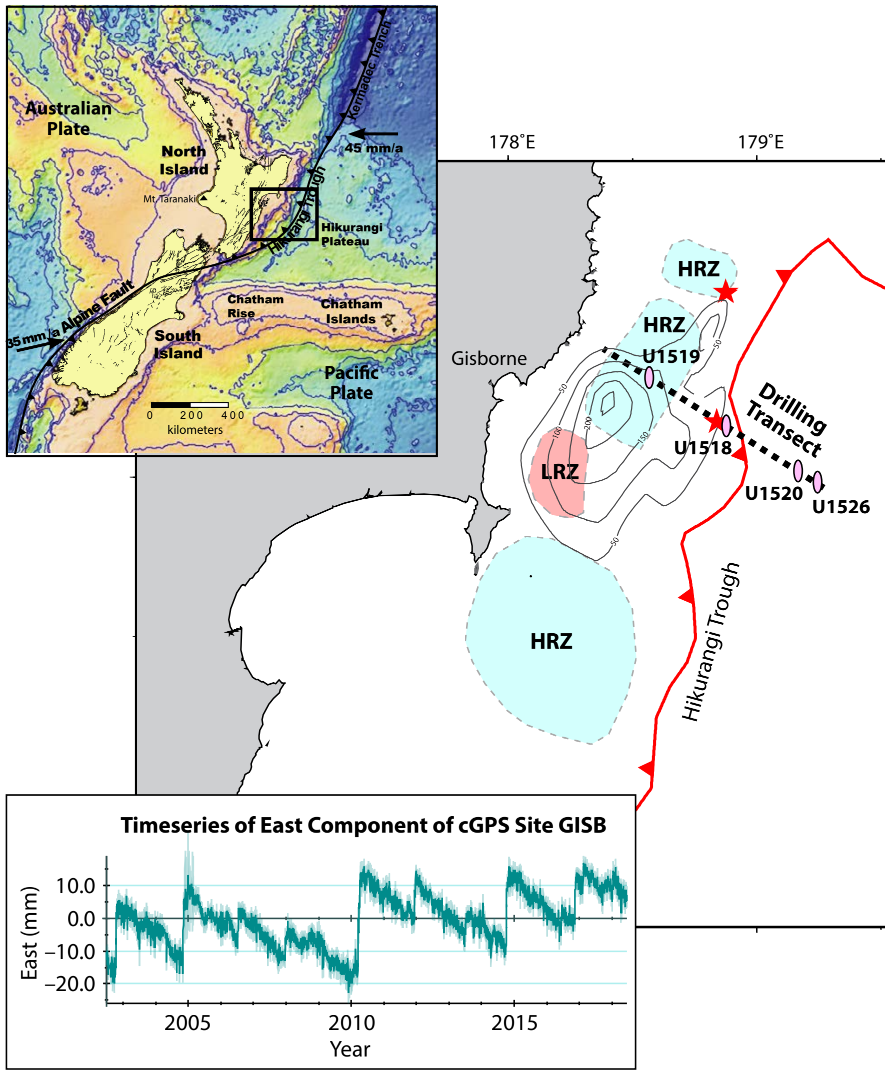
IODP DRILLING FOCUSED ON SHALLOW SSES AT THE HIKURANGI SUBDUCTION ZONE, NEW ZEALAND

Slow slip events at the northern Hikurangi subduction margin, New Zealand, are among the best-documented shallow SSEs on Earth. The regularity and well-characterized short repeat interval (one to two years) of the Hikurangi SSEs (Wallace and Beavan, 2010; Wallace et al., 2012) allow monitoring over multiple SSE cycles, with the potential to document the spatial and temporal distribution of strain accumulation and release in the very-near field of the SSEs, as well as any associated hydrogeologic phenomena. The close proximity of the seafloor to the north Hikurangi SSEs (< 2–15 km; Wallace et al., 2016; Figure 6) enables sampling of rocks that are eventually transported downdip to the known SSE source region, revealing the rock properties, composition, and lithologic and structural character of material that hosts slow slip.

IODP Expeditions 372 (Pecher et al., 2018) and 375 (Saffer et al., 2018) were mounted to investigate SSEs at northern Hikurangi, and together constitute the first-ever scientific drilling effort undertaken specifically to target transient slow slip behavior. The processes and in situ conditions that underlie subduction zone SSEs were examined by coring and logging while drilling (LWD) through one of the main active faults near the deformation front (Site U1518), the upper plate overlying the region of large slow slip (Site U1519), and the incoming sedimentary succession and igneous basement (Sites U1520 and U1526) (Figures 6 and 7). Expedition 375 also undertook installation of borehole observatories within the active fault (U1518) and upper plate (U1519). Together, the coring, logging, and observatory data will test a suite of hypotheses about the fundamental mechanics and behavior of slow slip events and their relationship to potentially damaging earthquakes along the subduction interface.

The scientific objectives of the Hikurangi IODP drilling programs are three-fold: (1) to document the physical, hydrogeological, and chemical properties, lithology, geometry, microstructure, and thermal state of one of the most active faults near the trench, as well as the inputs of sediment and upper igneous crust of the subducting Pacific Plate, with an emphasis on intervals that host, or will eventually host, SSEs; (2) to characterize the stress regime, thermal structure, porosity, permeability, lithology, pore fluid pressure state, fluid chemistry, flow pathways, and structural geology of the upper plate overlying the SSE source region; and (3) to install observatories in the upper plate and an active out-of-sequence thrust that span the SSE source region, in order to monitor volumetric strain (using pore pressure as a proxy) and the evolution of physical, hydrological, and chemical properties throughout the SSE cycle.

These objectives are designed to address key questions regarding the generation of slow slip and the mechanics of subduction megathrusts. In particular, an overarching working hypothesis to be tested by the data and samples acquired at the Hikurangi margin is that slow earthquakes occur in regions containing highly overpressurized fluids, under low effective normal stress, and on faults with transitional frictional behavior characterized by geometric and compositional heterogeneities. Data and samples from the Hikurangi margin will also enable evaluation of the role that temperature and metamorphism may play in these processes. The observatories, which will be in place for multiple SSE cycles, will reveal the influence of slow slip events on fluid flow and deformation within the fault zone and upper plate. Downhole pore pressure sensing in both observatories (at U1518 and U1519; Figure 7) will provide a sensitive proxy for volumetric strain, and will help resolve the detailed spatiotemporal evolution of shallow slow slip, as well as much smaller SSEs than is currently possible using conventional surface-based geodetic techniques (e.g., Araki et al., 2017).



HRZ: Zones of high amplitude reflectivity above the plate interface that is interpreted as fluid-rich subducted sediment

LRZ: Lens of low amplitude material between an upper and lower high-amplitude reflector with complex 3D geometry lies on or below the interface

FIGURE 6. Tectonic setting (upper left inset) and location of slip on the interface in September/October 2014 captured by a seafloor network of absolute pressure gauges (black contours, labeled in 50 mm increments; Wallace et al., 2016) and the reflective properties of the subduction interface (Bell et al., 2010) at northern Hikurangi. Black dashed line shows the location of the drilling transect (see Figure 7); pink ellipses are IODP Expedition 372 and 375 drill sites. Red stars indicate the locations of two tsunamigenic subduction interface earthquakes (M_w 6.9–7.1) that occurred in March and May of 1947. The lower left inset shows the east component of the position time series for a cGPS site near Gisborne to demonstrate the repeatability of SSEs since they were first observed in 2002.

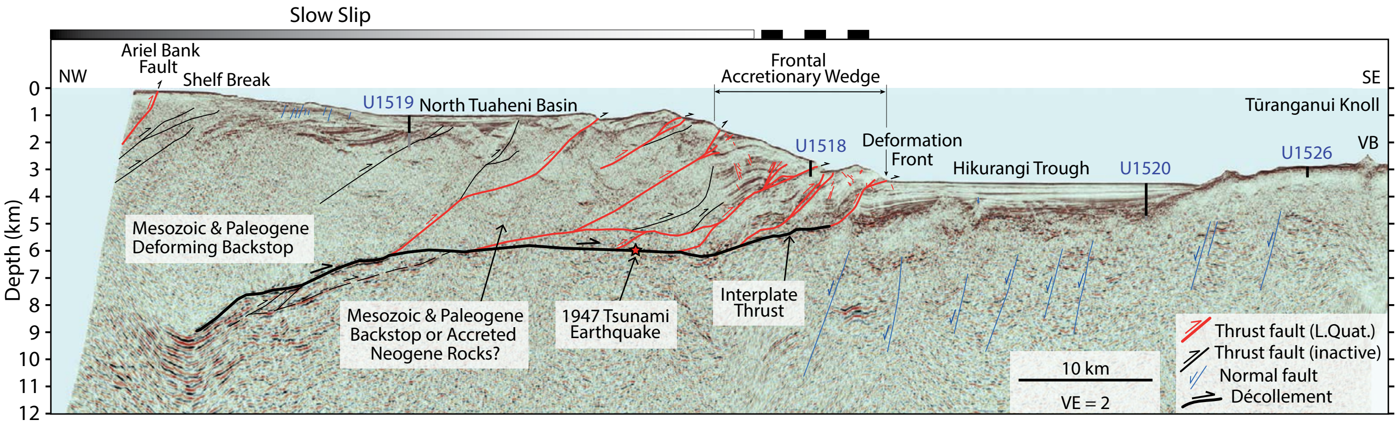


FIGURE 7. Depth-converted seismic Profile 05CM-04 from the Hikurangi margin drilling transect showing locations of the sites that were drilled during IODP Expeditions 372 and 375, as well as structural interpretation. Star = projected location of March 1947 tsunami earthquake. The location of the profile coincides with the drilling transect shown in Figure 6. VB = volcanic cone. VE = vertical exaggeration. Seismic profile and interpretations from Barker et al. (2018).

SUMMARY

The data and samples gathered during several recent IODP expeditions to study slow slip events in subduction zone megathrust settings have been and remain the subject of wide-ranging post-expedition research efforts. Data from borehole seismic observatories offshore Japan and Costa Rica are retrieved regularly, and in the case of the NanTroSEIZE observatories, are transmitted in real time via the DONET cabled network. The first data from similar CORK (sealed borehole) observatories offshore New Zealand at the northern Hikurangi subduction margin will be retrieved within the next few years.

In total, the powerful combination of these borehole observatories and IODP drilling, logging, and sampling of fault zones—where slow slip may occur—enables us to draw connections between fault slip behavior and fault architecture, frictional behavior, lithology, fluid composition, and physical properties. Over the coming years, the results from past and future scientific ocean drilling expeditions that target shallow slow slip events will produce an important step-change in our understanding of slow slip processes and the mechanics of subduction megathrusts.

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SPOTLIGHT 9. Published Scientific Ocean Drilling Results

Results from the past 50 years of scientific ocean drilling have been published in more than 35,000 articles, reports, dissertations, books, posters, and other literature (http://iodp.tamu.edu/publications/AGI_studies/AGI_study_2018.pdf). Approximately 30% of these are in open access publications produced by the Deep Sea Drilling Project, the Ocean Drilling Program, the Integrated Ocean Drilling Program, and the International Ocean Discovery Program. These publications include, but are not limited to, *Initial Reports of the Deep Sea Drilling Project*, *Initial Reports* and *Scientific Results* volumes of the Ocean Drilling Program, *Proceedings of the Integrated Ocean Drilling Program*, *Proceedings of the International Ocean Discovery Program,* and the *Scientific Drilling* journal.

Over 11,000 scientific papers presenting drilling results have been published in peer-reviewed journals. Of those, nearly 6,000 were published in journals with a high impact factor (IF > 2; Figure 1), with the drilling results consistently published each year (10 to 20 publications) in highly rated (IF > 9) multidisciplinary journals (e.g., *Nature*, *Science*, *Nature Geosciences, Proceedings of the National Academy of Sciences of the United States of America*). This rich and extensive publication record demonstrates that scientific ocean drilling generates first-order scientific results that are of interest both to the broader scientific community and to society.

— Brad Clement and Mitch Malone

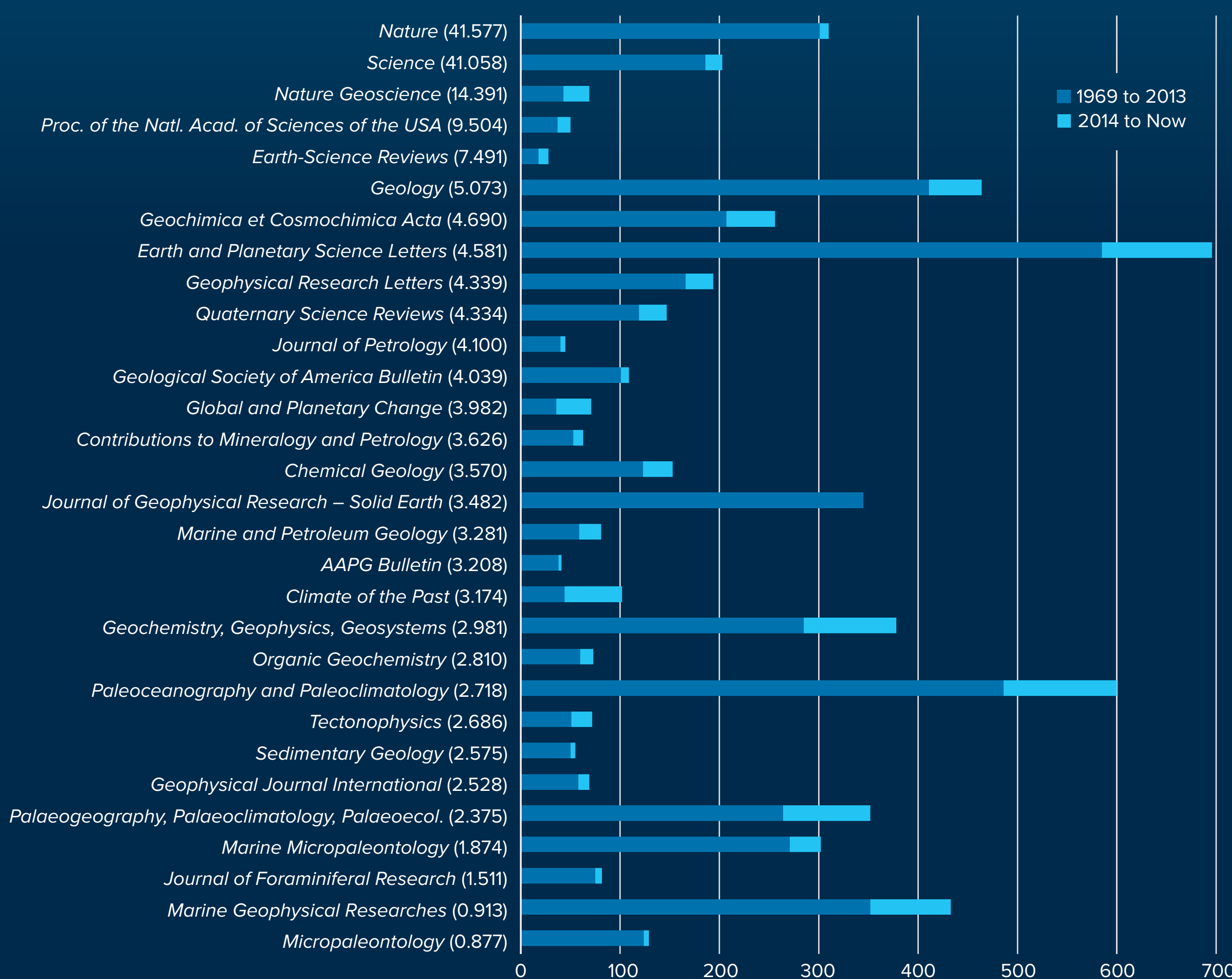


FIGURE 1. Highly rated peer-reviewed serials that have published scientific ocean drilling program-related expedition research results (1969–2018). Numbers in parentheses are Thompson/Reuters ISI impact factor as of 2017. Note that 2014 marks the start of the International Ocean Discovery Program.

OCEAN DRILLING PERSPECTIVES ON Meteorite Impacts

By Christopher M. Lowery, Joanna V. Morgan, Sean P.S. Gulick, Timothy J. Bralower, Gail L. Christeson, and the Expedition 364 Scientists

Derrick of the platform Liftboat *Myrtle* at night.
Photo credit: E. Le Ber, ECORD/IODP

ABSTRACT. Extraterrestrial impacts that reshape the surfaces of rocky bodies are ubiquitous in the solar system. On early Earth, impact structures may have nurtured the evolution of life. More recently, a large meteorite impact off the Yucatán Peninsula in Mexico at the end of the Cretaceous caused the disappearance of 75% of species known from the fossil record, including non-avian dinosaurs, and cleared the way for the dominance of mammals and the eventual evolution of humans. Understanding the fundamental processes associated with impact events is critical to understanding the history of life on Earth, and the potential for life in our solar system and beyond.

Scientific ocean drilling has generated a large amount of unique data on impact processes. In particular, the Yucatán Chicxulub impact is the single largest and most significant impact event that can be studied by sampling in modern ocean basins, and marine sediment cores have been instrumental in quantifying its environmental, climatological, and biological effects. Drilling in the Chicxulub crater has significantly advanced our understanding of fundamental impact processes, notably the formation of peak rings in large impact craters, but these data have also raised new questions to be addressed with future drilling. Within the Chicxulub crater, the nature and thickness of the melt sheet in the central basin is unknown, and an expanded Paleocene hemipelagic section would provide insights to both the recovery of life and the climatic changes that followed the impact. Globally, new cores collected from today's central Pacific could directly sample the downrange ejecta of this northeast-southwest trending impact.

Extraterrestrial impacts have been controversially suggested as primary drivers for many important paleoclimatic and environmental events throughout Earth history. However, marine sediment archives collected via scientific ocean drilling and geochemical proxies (e.g., osmium isotopes) provide a long-term archive of major impact events in recent Earth history and show that, other than the end-Cretaceous, impacts do not appear to drive significant environmental changes.

INTRODUCTION

Large meteorite impacts have significantly influenced Earth history, possibly driving the early evolution of life (e.g., Kring, 2000, 2003; Nisbet and Sleep, 2001) and the initial compositions of the ocean and the atmosphere (e.g., Kasting 1993). They also have the potential to completely reshape the biosphere (e.g., Alvarez et al., 1980; Smit and Hertogen, 1980). The Cretaceous-Paleogene (K-Pg) mass extinction, almost certainly caused by the impact of a meteorite on the Yucatán carbonate platform of Mexico 66 million years ago, known as the Chicxulub impact, is the most recent major mass extinction of the so-called Big Five (e.g., Raup and Sepkoski, 1982). It ended the dominance of non-avian dinosaurs, marine reptiles, and ammonites, and set the stage for the Cenozoic dominance of mammals that eventually led to the evolution of humans (Schulte et al., 2010; Meredith et al., 2011). The environmental effects of the Chicxulub impact and the resulting mass extinction occurred over a geologically brief time period, with the major climatic changes lasting years to decades (e.g., Brugger et al., 2017). The subsequent recovery of life provides an important analog for the potential recovery of biodiversity following geologically rapid anthropogenic extinction due to climate change, acidification, and eutrophication.

The K-Pg impact hypothesis was controversial when first proposed (Alvarez et al., 1980; Smit and Hertogen, 1980), but careful correlation of impact material from K-Pg boundary sections across the world led to its gradual acceptance (e.g., Schulte et al., 2010). The discovery of the Chicxulub crater (Penfield and Carmargo, 1981; Hildebrand et al., 1991) and its clear genetic relationship with K-Pg boundary ejecta provided compelling evidence for this hypothesis. Scientific ocean drilling has been instrumental in discovering widespread physical, chemical, and biological supporting evidence, and in documenting the global environmental and biotic effects of the impact (e.g., see summary in Schulte et al., 2010). Drilling by International Ocean Discovery Program Expedition 364 into the Chicxulub crater has yielded valuable insights into the mechanisms of large impact crater formation and the recovery of life (Morgan et al., 2016, 2017; Artemieva et al., 2017; Christeson et al., 2018; Lowery et al., 2018; Riller et al., 2018).

Although the K-Pg is the only mass extinction that is widely (though not universally) accepted to have been caused by an extraterrestrial collision, impacts have been suggested at one point or another as drivers for every major Phanerozoic extinction event (e.g., Rampino and Stothers, 1984) and many other major climate events (e.g., Kennett et al., 2009; Schaller et al., 2016). The discovery of an iridium layer at the K-Pg boundary as the key signature of extraterrestrial material (Alvarez et al., 1980) spurred the search for other impact horizons through careful examination of many other geologically significant intervals. So far no other geologic event or transition has met all the criteria to indicate causation by an impact (e.g., the presence of iridium and other platinum group elements in chondritic proportions, tektites, shock-metamorphic effects in rocks and minerals, perturbation of marine osmium isotopes, and, ideally, an impact crater), although many periods would meet at least one of these (e.g., Sato et al., 2013; Schaller et al., 2016; Schaller and Fung, 2018). The search for impact evidence continues.

For the last 50 years, analyses of geological and geophysical data collected by the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), Integrated Ocean Drilling Program, and International Ocean Discovery Program (IODP) have provided a unique perspective on Earth history. Rock samples collected by IODP and its sister organization, the International Continental scientific Drilling Program (ICDP), have provided insights into impact cratering processes and the effects of events of different magnitudes on the climate and the biosphere, supplying an exceptional record of processes that are ubiquitous across the solar system (and, presumably, beyond). This article focuses on ocean drilling perspectives on meteorite impacts. We examine the contributions of scientific ocean drilling to our understanding of impact events, from detailed records of extinction and chemical and physical perturbation in the marine realm to the mechanisms by which rocks are deformed to create peak rings (a discontinuous ring of hills) in impact craters. The exciting results of drilling in the Chicxulub crater in 2016 raise new questions and suggest promising new challenges and avenues of investigation of deep-sea records of impact events that can only be undertaken by a program such as IODP. (Note that important contributions from onshore drilling by the ICDP into the Chicxulub, Lake Bosumtwi, Chesapeake Bay, and Lake El'gygytgyn impact craters are summarized by, respectively, Urrutia-Fucugauchi et al., 2004; Koeberl et al., 2007; Gohn et al., 2008; and Melles et al., 2012).

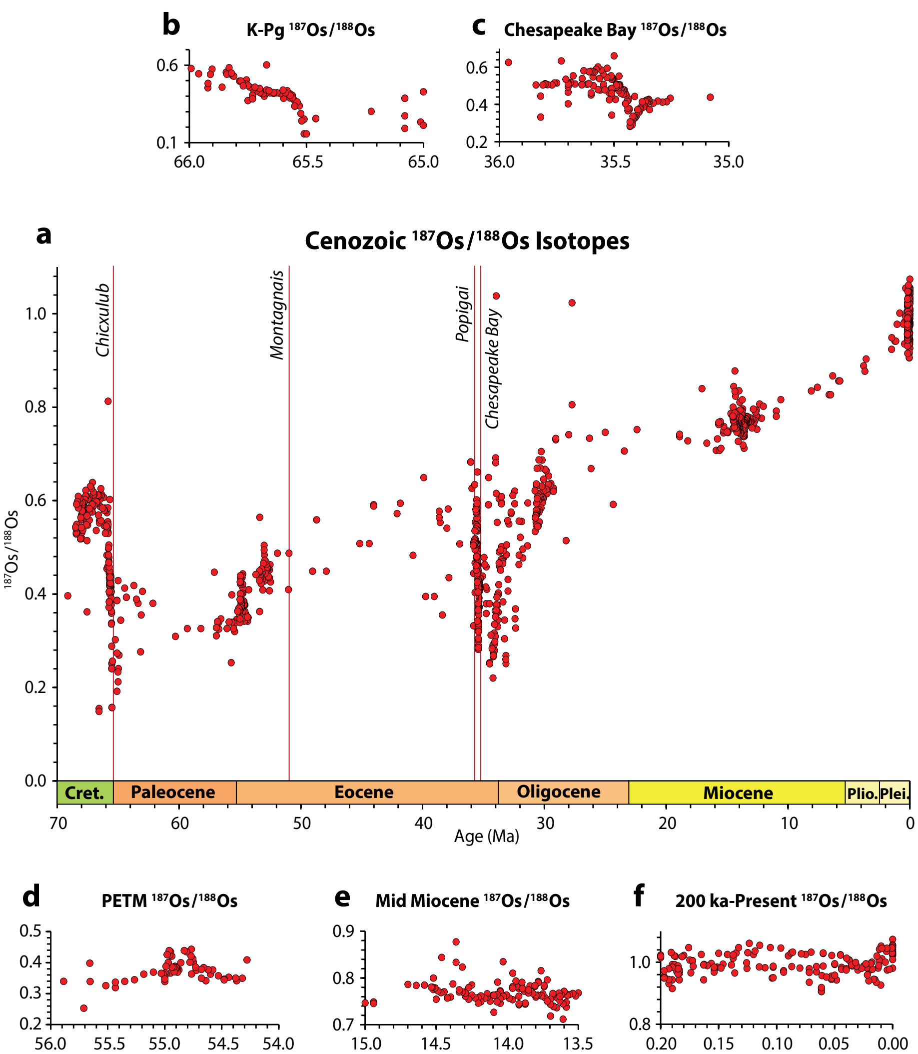


FIGURE 1. Marine osmium isotopes (a) through the Cenozoic (after Peucker-Ehrenbrink and Ravizza, 2012). These data, the majority of which come from DSDP/ODP/IODP cores, record the long-term trend toward more radiogenic (i.e., continental-weathering derived) $^{187}Os/^{188}Os$ ratios in the ocean throughout the Cenozoic. Superimposed on this long-term trend are several major, rapid shifts toward unradiogenic ratios driven by impact of extraterrestrial objects. This effect is evident in intervals associated with impact events, including (b) the Chicxulub impact and (c) the Chesapeake Bay impact. Other intervals of major environmental change lack the diagnostic negative excursion, including (d) the Paleocene-Eocene Thermal Maximum, (e) the Miocene Climate Transition, and (f) the Younger Dryas. Red lines are well-dated large (>35 km crater diameter) impacts (after Grieve, 2001). Note that these data are plotted against the 2012 Geologic Time Scale (Peucker-Ehrenbrink and Ravizza, 2012); more recent dating puts the K-Pg boundary at 66.0 million years ago (Renne et al., 2013).

MARINE RECORD OF IMPACTS

Scientific ocean drilling provides the raw materials that enable scientists to generate high-resolution composite records of geochemical changes in the ocean through time. One of the geochemical proxies used is the isotopic ratio of osmium ($^{187}Os/^{188}Os$) in seawater, as reflected in marine sediments. Osmium (Os) isotopes in ocean water are the result of secular changes in the amount of mantle-derived (depleted in ^{187}Os) and crustal materials (enriched in ^{187}Os) (Pegram et al., 1992). Changes in $^{187}Os/^{188}Os$ of marine sediments over time can be used as proxies for flood basalt volcanism (e.g., Turgeon and Creaser, 2008), weathering flux (Ravizza et al., 2001), ocean basin isolation (e.g., Poirier and Hillaire-Marcel, 2009), and, importantly for our purposes, the detection of impact events (Turekian, 1982; Peucker-Ehrenbrink and Ravizza, 2000, 2012; Paquay et al., 2008).

Chondritic meteors have an Os isotopic ratio similar to that of Earth's mantle, and extraterrestrial impacts result in a strong, rapid excursion to unradiogenic (i.e., closer to 0) marine $^{187}Os/^{188}Os$ ratios (Luck and Turekian, 1983; Koeberl, 1998; Reimold et al., 2014; Figure 1). The only two such excursions in the Cenozoic are Chicxulub (Figure 1b) and the late Eocene (~35 million years ago; Poag et al., 1994; Bottomley et al., 1997) dual impacts at Chesapeake Bay on the North American Atlantic coastal plain and Popigai in Siberia (Figure 1c; Robinson et al., 2009; Peucker-Ehrenbrink and Ravizza, 2012). Such Os isotope excursions would only be expected from chondritic impactors, but it is important to note that the scale of the impact is not necessarily reflected in the size of the Os excursion (Morgan, 2008). Other major climate events that have been proposed to be associated with impacts, such as the Paleocene-Eocene

Thermal Maximum (PETM; e.g., Schaller et al., 2016; Figure 1d), and the Younger Dryas (e.g., Kennett et al., 2009; Figure 1f) are not associated with any clear excursion toward unradiogenic values, despite relatively high sample resolution (e.g., Paquay et al., 2009). Rather, the PETM shows a positive excursion of Os isotope values associated with enhanced weathering during the event (Ravizza et al., 2001).

Ocean drilling has directly sampled ejecta from several Cenozoic craters in the form of black glassy spherical tektites, created from melt droplets caused by a meteor impact. Tektites from the late Eocene Chesapeake Bay and Popigai impacts were recovered from DSDP and ODP Sites 94 (Gulf of Mexico), 149 (Caribbean), and 612, 903, 904, and 1073 (New Jersey margin) in the Atlantic (Glass, 2002); from DSDP Sites 65, 69, 70, 161, 162, 166, 167, and 292 in the equatorial Pacific (Glass et al., 1985); and from DSDP Site 216 in the Northeast Indian Ocean (Glass, 1985). They have also been found in the South Atlantic at Maud Rise (ODP Site 689; Vonhof et al., 2000). These microtektites include a large number of clinopyroxene-bearing spherules (termed "microkrystites" by Glass and Burns, 1988) found in the Pacific and South Atlantic. An iridium anomaly was reported to occur in association with these ejecta (Alvarez et al., 1982), but higher-resolution work revealed that this iridium anomaly occurs below the microtektite layer (Sanfilippo et al., 1985). This positioning indicates that there were actually two impacts at this time (Chesapeake and Popigai), one that produced an iridium anomaly and microkrystites and a second that did not produce an iridium anomaly and that created chemically distinct microtektites (Glass et al., 1985; Vonhof and Smit, 1999). The iridium anomaly is also found at the Eocene-Oligocene Stratotype Section at Massignano, Italy, where it occurs ~12 m below or ~1 million years before the base of the Oligocene (Montanari et al., 1993). Nevertheless, some researchers have inferred a causal relationship between these impacts and latest Eocene cooling and faunal change (e.g., Keller, 1986; Vonhof et al., 2000; Liu et al., 2009), which would imply a climate feedback that amplified the short-term cooling directly caused by the impact (Vonhof et al., 2000).

> "Rock samples collected by IODP and its sister organization, the International Continental scientific Drilling Program (ICDP), have provided insights into impact cratering processes and the effects of events of different magnitudes on the climate and the biosphere, supplying an exceptional record of processes that are ubiquitous across the solar system (and, presumably, beyond)."

THE CHICXULUB IMPACT AND ITS PHYSICAL EFFECTS

The most important impact of the Phanerozoic, and the one that has been best studied by scientific ocean drilling, is the Chicxulub impact. The hypothesis that an impact caused the most recent major mass extinction was founded on elevated iridium levels in the K-Pg boundary clays within outcrops in Spain, Italy, and Denmark (Alvarez et al., 1980; Smit and Hertogen, 1980). The impact hypothesis was initially quite controversial, and one of the early objections was that iridium had only been measured at a few sites across a relatively small area of western Europe and may have reflected a condensed interval and not a discrete impact (Officer and Drake, 1985). Researchers then began to investigate and document other K-Pg boundary sites around the globe, many of which were DSDP/ODP drill sites (Figure 2). High iridium abundances were soon found at other sites (e.g., Orth et al., 1981; Alvarez et al., 1982), and the identification of shocked minerals within the K-Pg layer added irrefutable proof that it was formed by an extraterrestrial impact (Bohor et al., 1984). When a high-pressure shock wave passes through rocks, common minerals such as quartz and feldspar are permanently deformed (referred to as shock metamorphism) and produce diagnostic features (e.g., Reimold et al., 2014) that, on Earth, are only found in association with impacts and nuclear test sites. Since 1985, many ODP and IODP drill sites have recovered (and often specifically targeted) the K-Pg boundary (Figure 2), further contributing to our understanding of this event and demonstrating that ejecta materials were deposited globally (Figure 3).

The Chicxulub impact structure, on the Yucatán Peninsula, Mexico, was first identified as a potential impact crater by Penfield and Carmargo-Zanoguera (1981), and then as the site of the K-Pg impact by Hildebrand et al. (1991). These authors noted that the size of the shocked quartz and thickness of the K-Pg boundary deposit increased globally toward the Gulf of Mexico, and they located the Chicxulub crater by its association with strong, circular, potential field gravity anomalies. Core samples from onshore boreholes drilled by Petróleos Mexicanos ("Pemex") confirmed the crater's impact origin. Although some authors have argued against a link between Chicxulub and the K-Pg boundary (see Keller et al., 2004, 2007, for mature forms of that position), accurate $^{40}Ar/^{39}Ar$ dating of impact glass within the K-Pg layer (Renne et al., 2013, 2018), as well as dating of microcrystalline melt rock (Swisher et al., 1992) and shocked zircon (Krogh et al., 1993; Kamo et al., 2011) from Chicxulub and the K-Pg layer, clearly demonstrate that Chicxulub is the site of the K-Pg impact. Hildebrand et al. (1991) also noted that Gulf of Mexico DSDP Sites 94, 95, 536, and 540 contained deepwater gravity flows and turbidity-current deposits adjacent to Campeche Bank, and DSDP Sites 603B, 151, and 153, as well as outcrops along the Brazos River in Texas, contained potential tsunami wave deposits (Bourgeois et al., 1988), all of which suggested these deposits were a result of the Chicxulub impact. Increasingly, opponents of the impact hypothesis have accepted an end-Cretaceous age for the Chicxulub crater, and have focused their arguments on the Deccan Traps in India as the sole or contributing cause of the mass extinction (see Chenet et al., 2009; Punekar et al, 2014; Mateo et al., 2017; and Keller et al., 2018, and references therein for a recent summary; Schulte et al., 2010, remains the best rebuttal of these arguments).

Many studies have subsequently confirmed that at sites proximal to Chicxulub

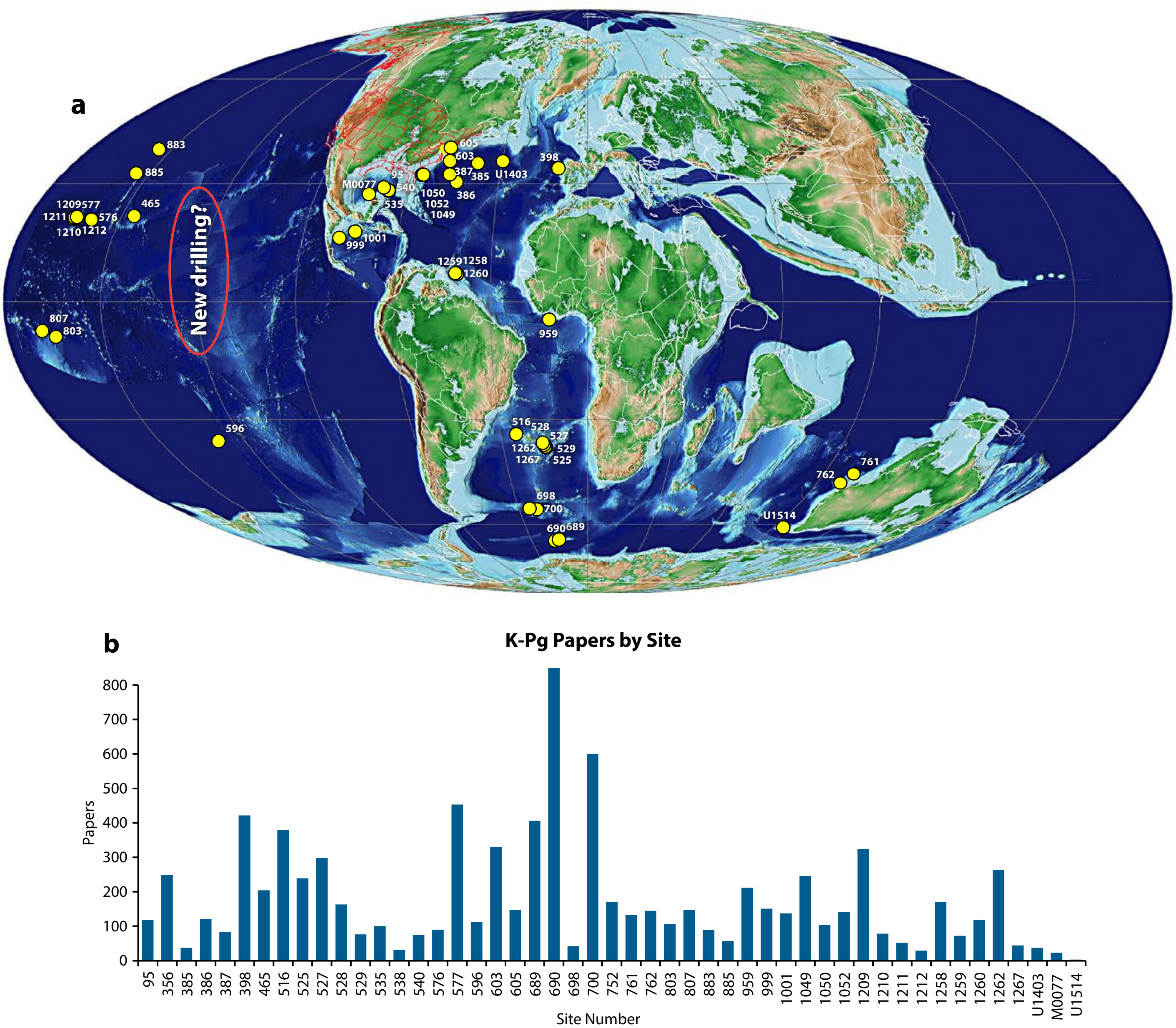


FIGURE 2. (a) Map of DSDP/ODP/IODP Sites that recovered the K-Pg boundary, up to Expedition 369. The base map is adapted from the PALEOMAP Project (Scotese, 2008). (b) Number of K-Pg papers by site, according to Google Scholar as of November 30, 2018 (search term: Cretaceous AND Tertiary OR Paleogene OR Paleocene AND 'Site ###'). As with any such search, there are some caveats, for example, inclusion of papers that match the search terms but are not strictly about the K-Pg, and papers that are missing because they are not cataloged by Google Scholar. However, this is a good approximation of the reams of articles that have been written about the K-Pg based on DSDP, ODP, and IODP cores, and the clear impact (sorry) of scientific ocean drilling on the K-Pg literature. n = 8,679, but there are duplicates because some papers cover multiple sites. The most recent site is U1514 (n = 3).

(<2,000 km), the impact produced multiple resurge, tsunami, gravity flow, and shelf collapse deposits (e.g., Bohor and Betterton, 1993; Bralower et al., 1998; Grajales-Nishimura et al., 2000; Schulte et al., 2010; Hart et al., 2012; Vellekoop et al., 2014). Well logs, DSDP cores, and seismic data show margin collapse deposits reach hundreds of meters thick locally, making the K-Pg deposit in the circum-Gulf of Mexico the largest known single event deposit (Denne et al., 2013; Sanford et al., 2016). Complex stratigraphy (Figure 3) and a mixture of nannofossil and foraminiferal assemblages of different ages that contain impact-derived materials characterize proximal deepwater DSDP and ODP sites in the Gulf of Mexico (DSDP Sites 95, 535–538, and 540) and the Caribbean (ODP Sites 999 and 1001), all exhibiting sequential deposition of material from seismically driven tsunamis, slope collapses, gravity flows, and airfalls (Sigurdsson et al., 1997; Bralower et al., 1998; Denne et al., 2013; Sanford et al., 2016). Bralower et al. (1998) termed this distinct assemblage of materials the K-Pg boundary "cocktail."

At intermediate distances from Chicxulub (2,000–6,000 km), the K-Pg boundary layer is only 1.5–3 cm thick, as observed in North America (Smit et al., 1992; Schulte et al., 2010), on Demerara Rise in the western Atlantic at ODP Site 1207 (K.G. MacLeod et al., 2007; Schulte et al., 2009), and on Gorgonilla Island, Colombia (Bermúdez et al., 2016). At the first two locations, it has a dual-layer stratigraphy. The lower layer contains goyazite and kaolinite spherules, which have splash-form morphologies such as tear drops and dumbbells, and is overlain by the "boundary clay" that contains the iridium anomaly and nickel-rich spinels (Smit and Romein, 1985; Bohor et al., 1989, 1993; Bohor and Glass, 1995). The similarity between spherules found in Haiti (~800 km from Chicxulub) and those found in the lower layer in North America has led to their joint interpretation as altered microtektites (Smit and Romein, 1985; Sigurdsson et al., 1991; Bohor et al., 1993; Bohor and Glass, 1995). Large-scale mass wasting has also been documented along the North Atlantic margins of North America and Europe, including on Blake Plateau (ODP Site 1049), Bermuda Rise (DSDP Sites 386 and 387), the New Jersey margin (DSDP Site 605), and the Iberian abyssal plain (DSDP Site 398) (Klaus et al., 2000; Norris et al., 2000).

At distal sites (>6,000 km), the K-Pg boundary becomes a single layer with a fairly uniform 2–3 mm thickness, and it has a chemical signature similar to the upper layer in North America (e.g., Alvarez et al., 1982; Rocchia et al., 1992; Montanari and Koeberl, 2000; Claeys et al., 2002). See, for example, DSDP Site 738 on the southern Kerguelen Plateau (Thierstein et al., 1991), DSDP Site 577 on Shatsky Rise (Zachos et al., 1985), DSDP Site 525 in the South Atlantic (Li and Keller, 1998), ODP Site 761 on Exmouth Plateau (Pospichal and Bralower, 1992), and ODP Site 1262 on Walvis Ridge (Bernaola and Monechi, 2007). The most abundant component (60%–85%) of the distal ejecta layer is microkrystites with a relict crystalline texture (Smit et al., 1992) that are thought to have formed from liquid condensates within the expanding plume (Kyte and Smit, 1986). Ubiquitous alteration of these microkrystites means that they are now primarily composed of clay (smectite, illite, and limonite). Some spherules contain skeletal magnesioferrite spinel (Smit and Kyte 1984; Kyte and Smit, 1986; Robin et al., 1991) that appears to be the only pristine phase to have survived diagenetic alteration (Montanari et al., 1983; Kyte and Bostwick, 1995). Shocked minerals are present in the K-Pg layer at all distances from Chicxulub, and are co-located with the elevated iridium unit (Smit, 1999).

DSDP, ODP, and IODP sites (Figure 2) have all been employed in mapping the global properties of the K-Pg layer. Sites close to the crater appear to have a slightly lower total iridium flux at $10–45 \times 10^{-9}$ g cm^{-2} (e.g., Rocchia et al., 1996; Claeys et al., 2002; K.G. MacLeod et al., 2007), as compared to a global average of ~55×10^{-9} g cm^{-2} (Kyte, 2004). Maximum iridium concentrations are quite variable (<1 to >80 ppb; Claeys et al., 2002). Attempts have been made to locate the ultimate carrier of the iridium in the sediment layer, but it is evidently too fine-grained to be identified with conventional techniques. Siderophile trace elements in the distal and upper K-Pg layer exhibit a chondritic distribution (Kyte et al., 1985), the isotopic ratio of the platinum group element osmium is extraterrestrial (Luck and Turekian, 1983; Meisel et al., 1995), and the chromium isotopic composition indicates that the impactor was a carbonaceous chondrite (Kyte, 1998; Shukolyukov and Lugmair, 1998).

The most common explanation for the origin of the microtektites at proximal and intermediate sites is that they are formed from melted target rocks that were ejected from Chicxulub and solidified en route to their final destination (e.g., Pollastro and Bohor, 1993; Alvarez et al., 1995). Ejecta at distal sites and within the upper layer at intermediate sites, including the shocked minerals and microkrystites, are widely thought to have been launched on a ballistic trajectory from a rapidly expanding impact plume (Argyle, 1989; Melosh et al., 1990). There are, however, several observations that are difficult to reconcile with these explanations. For example: (1) microkrystites within the global layer all have roughly the same mean size (250 µm) and concentration (20,000 cm^{-2}) (Smit, 1999), whereas shocked minerals show a clear decrease in number and size of grains with increasing distance from Chicxulub (Hildebrand et al., 1991; Croskell et al., 2002); (2) if shocked quartz were ejected at a high enough velocity to travel to the other side of the globe, the quartz would anneal on reentry (Alvarez et al., 1995; Croskell et al., 2002); and (3) if the lower layer at intermediate sites were formed from melt droplets ejected from Chicxulub on a ballistic path, the thickness of the lower layer would decrease with distance from Chicxulub, whereas across North America, it is close to constant. The interaction of reentering ejecta with Earth's atmosphere appears to be necessary to explain all of these observations, with the ejecta being redistributed laterally by atmospheric heating and expansion (Goldin and Melosh, 2007, 2008; Artemieva and Morgan, 2009; Morgan et al., 2013).

Differences in the K-Pg boundary layer around the globe have been used to infer different angles and directions for the Chicxulub impactor. Schultz and D'Hondt (1996) argued that several factors, including the dual-layer stratigraphy and particularly large fragments of shocked quartz in North America, indicated an impact direction toward the northwest. However, comparable 2 cm thick K-Pg layers at sites to the south of Chicxulub at equivalent paleodistances have been identified (Schulte et al., 2009; Bermúdez et al., 2016), and it now appears that the ejecta layer is roughly symmetric, with the number and size of shocked quartz grains decreasing with distance from Chicxulub (Croskell et al., 2002; Morgan et al., 2006). One asymmetric aspect of the layer is the spinel chemistry: spinel from the Pacific (e.g., DSDP Site 577) is characterized by higher Mg and Al content than European (e.g., Gubbio, Italy) and Atlantic spinel (e.g., DSDP Site 524; Kyte and Smit, 1986). The higher Mg-Al Pacific spinel represents a higher temperature phase, and thus the impact direction must have been toward the west, because the plume would be hottest in the downrange direction (Kyte and Bostwick, 1995). However, thermodynamic models of sequential condensation within the cooling impact plume suggest the opposite: that the spinels from Europe and the Atlantic represent the higher temperature phases and, thus, that the impact direction was toward the east (Ebel and Grossman 2005). An argument that sought to use position of crater topography relative to the crater center (Schultz and D'Hondt, 1996) has been questioned through comparisons with Lunar and Venutian craters

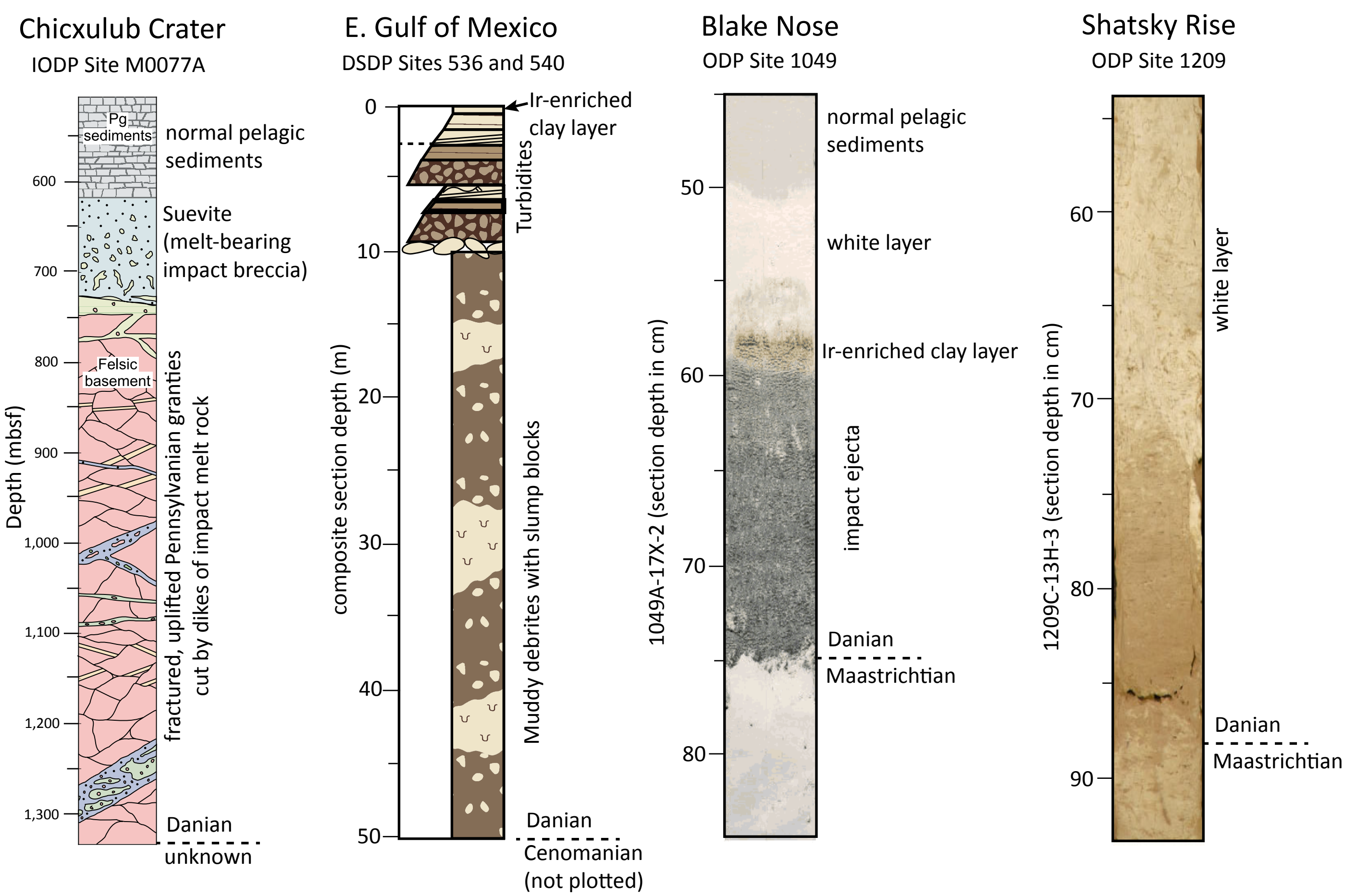


FIGURE 3. Representative K-Pg boundary sections from scientific ocean drilling cores. The peak ring of the Chicxulub crater itself shows pelagic post-impact sediments overlaying downward-coarsening suevite on top of impact melt rock, which in turn overlays fractured pre-impact granite cut by impact dikes (Morgan et al., 2016). Eastern Gulf of Mexico cores show the proximal deep-sea expression of the boundary layer, with massive slumps caused by platform margin collapse overlain by turbidites associated with secondary mass wasting, overlain by fallout of iridium-rich clay (Sanford et al., 2016). Blake Nose represents the dual-layer stratigraphy of many mid-distance localities, with impact ejecta overlain by an iridium-rich clay layer (Schulte et al., 2010). Shatsky Rise is typical of distal deep-sea sites, with a color change the only core-scale evidence of the impact (Schulte et al., 2010). The Chicxulub crater illustration is redrawn from Morgan et al. (2016), the eastern Gulf of Mexico image is redrawn from Sanford et al. (2016), and the Blake Nose and Shatsky Rise core photographs are from the IODP Janus database.

with known impact trajectories (Ekholm and Melosh, 2001; McDonald et al., 2008). The best estimate of impact direction to date, based on three-dimensional numerical simulations of crater formation that incorporate new data from IODP Site M0077 in the Chicxulub crater, indicates that an impact toward the southwest at a ~60° angle produces the best match between the modeled and observed three-dimensional crater structure (Collins et al., 2017).

OCEAN DRILLING PERSPECTIVE ON MASS EXTINCTION AND THE SUBSEQUENT RECOVERY OF LIFE

Paleontologists have long recognized a major mass extinction at the end of the Cretaceous with the disappearance of non-avian dinosaurs, marine reptiles, and ammonites, although the first indication of the rapidity of this event came from microfossils. The earliest studies of the extinction of the calcareous microfossils across the K-Pg boundary came from outcrops on land (e.g., Luterbacher and Premoli-Silva, 1964; Perch Nielsen et al., 1982; Percival and Fischer, 1977; Romein, 1977; Smit, 1982; M.J. Jiang and Gartner, 1986; Hollis, 1997; Harwood, 1988; Hollis and Strong, 2003). However, the full taxonomic scope of the extinction and how it related to global biogeography and ecology is largely known from scientific ocean drilling (e.g., Thierstein and Okada, 1979; Thierstein, 1982; Pospichal and Wise, 1990; N. MacLeod et al., 1997; Bown et al., 2004). Deep-sea sites also serve as the basis for our understanding of the subsequent recovery of life (Bown, 2005; Coxall et al., 2006; Bernaola and Monechi, 2007; S. Jiang et al., 2010; Hull and Norris, 2011; Hull et al., 2011; Koutsoukos, 2014; Birch et al., 2016; Lowery et al., 2018). The K-Pg boundary has been recovered in dozens of cores from all major ocean basins, including some from the earliest DSDP legs (Figure 2; Premoli Silva and Bolli, 1973; Perch-Nielsen, 1977; Thierstein and Okada, 1979; see summary of terrestrial and marine K-Pg sections in Schulte et al., 2010). Deep-sea cores generally afford excellent microfossil preservation, continuous recovery, and tight stratigraphic control, including magnetostratigraphy and orbital chronology (Röhl et al., 2001; Westerhold et al., 2008).

Studies of deep-sea sections have exposed the severity of the mass extinction among the calcareous plankton, with over 90% of heterotroph foraminifera and autotroph nannoplankton species becoming extinct (Thierstein, 1982; D'Hondt and Keller, 1991; Coxall et al., 2006; Hull et al., 2011). The extinction was highly selective, as siliceous groups experienced relatively low rates of extinction (Harwood, 1988; Hollis et al., 2003). Among the calcareous plankton groups, survivors include high-latitude and near-shore species (D'Hondt and Keller, 1991; Bown, 2005), suggesting that these species adapted to survive variable environments in the immediate aftermath of the impact. Benthic foraminifera survived the impact with little extinction (Culver, 2003).

A key component of the post-extinction recovery of life on Earth is the revival of primary productivity. Photosynthesis favors ^{12}C over ^{13}C, enriching organic material in the former. Sinking of dead organic matter in the ocean removes ^{12}C from the upper water column; thus, under normal conditions, there is a carbon isotope gradient from the surface waters to the seafloor. After the Chicxulub impact, this vertical gradient was non-existent for ~4 million years (e.g., Coxall et al., 2006). This phenomenon was originally interpreted as indicating the complete or nearly complete cessation of surface ocean productivity (Hsü and McKenzie, 1985; Zachos et al., 1989; the latter from DSDP Site 577 on Shatsky Rise), a hypothesis that became known as the Strangelove Ocean (after the 1964 Stanley Kubrick movie; Hsü and McKenzie, 1985). D'Hondt et al. (1998) suggested that surface ocean productivity continued, but the extinction of larger organisms meant that there was no easy mechanism (e.g., fecal pellets) to export this organic matter to the deep sea—a modification of the Strangelove Ocean hypothesis that they called the Living Ocean hypothesis (D'Hondt, 2005; see also Adams et al., 2004). The observed changes in carbon isotopes can be explained by just a slight increase (from 90% to 95%) in the fraction of organic matter remineralized in the upper ocean (D'Hondt et al., 1998; Alegret et al., 2012), although a more precipitous drop in export productivity (Coxall et al., 2006) has also been suggested. The lack of a corresponding benthic foraminiferal extinction indicates that the downward flux of organic carbon may have decreased somewhat but remained sufficiently elevated to provide the carbon necessary to sustain the benthic community (Hull and Norris, 2011; Alegret et al., 2012). Research on barium fluxes in deep-sea sites across the ocean shows that, in fact, export productivity was highly variable in the early Danian (the age that immediately followed the end of the Cretaceous, when K-Pg extinction begins), with some sites recording an *increase* in export production during the period of supposed famine in the deep sea (Hull and Norris, 2011).

However, any shift in the surface-to-deep carbon isotope gradient does have significant implications for biogeochemical cycling. The extinction of pelagic calcifiers such as planktic foraminifera and calcareous nannoplankton caused profound changes in the cycling of carbon from the surface to the deep sea. Pelagic calcifiers are a key component of the carbon cycle as they export carbon in the form of $CaCO_3$ from the surface ocean to the seafloor. The near eradication of these groups must have made surface-to-deep cycling less efficient, explaining the decreased carbon isotope gradient (Hilting et al., 2008; Alegret et al., 2012; Henehan et al., 2016). This also led to the weakening of the marine "alkalinity pump" (D'Hondt, 2005; Henehan et al., 2016). The resulting carbonate oversaturation improved carbonate preservation in the deep sea, which can be observed as a white layer that overlies the K-Pg boundary at numerous sites, including the eastern Gulf of Mexico (DSDP Site 536; Buffler et al., 1984), the Caribbean (ODP Sites 999 and 1001; Sigurdsson et al., 1997), Shatsky Rise in the western Pacific (Figure 3; ODP Sites 1209–1212; Bralower et al., 2002), and in the Chicxulub crater (IODP Site M0077; Morgan et al., 2017).

Records from cores across the ocean basins indicate that the post-extinction recovery of export productivity (e.g., Hull and Norris, 2011) and calcareous plankton diversity (e.g., S. Jiang et al., 2010) was geographically heterogeneous, with some localities recovering rapidly and others taking hundreds of thousands (for productivity) to millions (for diversity) of years to recover. Among the nannoplankton, Northern Hemisphere assemblages are characterized by a series of high-dominance, low-diversity "boom-bust" species (Bown, 2005), while Southern Hemisphere assemblages contain a somewhat more diverse group of surviving species (Schueth et al., 2015). In general, diversity of Northern Hemisphere assemblages took longer to recover (S. Jiang et al., 2010). Recovery of export productivity likewise appears to have been slower in the North Atlantic and Gulf of Mexico (e.g., S. Jiang et al., 2010; Hull and Norris, 2011; Alegret et al., 2012), suggesting that sites proximal to the impact crater had a slower recovery. Some authors (e.g., S. Jiang et al., 2010) attributed this to direct environmental effects of the impact, such as the uneven distribution of toxic metals in the ocean. If recovery is slower closer to the crater, then it should be slowest in the crater itself. However, recent drilling within the Chicxulub crater shows rapid recovery of life, with planktic and benthic organisms appearing within just a few years of the impact and a healthy, high-productivity ecosystem established within 30,000 years of the impact, much faster than estimates for other Gulf of Mexico and North Atlantic sites (Lowery et al., 2018). This rapid recovery rules out an environmental driver for heterogeneous recovery and instead suggests that natural ecological factors, including incumbency, competitive exclusion (e.g., Hull et al., 2011; Schueth et al., 2015), and morphospace reconstruction (Lowery and Fraass, 2018), were the dominant controls on the recovery of the marine ecosystem. The recovery of diversity took millions of years to even begin to approach pre-impact Cretaceous levels (Bown et al., 2004; Coxall et al., 2006; Fraass et al., 2015). This delay in the recovery of diversity appears to be a feature of all extinction events (Kirchner and Weil, 2000; Alroy, 2008) and bodes ill for the recovery of the modern biosphere after negative anthropogenic impacts of, for example, ocean acidification and hypoxia, subside.

UNIQUE INSIGHT INTO THE CHICXULUB CRATER

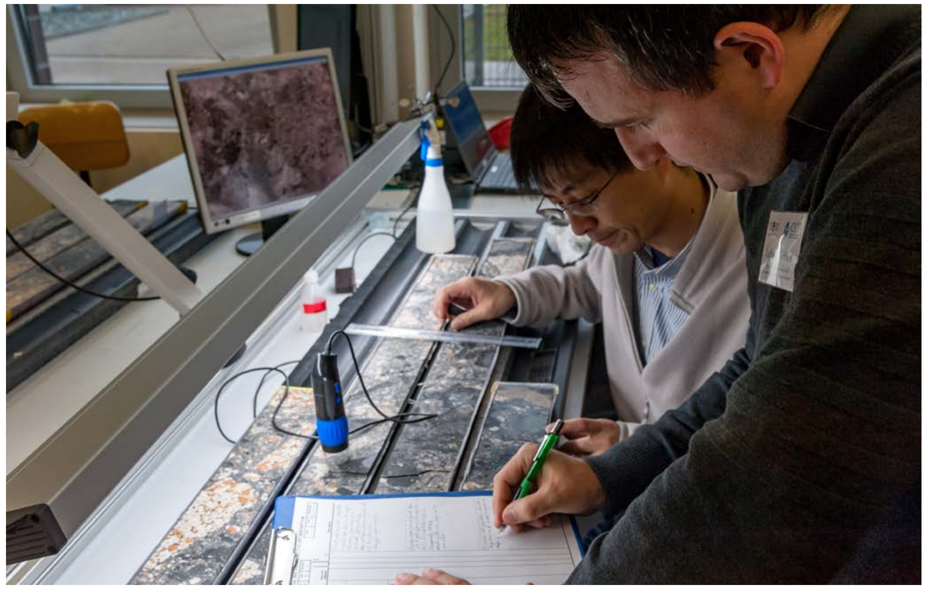
In 2016, the joint IODP-ICDP Expedition 364 drilled into the peak ring of the Chicxulub impact crater at Site M0077 (Morgan et al., 2017). Peak rings are elevated topography that protrude through the crater floor in the inner part of large impact structures. Prior to drilling, there was no consensus on the nature of the rocks that form peak rings or their formational mechanism (Baker et al., 2016). To form large craters like Chicxulub, rocks must temporarily behave in a fluid-like manner during crater formation (Melosh, 1977; Riller et al., 2018). Two hypotheses, developed from observations of craters on other planets, provided possible explanations for the processes by which peak rings form. The first, the dynamic collapse model (first put forward by Murray, 1980) predicted that the Chicxulub peak ring would be formed from deep crustal rock, presumably crystalline basement. The second, the nested melt-cavity hypothesis (conceived by Cintala and Grieve, 1998) predicted that the Chicxulub peak ring would be underlain by shallow crustal rock, presumably Cretaceous carbonates. Thus, Expedition 364 was able to answer a major question about impact cratering processes simply by determining what rock comprises the peak ring (Figure 3). Geophysical data acquired prior to drilling indicated that there are sedimentary rocks several kilometers beneath the Chicxulub peak ring, and that the peak-ring rocks have a relatively low velocity and density, suggesting that they are highly fractured (Morgan et al., 1997; Morgan and Warner, 1999; Gulick et al., 2008, 2013; Morgan et al., 2011).

The discovery that the peak ring was formed from fractured, shocked, uplifted granitic basement rocks supports the dynamic collapse model of peak-ring formation (Morgan et al., 2016; Kring et al., 2017). Structural data from wireline logging, CT scans, and visual core descriptions provide an exceptional record of brittle and viscous deformation mechanisms within the peak-ring rocks. These data reveal how deformation evolved during cratering, with dramatic weakening followed by a gradual increase in rock strength (Riller et al., 2018). The peak-ring rocks have extraordinary physical properties: the granitic basement has P-wave velocities and densities that are, respectively, ~25% and ~10% lower than expected, and a porosity of 8%–10%. These values are consistent with numerical simulations that predict the peak-ring basement rocks represent some of the most shocked and damaged rocks in an impact basin (Christeson et al., 2018). Site M0077 cores and measurements have been used to refine numerical models of the impact and provide new estimates on the release of cooling climatic gases by the Chicxulub impact. Previous studies estimated that the Chicxulub impact released anywhere from 30–1,920 Gt of sulfur from the evaporite-rich target rocks and formed sulfate aerosols in the atmosphere that block incoming solar radiation (see Tyrrell et al., 2015, and references therein)—a recent global climate model indicates that a modest injection of 100 Gt of sulfur may have resulted in a 26°C drop in global temperatures (Brugger et al., 2017). New impact models calibrated with data from Site M0077 suggest that between 195 Gt and 455 Gt of sulfur were released and may have led to even more radical cooling during the so-called "impact winter" (Artemieva et al., 2017). However, it appears that only the most extreme estimates of sulfur release would have driven ocean acidification severe enough to explain the extinction of calcareous plankton (Tyrrell et al., 2015), suggesting that the sharp reduction in sunlight for photosynthesis drove the extinction.

NEW CHALLENGES

The scientific community's understanding of the Chicxulub impact event and the K-Pg mass extinction has grown immensely since Smit and Hertogen (1980) and Alvarez et al. (1980) proposed the impact hypothesis, and many of the advances were the direct result of scientific ocean drilling data. However, there is still a great deal that we do not know. New K-Pg boundary sites from undersampled regions (the Pacific, the Indian Ocean, and the high latitudes) are essential to reconstruct environmental gradients in the early Paleocene and to understand geographic patterns of recovery and global environmental effects as well as what drives them. IODP Site U1514, on the Naturaliste Plateau on the Southwest Australian margin (Figure 2), drilled in 2017 on Expedition 369 (Huber et al., 2018), is a perfect example of the kind of new site we need to drill—at a high latitude and far from existing K-Pg boundary records.

New data from the Chicxulub crater have resulted in refined impact models that suggest the asteroid impacted toward the southwest (Collins et al., 2017), in contrast with previously inferred directions that placed the Northern Hemisphere in the downrange direction. Although the most proximal Pacific crust at the time of impact has since been subducted, very little drilling has been conducted on older crust in the central and eastern Pacific (red circle in Figure 2). New drilling on seamounts and rises on the easternmost Cretaceous crust in the equatorial Pacific could shed new light on the environmental and biological consequences of the Chicxulub impact in a close-by and downrange location. Samples from these locations may finally yield some fragments of the impactor.



Impact Petrologists Ludovic Ferrière (Natural History Museum, Austria) and Naotaka Tomioka (JAMSTEC) at the visual core description table at the IODP Bremen Core Repository during the onshore science party for IODP Expedition 364, Chicxulub: Drilling the K-Pg Impact Crater. *Photo credit: V. Diekamp, ECORD/IODP*

In the end, the Chicxulub structure remains an important drilling target to address questions that can only be answered at the K-Pg impact site. IODP Site M0077, which was drilled at the location where the peak ring was shallowest, recovered a relatively thin Paleocene section with an unconformity present prior to the Paleocene-Eocene boundary. Seismic mapping within the crater demonstrates that the Paleocene section greatly expands into the annular trough (Figure 4), providing an exciting opportunity to study the return of life to the impact crater at an even higher resolution than Lowery et al. (2018) achieved. Additionally, continuous coring within an expanded Paleocene section and the underlying impactites would better constrain climatologic inputs from the vaporization of evaporites.

Equally intriguing is the interaction of impact melt rock, suevite, and post-impact hydrothermal systems for studying how subsurface life can inhabit and evolve within an impact basin. Such settings were common on early Earth and provide an analog for the chemical evolution of pre-biotic environments as well as biologic evolution in extreme environments. Full waveform images (Figure 4) suggest tantalizing morphologic complexities within the low-velocity suevite layer above the high-velocity central melt sheet that are tempting to interpret as ancient hydrothermal vent systems of the kind often seen at mid-ocean ridges. Drilling into the Chicxulub melt sheet would be ideal for studying the hydrogeology and geomicrobiology of impact melt sheets buried by breccias as a (new) habitat for subsurface life, providing an opportunity for scientific ocean drilling to sample the best analog for the habitat in which life may have initially formed on early Earth and on rocky bodies across the solar system and beyond.

The successful cooperation between IODP and ICDP during Expedition 364 serves as a model for future drilling in the Chicxulub crater as well as for future IODP mission-specific platform expeditions. High-quality marine seismic data from an offshore portion of the Chicxulub crater (Morgan et al., 1997; Gulick et al., 2008; Christeson et al., 2018) permitted detailed characterization of the subsurface before drilling even

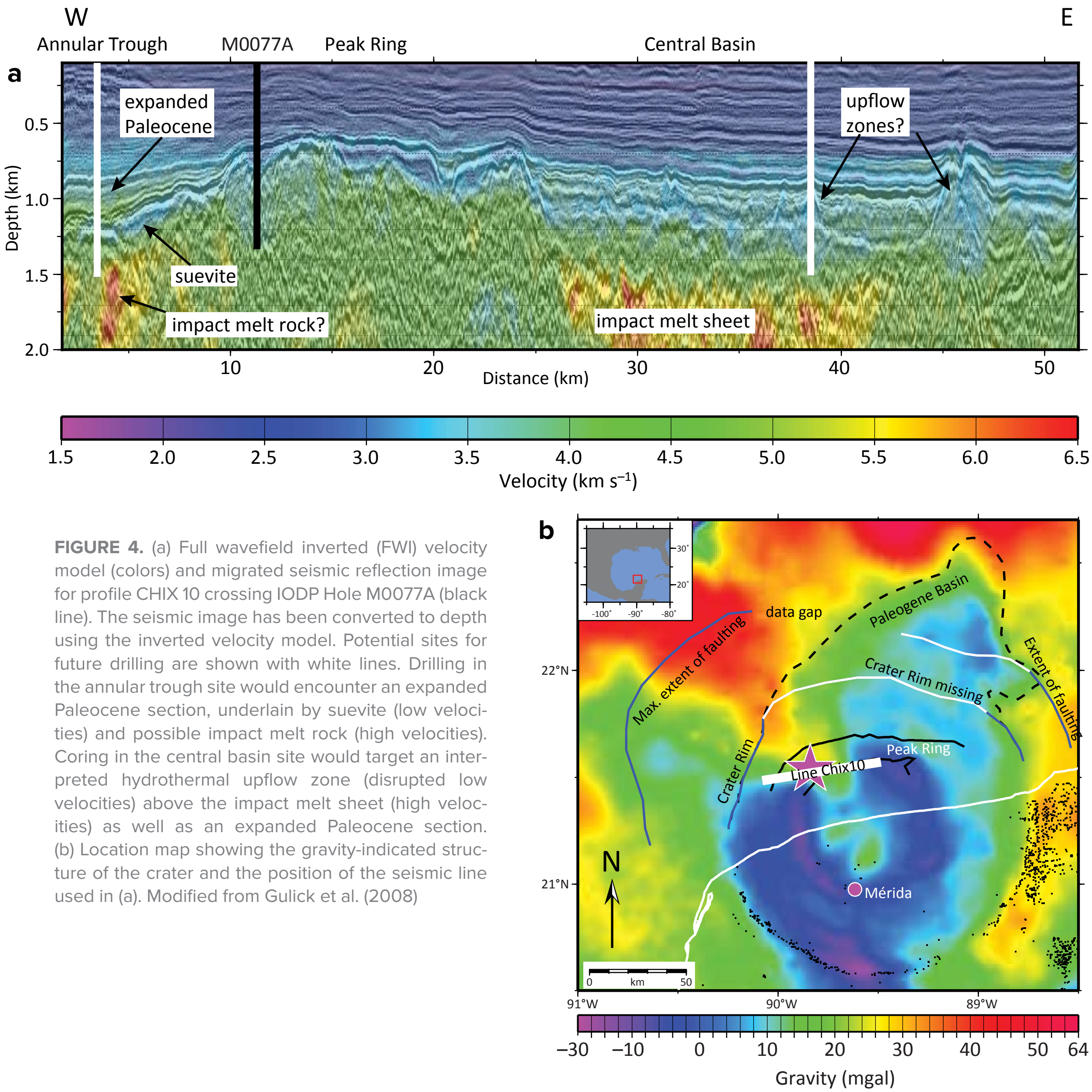


FIGURE 4. (a) Full wavefield inverted (FWI) velocity model (colors) and migrated seismic reflection image for profile CHIX 10 crossing IODP Hole M0077A (black line). The seismic image has been converted to depth using the inverted velocity model. Potential sites for future drilling are shown with white lines. Drilling in the annular trough site would encounter an expanded Paleocene section, underlain by suevite (low velocities) and possible impact melt rock (high velocities). Coring in the central basin site would target an interpreted hydrothermal upflow zone (disrupted low velocities) above the impact melt sheet (high velocities) as well as an expanded Paleocene section. (b) Location map showing the gravity-indicated structure of the crater and the position of the seismic line used in (a). Modified from Gulick et al. (2008)

began (Whalen et al., 2013). In turn, this allowed Hole M0077A to precisely target not just the peak ring but a small depression on top of the peak ring expected to contain earliest Paleocene age sediments that provided the basis for unprecedented study of this unique interval at ground zero (Lowery et al., 2018, and a number of upcoming papers). As we plan for the next 50 years of scientific ocean drilling, we should look for additional opportunities to leverage the clarity and resolution of marine seismic data with the precision drilling possible from a stable platform provided by ICDP (Expedition 364 achieved essentially 100% recovery; Morgan et al., 2017).

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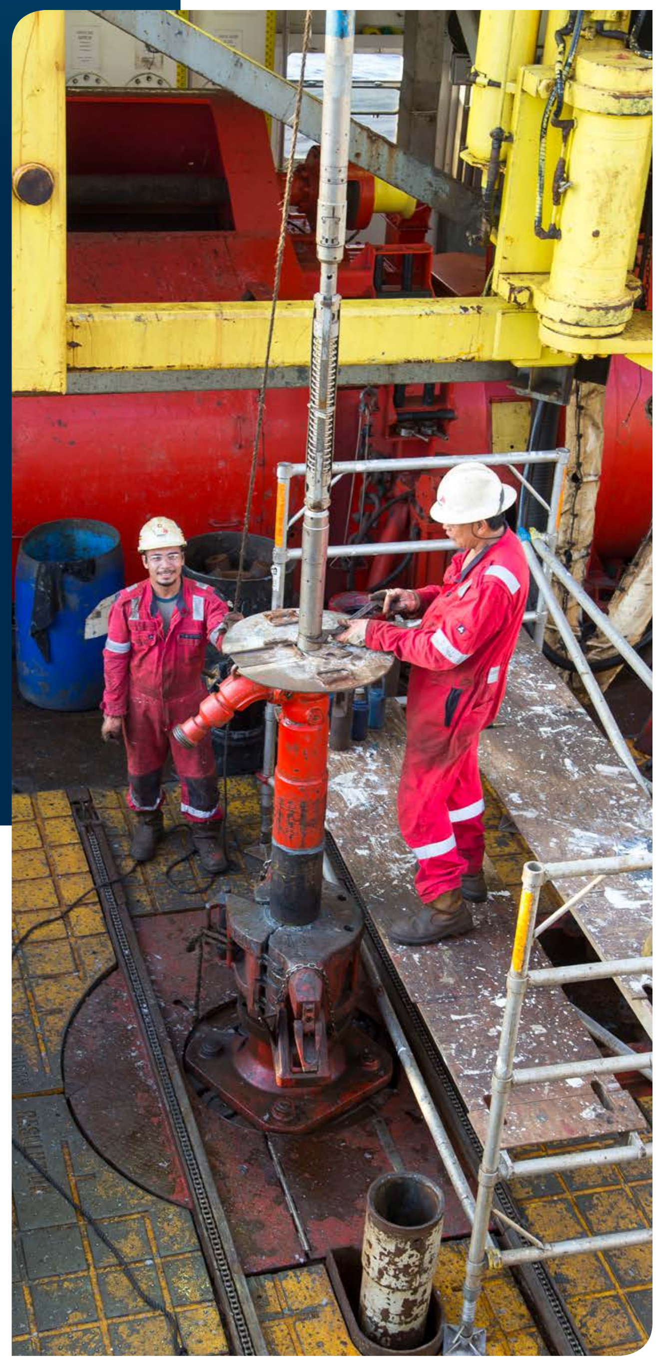
SPOTLIGHT 10. Future Opportunities in Scientific Ocean Drilling: Natural Hazards

The source regions of undersea natural hazards, including earthquakes and slope failures, are prominent targets for scientific ocean drilling. The marriage of coring and integrated borehole instrumentation has changed our view of these phenomena, revealing variations in subsurface conditions that precede and follow them.

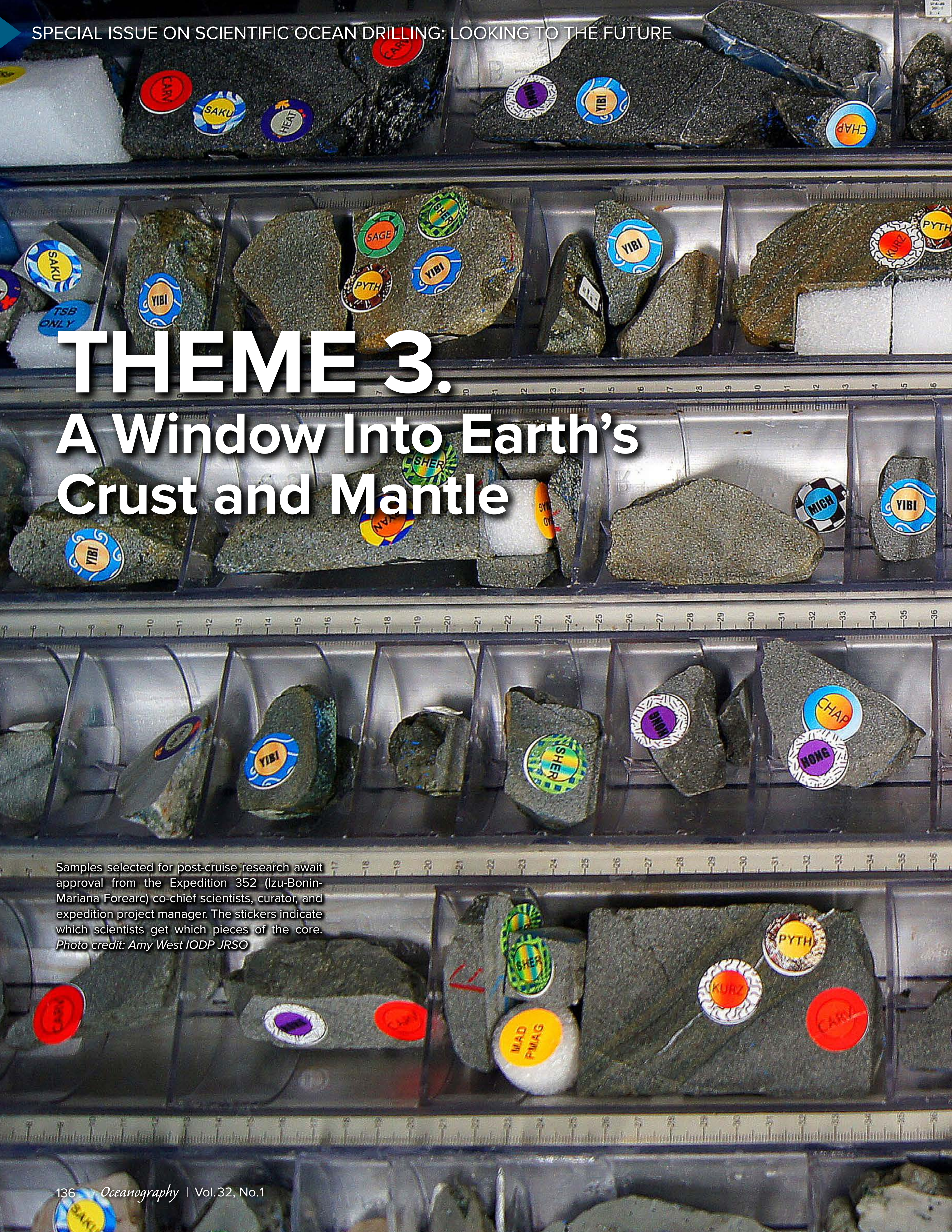
Since 2004, a series of devastating tsunamis, earthquakes, and submarine landslides resulted in the loss of hundreds of thousands of lives and caused hundreds of billions of dollars worth of damage. Meanwhile, revolutions in instrumentation and remote sensing are enabling us to detect and monitor such events in novel ways and in ever-greater detail. For example, successful borehole observatory installations along the Costa Rica, Hikurangi, and Nankai subduction margins are identifying transient slow fault slip events that were previously undetectable. These successes demonstrate the value of expanded monitoring efforts at subduction and transform fault systems globally (e.g., Cascadia, Alaska, Peru-Chile) to learn more about the diversity of fault environments and behaviors.

Future work will illuminate the earthquake cycle by integrating ever-higher resolution seafloor maps and subsurface images with geological and mechanical research on samples recovered by scientific ocean drilling from fault zones, in situ logging measurements of rock properties and stress recorded in downhole logs, and long-term borehole observations. In addition to movement on active fault systems, submarine slope stability, hazards from gas venting and gas hydrate deposits, and the resulting mass transport and turbidite flows are all significant sources of tsunami hazard. The time is ripe for pursuing ambitious new drilling targets, including collecting cores and in situ measurements to study both the history of and conditions for slope failure on both sedimented continental margins and the flanks of volcanic islands and seamounts.

— Harold J. Tobin and Demian M. Saffer

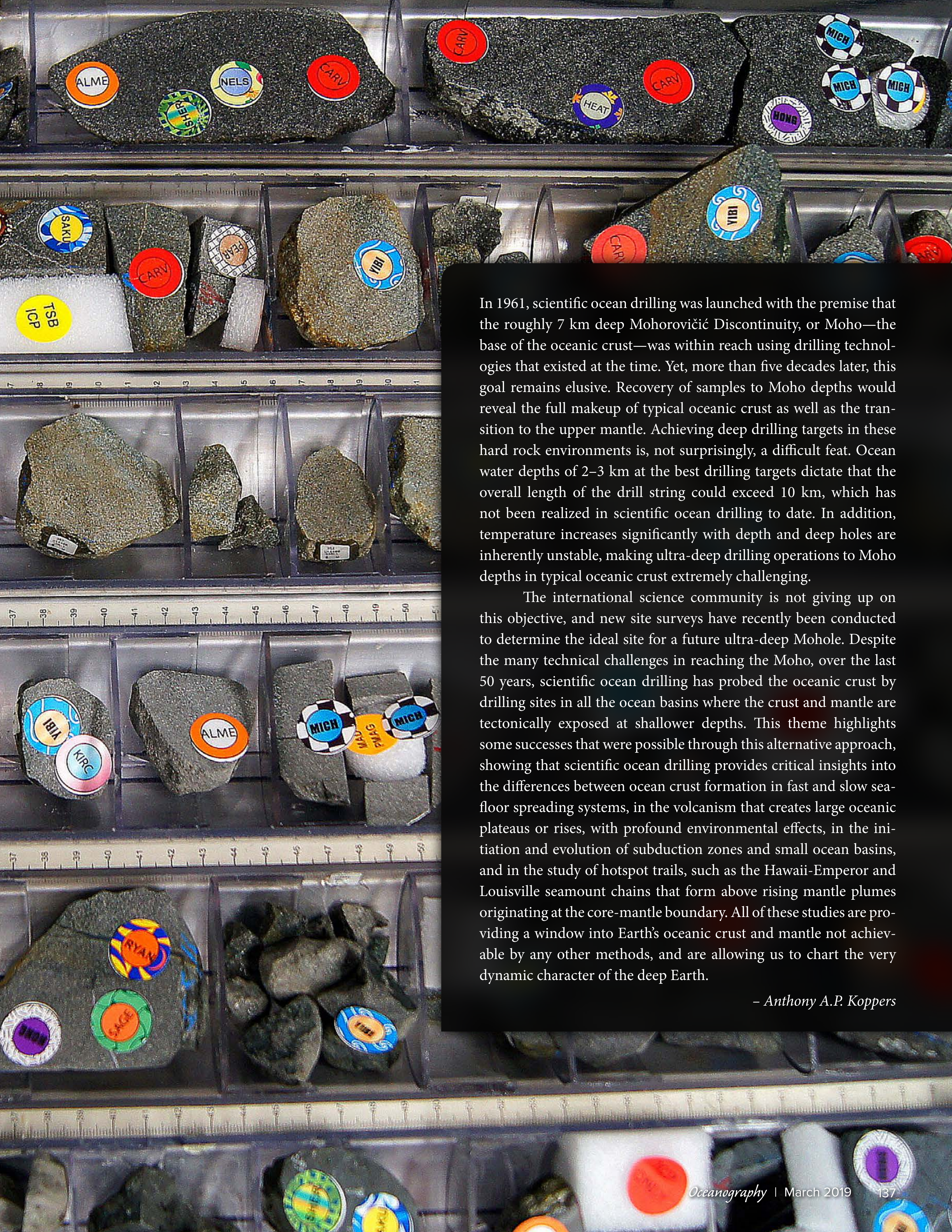


Siem Offshore personnel assemble a logging tool string on the rig floor of *JOIDES Resolution* during IODP Expedition 362, Sumatra Seismogenic Zone. *Photo credit: Tim Fulton, IODP JRSO*



THEME 3.
A Window Into Earth's Crust and Mantle

Samples selected for post-cruise research await approval from the Expedition 352 (Izu-Bonin-Mariana Forearc) co-chief scientists, curator, and expedition project manager. The stickers indicate which scientists get which pieces of the core. *Photo credit: Amy West IODP JRSO*



In 1961, scientific ocean drilling was launched with the premise that the roughly 7 km deep Mohorovičić Discontinuity, or Moho—the base of the oceanic crust—was within reach using drilling technologies that existed at the time. Yet, more than five decades later, this goal remains elusive. Recovery of samples to Moho depths would reveal the full makeup of typical oceanic crust as well as the transition to the upper mantle. Achieving deep drilling targets in these hard rock environments is, not surprisingly, a difficult feat. Ocean water depths of 2–3 km at the best drilling targets dictate that the overall length of the drill string could exceed 10 km, which has not been realized in scientific ocean drilling to date. In addition, temperature increases significantly with depth and deep holes are inherently unstable, making ultra-deep drilling operations to Moho depths in typical oceanic crust extremely challenging.

The international science community is not giving up on this objective, and new site surveys have recently been conducted to determine the ideal site for a future ultra-deep Mohole. Despite the many technical challenges in reaching the Moho, over the last 50 years, scientific ocean drilling has probed the oceanic crust by drilling sites in all the ocean basins where the crust and mantle are tectonically exposed at shallower depths. This theme highlights some successes that were possible through this alternative approach, showing that scientific ocean drilling provides critical insights into the differences between ocean crust formation in fast and slow seafloor spreading systems, in the volcanism that creates large oceanic plateaus or rises, with profound environmental effects, in the initiation and evolution of subduction zones and small ocean basins, and in the study of hotspot trails, such as the Hawaii-Emperor and Louisville seamount chains that form above rising mantle plumes originating at the core-mantle boundary. All of these studies are providing a window into Earth's oceanic crust and mantle not achievable by any other methods, and are allowing us to chart the very dynamic character of the deep Earth.

– Anthony A.P. Koppers

What Lies Beneath

THE FORMATION AND EVOLUTION OF OCEANIC LITHOSPHERE

By Katsuyoshi Michibayashi, Masako Tominaga, Benoît Ildefonse, and Damon A.H. Teagle

Reentry cone deployment through the *JOIDES Resolution* moonpool, Expedition 375, Hikurangi Subduction Margin. *Photo credit: Tim Fulton, IODP JRSO*

ABSTRACT. Sampling the upper mantle via scientific ocean drilling remains elusive. Although the technologies required for drilling to the Moho still don't exist, we have made significant progress over the last five decades in piecing together the complex geology of the oceanic crust. Here, we highlight key findings that reveal the architecture of oceanic crust and the thermal, physical, and chemical processes that are responsible for the growth and structure of the oceanic lithosphere. These advances result from enduring efforts to drill and collect downhole geophysical logs of oceanic crust near both slow and fast spreading ridges.

INTRODUCTION

Scientific ocean drilling commenced through the initiation of Project Mohole in 1961, about the same time as Apollo moon landing ambitions were first articulated. It has been almost 60 years since the American Miscellaneous Society conceived of the idea for Project Mohole and 50 years since the launch of the Deep Sea Drilling Project (DSDP) in 1968. Scientific ocean drilling is an essential approach to directly access Earth's interior and is arguably science's most successful international collaboration. Although this cooperation has greatly expanded from the DSDP (1968–1983), through the Ocean Drilling Program (ODP, 1983–2003) to the Integrated Ocean Drilling Program (IODP, 2003–2013), and to the International Ocean Discovery Program (IODP, 2013–2023), gaining a better understanding of the dynamics of our planet remain challenging due to the technical difficulties of drilling holes deeper than 100–200 m into the oceanic crust's igneous basement.

A compilation of holes drilled into in situ oceanic crust by scientific ocean drilling since the beginning of DSDP through 2018 highlights the problem: only 38 holes are deeper than 100 m and only 20 are deeper than 200 m (Figures 1 and 2; e.g., Ildefonse et al., 2007b, 2014). The first attempt was DSDP Hole 332A drilled on Leg 37 in 1974 (Aumento et al., 1977). The total amount of igneous oceanic crust recovered represents less than 2% of the material archived in the DSDP, ODP, and IODP core repositories. Despite this relative paucity of material, scientific ocean drilling has provided essential and hitherto unavailable observations that are advancing our understanding of the processes that "repave" nearly 70% of Earth's surface over short geological timescales (<200 million years). We have better knowledge of oceanic crust architecture, magmatic accretion processes in

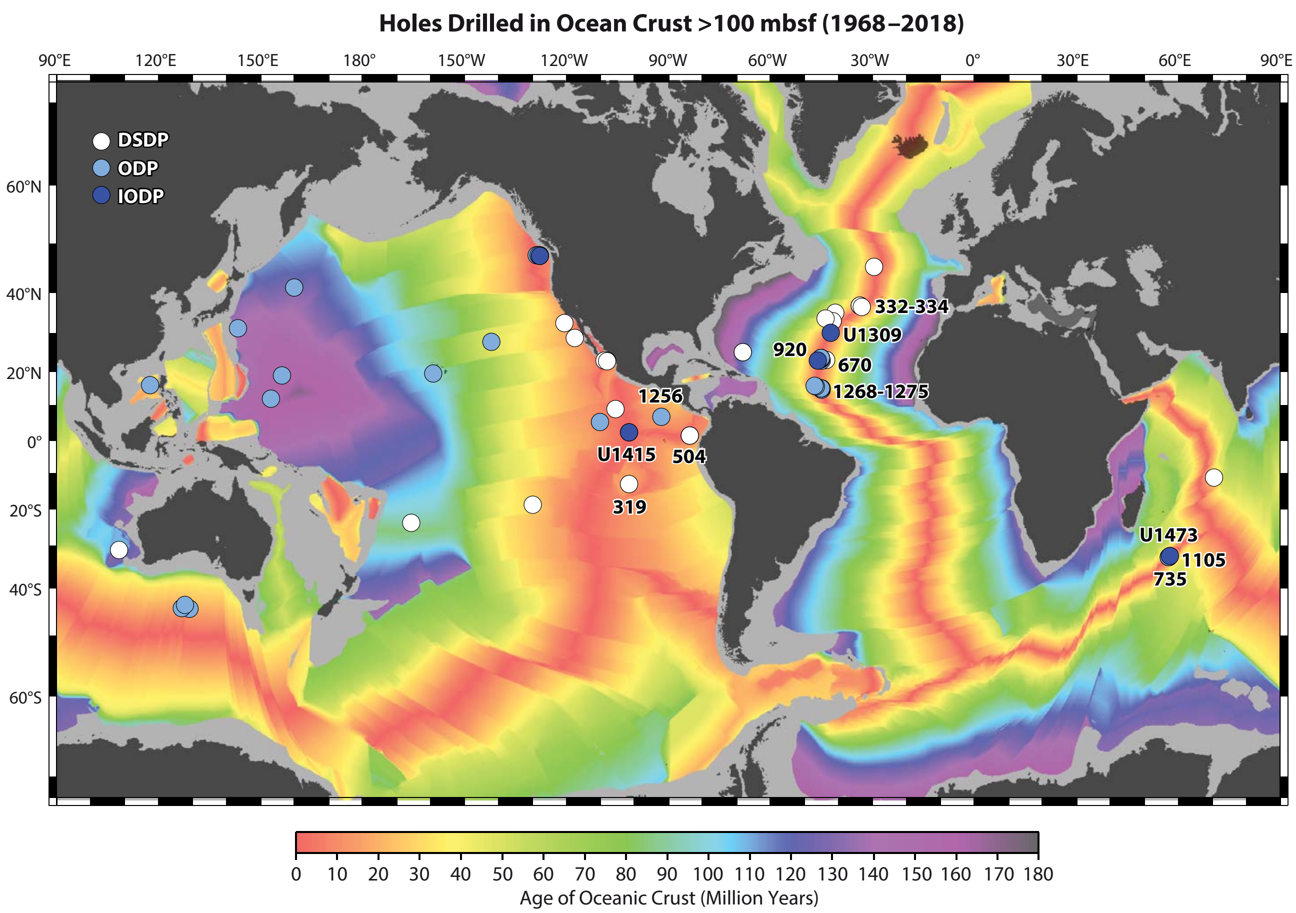


FIGURE 1. Compilation showing holes drilled >100 meters below seafloor (mbsf) into the basement of intact oceanic crust and tectonically exposed lower crust and upper mantle from 1968 to 2018 (see drill hole sections in Figure 2). Sites mentioned in the text are labeled. Seafloor age based on age grid by Müller et al. (2008, revised version 3; www.earthbyte.org/). This map does not include "hard rock" drill holes in seamounts, oceanic plateaus, back-arc basement, hydrothermal mounds, or passive continental margins.

the centers of mid-ocean ridge spreading centers, and the nature and magnitudes of hydrothermal exchange between the ocean and the oceanic lithosphere, and scientific ocean drilling samples led to the discovery of a deep microbial rock-hosted biosphere.

With the results from 50 years of scientific ocean drilling, we now know that in all ocean basins a volcanic basement lies beneath an almost omnipresent blanket of sediments, created by a system of mid-ocean ridges that together form the largest magmatic province on Earth, generating more than 20 km^3 of new oceanic crust each year. Roughly two-thirds of the magma derived from the partial melting of upper mantle peridotite cools and crystallizes as plutons in the lower portion of the oceanic crust; the remainder erupts as basalt and forms the upper one-third of this basement.

Here, we focus on the importance of basement drilling and the advancements in our understanding of the key differences in ocean crust architecture as a function of plate tectonic setting and related thermal, physical, and chemical processes. We summarize early attempts in the 1960s and current plans to reach the Mohorovičić Discontinuity (Moho) at the lower ocean crust boundary with the upper mantle, and we discuss how scientific ocean drilling has informed us on the major differences in oceanic crust created in fast and ultra-slow spreading settings.

PROJECT MOHOLE

Project Mohole[1] has been an iconic aspiration in the Earth sciences, a fundamental driver of scientific ocean drilling and a focus of five decades of enduring collaborations between the United States and its international partners (Hsü, 1992). Originally, Project Mohole provided a geoscience foil to the nascent US space program. The essence of Project Mohole was to retrieve samples of Earth's mantle by penetrating the Moho, a major global seismic boundary between Earth's crust and upper mantle. Seismologists had already subdivided the oceanic crust into seismic layers: Layer 1 comprising low P-wave velocity sediments ($V_p < 3$ km s^{-1}); Layer 2 having low P-wave velocity and a steep velocity gradient, with V_p ranging from ~3.5 km s^{-1} to ~6.7 km s^{-1}, typical of basalt; and Layer 3 having high velocity and a more gentle velocity gradient (V_p of 6.7–7.1 km s^{-1}) that we now know is typical of gabbro. However, an abrupt increase at the base of Layer 3 to V_p >8 km s^{-1} was found to mark the Moho and was interpreted to be the boundary between the gabbros of the lower oceanic crust and the ultramafic (peridotitic) rocks of the uppermost mantle.

The ultimate proposal was to drill to the Moho in the deep ocean where Earth's crust is relatively thin (~6 km; National Research Council, 1957; Bascom, 1961). Attempting such an effort on land would have been impractical because the drilling equipment would have to withstand high in situ temperatures at great depths while drilling through the much thicker (>30 km) continental crust. In addition, cores sampled by ocean drilling offer a simpler and "cleaner" record of major geological processes, rather than the complex geology sampled by a terrestrial deep hole that would have resulted from multiple global tectonic ~400–500 million-year-long "Wilson cycles." If successful, the highly ambitious and technically challenging Project Mohole would have yielded new observations on the age and composition of the seafloor, while providing evidence for the theory of continental drift that at the time remained controversial and strongly debated.

Project Mohole comprised a three-phase plan (National Research Council, 1959). Phase 1 focused on modifying a

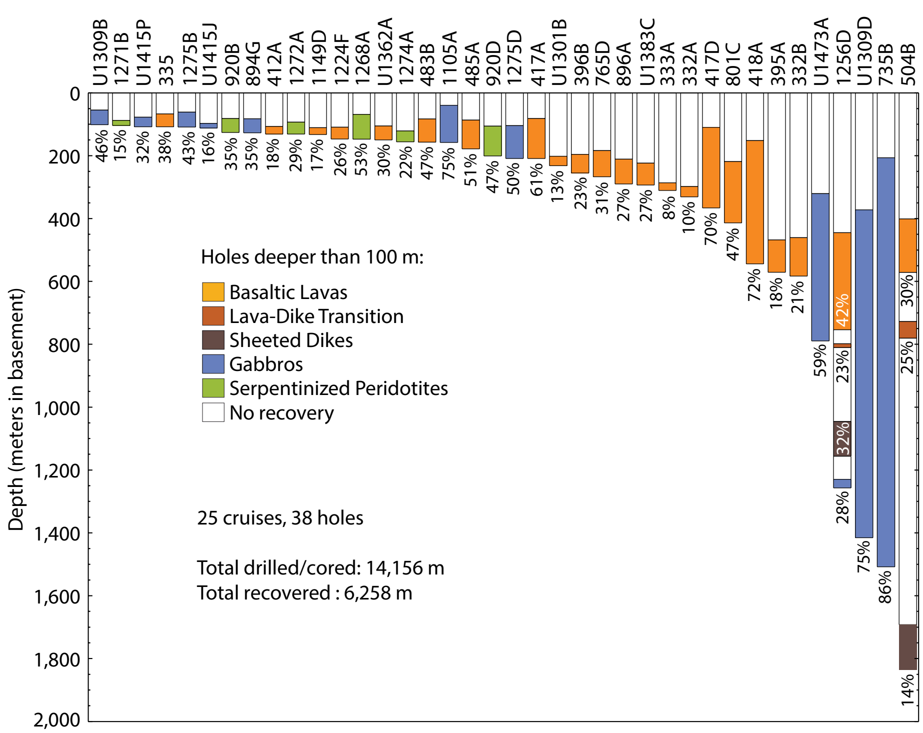


FIGURE 2. Compilation showing scientific ocean drilling holes that penetrated >100 m into the basement of intact oceanic crust and tectonically exposed lower crust and upper mantle from 1968 to 2018 (see drill hole locations in Figure 1). The number designation for each hole and the recovery (in percent) for each of the basement lithologies are indicated. This compilation does not include "hard rock" drill holes in seamounts, oceanic plateaus, back-arc basement, hydrothermal mounds, or passive continental margins.

[1] The US National Academies of Sciences, Engineering and Medicine offer a special website, Project Mohole: Commemorating the Accomplishments of Project Mohole—1961–2011, where a unique collection of photographs, video, original narratives, and historical documents can be found (http://www.nationalacademies.org/mohole/index.html).

drilling vessel for deepwater operations and testing the vessel and equipment in deep water far offshore. This required the development of new capabilities, including: (1) navigational and thruster technologies to keep a floating vessel at a single deep-ocean location, now known as "dynamic positioning" and a universal feature on any modern-day research vessel, and (2) a strategy that would allow subsequent visits to reenter the drill holes and resume drilling efforts (Bascom, 1961). The scientific objective of Phase 1 was to core as deep as possible into the ocean bottom, while Phase 2 was planned to use a more advanced vessel, and Phase 3 was intended to culminate in drilling through the Moho.

After ocean-going trials off La Jolla, California, Project Mohole Phase 1 began with drilling experiments near Guadalupe, Mexico, in March and April 1961. The drilling barge *CUSS I* (named after the four oil companies that had developed it: Continental, Union, Shell, and Superior) drilled 183 m into the seafloor in 3,558 m of water, and yielded 13 m of basalt beneath 170 m of sediment (National Research Council [U.S.] AMSOC Committee, 1961). This was the first in situ demonstration that the oceanic basement comprises (young) basaltic lavas, and that seismic Layer 2 is basalt. Project Mohole Phase 1 was a major early step in the exploration of Earth's interior, with scientists receiving a congratulatory telegram from US President John F. Kennedy: "The success of the drilling in almost 12,000 feet of water near Guadalupe and the penetration of the oceanic crust down to the volcanic formations constitute a remarkable achievement and an historic landmark in our scientific and engineering progress" (The National Academies of Sciences, Engineering and Medicine, 2011; see Becker et al., 2019, in this issue, Figures 1 and 2 for photos of *CUSS I* and this telegram).

Notwithstanding this early success, Project Mohole became mired in political controversy and was terminated in 1966 before further holes were drilled. Despite Project Mohole not achieving its original goal of drilling to the mantle, the project contributed to a "movement" in the solid Earth community, cumulating in the global acceptance of the theory of plate tectonics. Moreover, Project Mohole not only showed that scientific ocean drilling could successfully drill into and recover core samples from oceanic basement but also illustrated that ocean drilling is an essential tool for gathering otherwise inaccessible information about how our dynamic planet operates (Teagle and Ildefonse, 2011). Project Mohole led to formation of the US Deep Sea Drilling Project (DSDP), whose first expedition sailed in 1968.

EARLY YEARS: PENROSE MODEL AND CORING IN OCEANIC CRUST

The earliest years of DSDP concentrated on recovering long sediment cores to refine marine sediment-based biostratigraphy models and to validate the theory of seafloor spreading by dating the sediments directly overlying the oceanic basement (DSDP Leg 3; Maxwell et al., 1970). When the very top of the oceanic basement was "tapped" below the sediment column, recovered samples were recognized as pillow lavas, providing the first direct evidence of lava that was rapidly cooled in a subaqueous environment. These samples became the center of a debate on the origin of commonly juxtaposed rock strata observed in locations such as the Troodos Massif, Cyprus (e.g., Gass, 1968; cf. Miyashiro, 1973) and other orogenic belts. Geologists working on these so-called ophiolites reached a consensus statement during the 1972 Penrose Field Conference that defined these rock sequences in the context of the new paradigm of seafloor spreading, in what is now referred to as the Penrose model (Anonymous, 1972). This statement developed the widely accepted model that ophiolites are ancient and largely intact sections of oceanic crust preserved on land that comprise, from bottom to the top: (1) ultramafic rocks of the upper mantle, (2) gabbros, (3) a sheeted dike complex, (4) basaltic lavas, commonly pillow basalts, and (5) associated sedimentary deposits such as ribbon cherts, thin shale interbeds, and minor limestones (Figure 3a). The Penrose model raised the enduring science question as to whether ophiolites represent a direct analog for in situ oceanic crust beneath the modern seafloor (e.g., Panayotou, 1980; Gass, 1990), and this question, in turn, has been an important motivation for drilling the oceanic crust (e.g., Dilek et al., 2000).

The first international efforts to drill deeply into the oceanic crust were DSDP Leg 34 in 1973–1974 on the Nazca Plate in the Eastern Pacific Ocean (Yeasts et al., 1976), and DSDP Leg 37 in 1974 on the western flank of the Mid-Atlantic Ridge, south of the Azores Plateau (Aumento et al., 1977). These legs recovered, for the first time, tens of meters of basaltic core samples from upper oceanic crust (e.g., 59 m in Site 319 during Leg 34; >100 m in Holes 332A,B and 333A during Leg 37; Figures 1 and 2). It is also noteworthy that cores from Leg 37 Site 334 in the Atlantic recovered small amounts of gabbro and serpentinized peridotite from the presumed deeper layer in a typical Penrose style of oceanic lithosphere, at relatively shallow (117 meters below sediment-basement contact) subseafloor depths (Aumento et al., 1977), suggesting a vertical and lateral crustal heterogeneity and demonstrating that the Penrose model is an end member model itself (Figure 3; Ildefonse et al., 2014).

DEEP DRILLING IN FAST-SPREADING CRUST

Although less than 20% of the modern mid-ocean ridge system is creating new seafloor at fast rates (>80 mm yr^{-1} full rate), nearly half of the oceanic crust created over the last 200 million years formed at fast-spreading ridges (Teagle et al., 2012; Ildefonse et al., 2014). Deep drilling into oceanic crust at a few sites in the Eastern Pacific, including the Cocos Plate (ODP Holes 504B and 1256) and the Hess Deep (IODP Site U1415), has

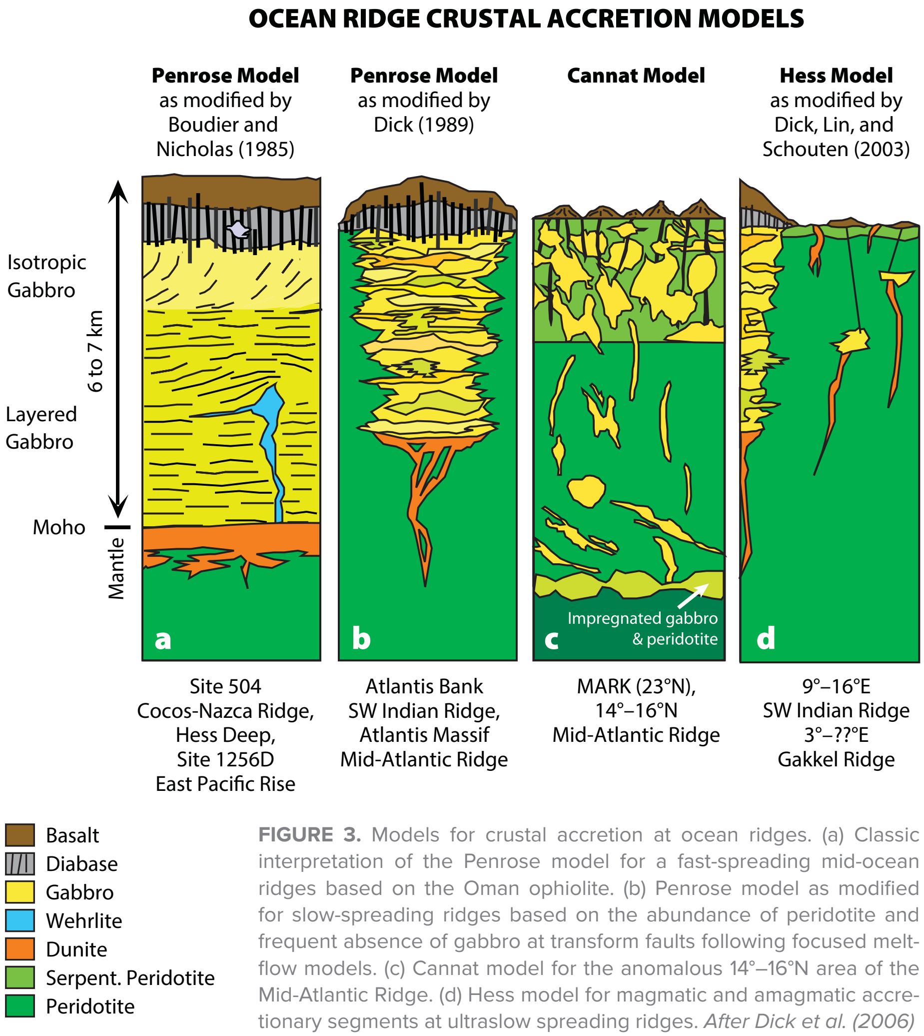


FIGURE 3. Models for crustal accretion at ocean ridges. (a) Classic interpretation of the Penrose model for a fast-spreading mid-ocean ridges based on the Oman ophiolite. (b) Penrose model as modified for slow-spreading ridges based on the abundance of peridotite and frequent absence of gabbro at transform faults following focused melt-flow models. (c) Cannat model for the anomalous 14°–16°N area of the Mid-Atlantic Ridge. (d) Hess model for magmatic and amagmatic accretionary segments at ultraslow spreading ridges. *After Dick et al. (2006)*

led to a widely accepted model of ocean crust architecture that is very similar to, and confirms in large terms, the Penrose model. Drilling has also provided insights into the nature of key seismic boundaries found in fast-spreading oceanic crust and into the role of alteration, grain size and texture, and composition in controlling these boundaries.

DSDP/ODP Reference Hole 504B: Nazca Plate

DSDP/ODP Hole 504B, located in 6 million year old crust 200 km south of the Costa Rica Rift in the eastern equatorial Pacific, has long been a "reference" site for intact oceanic crust formed at an intermediate- to fast-spreading center (Figures 1 and 2) between the oceanic Cocos (north) and Nazca (south) tectonic plates. It is the deepest hole drilled into the igneous oceanic crust, penetrating 2,111 meters below seafloor (mbsf) and 1,836.5 m into the subbasement over the course of seven ODP and DSDP legs since 1979 (DSDP Legs 69, 70, and 83, and ODP Legs 111, 137, 149, and 148; Cann et al., 1983; Anderson et al., 1985; Alt et al., 1986, 1993, 1996; Becker et al., 1988, 1992; Dick et al., 1992). The hole was also visited during DSDP Leg 92 in 1983 for downhole logging and sampling of borehole fluids (Leinen et al., 1986) and will be revisited in 2019 (IODP Expedition 385T; Tominaga et al., in press). ODP Leg 148 in 1993 was the last time Hole 504B was deepened, this time by 111 m. Further penetration is currently prevented because portions of a drill bit are stuck in the hole (Alt et al., 1993).

The lithologic sequence in Hole 504B consists (from top to bottom) of 274.5 m of sediment, 571.5 m of volcanic rocks, a 209 m transition zone, and 1,050 m of a sheeted dike complex (Figure 2; Alt et al., 1996). The hydrothermal alteration of the volcanic section in Hole 504B involves a series of processes that entail interaction with oxidizing seawater at low temperatures, with intensity decreasing downward. These processes and their effects on the volcanic section are generally similar to those in other oceanic upper crustal sections. The transition zone and upper dikes (down to 1,500 mbsf) were altered in a subsurface mixing zone, where hydrothermal fluids upwelling through the dikes mixed with cooler seawater circulating in the overlying more permeable volcanic rocks. Mineral assemblages in the cored permeable pillow basalts in the transition zone indicate that during hydrothermal circulation, a maximum temperature of ~350°–380°C may have been reached. This is typical of greenschist facies metamorphism that includes such alteration minerals as chlorite, actinolite, and albite-oligoclase (Alt et al., 1996). The lower dikes (1,500–2,111 mbsf) were hydrothermally altered at temperatures exceeding 400°C, resulting in the formation of hornblende and calcic secondary plagioclase, which then subsequently were overwritten by similar reactions that produced the pillow basalt greenschist assemblages at ~300°–400°C. Alteration of the sheeted dikes from Hole 504B is heterogeneous, with recrystallization controlled by fracturing and fluid access (Alt et al., 1996). Defining the position of the seismic transition between Layer 2 (basalts) and Layer 3 (gabbros) in Hole 504B depends upon the scale of observation, but appears to correlate with observed progressive changes in porosity and hydrothermal alteration (Alt et al., 1996). Therefore, the nature of the transition from sheeted dikes to gabbros in Hole 504B remains obscured.

ODP-IODP Superfast Hole 1256D: Cocos Plate

ODP Hole 1256D (Figures 1 and 2) was designed as a deep borehole to sample the cumulate gabbros of the lower oceanic crust and to penetrate deeper into the oceanic crustal sequence than Hole 504B. Hole 1256D is located in 3,635 m of water in the Guatemala Basin (6°44.2'N, 91°56.1'W) on the Cocos Plate in the eastern equatorial Pacific Ocean. Ocean crust at the site formed around 15 million years ago during a sustained episode of superfast ocean ridge spreading (>200 mm yr^{-1}; Wilson, 1996) at the East Pacific Rise. The site formed on a ridge segment that is at least 400 km long, located ~100 km north of the ridge-ridge-ridge (RRR) triple junction between the Cocos, Pacific, and Nazca Plates.

The deep drilling campaign at Site 1256 was aimed at understanding the formation, architecture, and evolution of oceanic crust formed at "superfast" plate spreading rates. It has been the focus of four scientific ocean drilling cruises (ODP Leg 206 and IODP Expeditions 309, 312, and 335; Wilson et al., 2003; Teagle et al., 2006, 2012). Hole 1256D was the first scientific ocean drilling borehole prepared for deep drilling in oceanic crust. A large funnel, or reentry cone, was installed at the seafloor and then secured downhole with almost 270 m of 16-inch casing through the 250 m thick sedimentary overburden, and then cemented into the uppermost basement (Wilson et al., 2003). During ODP Leg 206, the borehole was deepened through an ~810 m thick sequence of basaltic lavas and a thin (~346 m) sheeted dike complex, the lower 60 m of which shows evidence for the formation of granoblastic textures (i.e., rocks with a dense arrangement of large equidimensional minerals with sutured boundaries) that typically result from high temperature contact metamorphism (Teagle et al., 2006). During IODP Expedition 312, the first gabbroic rocks were encountered at 1,407 mbsf (Wilson et al., 2006; Teagle et al., 2006) at a depth where the hole entered a complex dike–gabbro transition zone that includes two gabbro lenses (20–50-m thick) intruding into basalt dikes with the same high-temperature granoblastic textures (Figure 4). IODP Expedition 335 returned to Hole 1256D in 2011 with the ambition of deepening the hole several hundred meters into the cumulate gabbroic rocks of intact lower oceanic crust. However, drilling in this hole advanced only minimally to 1,521 mbsf (Figure 4), as a number of significant engineering challenges were encountered during the expedition that prevented deepening of the hole beyond this "hardened" metamorphic unit (Teagle et al., 2012).

Based on regional seismic refraction data, the transition from basalt Layer 2 to gabbro Layer 3 at Site 1256 occurs between 1,200 m and 1,500 m into basement (Wilson et al., 2003). An examination of shipboard and post-cruise discrete sample measurements, wireline logging data, and vertical seismic velocity profiling suggests that the base of Hole 1256D is at, or very close to, the Layer 2–3 transition (Swift et al., 2008; Gilbert and Salisbury, 2011). In addition, simple mass balance calculations indicate that the average basalt in Hole 1256D must

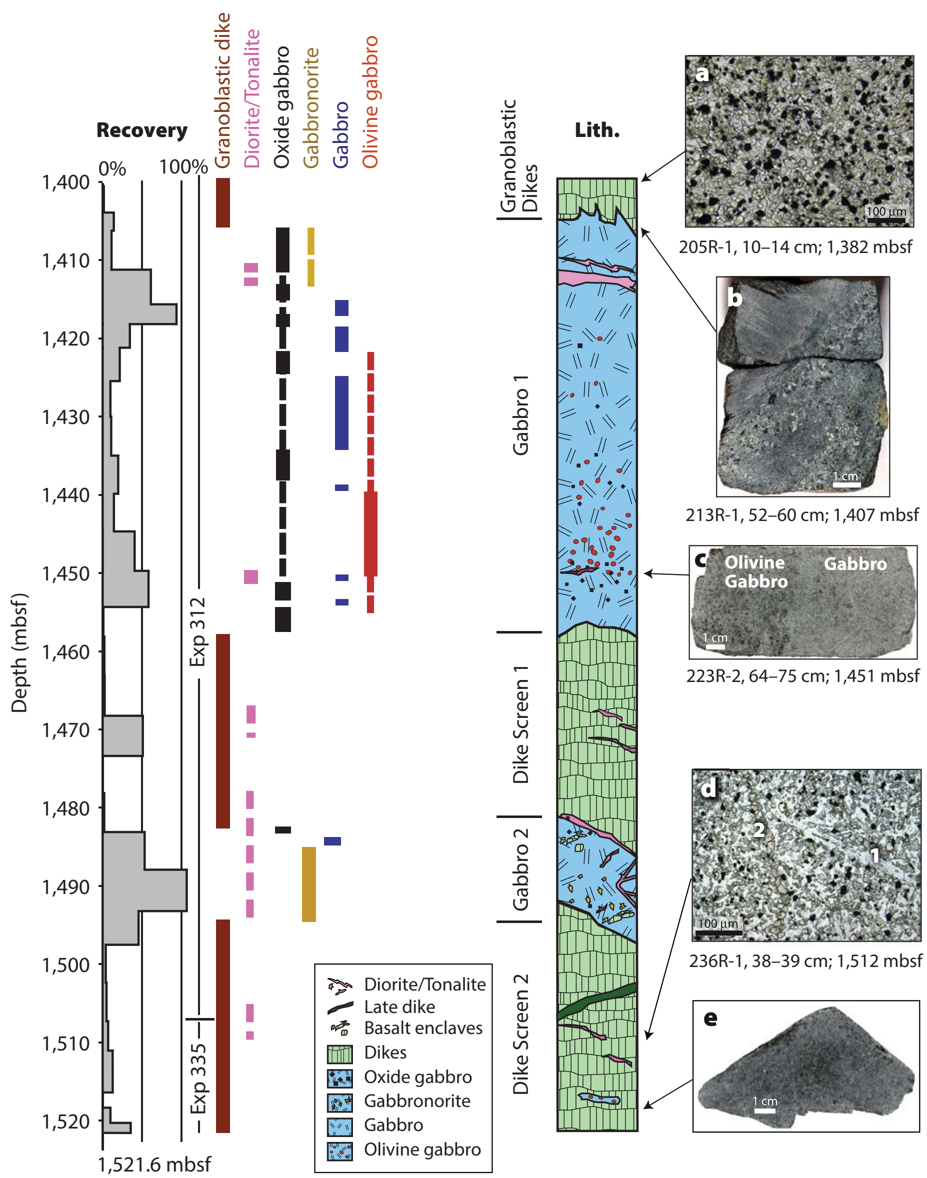


FIGURE 4. Plutonic section from the lower portion of Hole 1256D on the Cocos Plate with a few representative photomicrographs of key samples (modified after Ildefonse et al., 2014). The distribution of rock types is expanded proportionately in zones of incomplete recovery. (a) Photomicrograph of a dike completely recrystallized to a granoblastic texture. (b) Uppermost dike/gabbro boundary. (c) Sharp modal contact between a medium-grained olivine gabbro and a gabbro. (d) Photomicrograph of a granoblastic basalt. (e) Medium-grained, orthopyroxene-bearing olivine gabbro.

have lost more than 30% of its original liquid mass, implying that at least 300 m of cumulate gabbro formed as a residue during ocean crust formation must be present in the crust below the present base of Hole 1256D (Teagle et al., 2006). However, encountering gabbro already at a shallower depth within Layer 2 reinforces previous inferences that factors such as porosity and hydrothermal alteration (Detrick et al., 1994; Alt et al., 1996; Carlson, 2010) are more important than rock type or grain size in controlling the location of the seismic Layer 2–3 transition. This is an important advance in our understanding of oceanic crustal architecture, despite the fact that the Moho at the base of the oceanic crust could still be thousands of meters below the hole. Future scientific ocean drilling and the deepening of Hole 1256D is required to characterize the true nature of the Layer 2–3 "basalt to gabbro" seismic transition at Site 1256.

IODP Site U1415: Hess Deep

IODP Hess Deep Expedition 345 in 2012/2013 was designed to sample lower crustal primitive gabbroic rocks that formed at the fast-spreading East Pacific Rise (EPR) in order to test models of magmatic accretion and the intensity of hydrothermal cooling at depth (Gillis et al., 2014a, 2014b). The Hess Deep rift zone in the equatorial Pacific Ocean formed by deep lithospheric extension in front of the westward-propagating Cocos-Nazca spreading center, exposing oceanic crust that formed at the fast-spreading (130 mm yr^{-1}) EPR (Gilles et al., 2014a). This site is unique in that it is the only place where the lower crust and the upper crust have been extensively sampled by submersible or remotely operated vehicle (ROV) as well as drilling, by ODP Leg 147 (Gillis et al., 1993). Previous studies of known seafloor exposures of lower plutonic rocks have suggested that layering exists in the gabbroic section.

IODP Site U1415 recovered primitive olivine gabbros and troctolites (a pyroxene-depleted version of gabbro) at one 35 m deep hole (U1415I) and two ~110 m deep holes (U1415J and U1415P shown in Figures 1 and 2) located within 100 m of each other (Gilles et al., 2014b). The cores recovered at Site U1415 can be placed more than 2 km beneath the sheeted dike-plutonic transition and thus may represent the lower plutonic half of the EPR fast-spreading crust (Gilles et al., 2014a). The abundance of layering in the material recovered from Site U1415, along with the absence of other intermixed, more evolved lithologies, distinguishes the lower gabbroic crust at Hess Deep from crustal sections recovered from other ODP-IODP expeditions to slow-spreading ridges. These observations support previous models that invoke strong spreading rate and thermal control on magma chamber processes at mid-ocean ridges; however, the style of layering and banding, as well as the observed lithologies, differ from the mid-ocean ridge basalt-like Oman ophiolite, which has been used as a fast-spreading-ridge analogue and informed the initial Penrose model (Figure 3; Gillis et al., 2014a). IODP Hess Deep Expedition 345 thus provides a reference section for primitive fast-spreading lower crust that did not previously exist. This highlights the need for scientific ocean drilling to address questions related to the origin, evolution, and heterogeneity of the lower oceanic crust.

DEEP DRILLING IN SLOW-SPREAD CRUST AND OCEANIC CORE COMPLEXES

It is well known from dredging and ROV sampling that a continuous gabbroic layer does not exist at slow-spreading ridges and at tectonically formed oceanic core complexes exposed in these slow spreading environments (e.g., Whitehead et al., 1984; Mutter et al., 1985; McCarthy et al., 1988; Dick, 1989; Cannat, 1993; Tucholke and Lin, 1994). Moreover, the abundance of serpentinized peridotite in dredge hauls from rift valley and fracture zone walls (Aumento and Loubat, 1971; Thompson and Melson, 1972; Fisher et al., 1986; Dick, 1989; Cannat, 1993) raised the possibility that serpentinization can be a significant component of seismic Layer 3 "gabbros" in these settings (Figure 3), as originally suggested by Hess (1962). Without scientific ocean drilling, no truly representative section of seismic Layer 3 (which may not be the same everywhere) is likely to be obtained in situ in these oceanic slow spreading settings and core complexes, leaving its composition, state of alteration, and internal structure almost entirely a matter of inference.

ODP Hole 735B: Atlantis II Fracture Zone

In 1997, ODP drilled Hole 735B through a 1,508 m section of coarse gabbro in tectonically exposed lower crust on a wave-cut platform that flanks the Atlantis II Fracture Zone on the slow-spreading Southwest Indian Ridge (Figures 1 and 2). The sequence of rocks sampled in Hole 735B (Figure 5) is unlike that in a Penrose-type ophiolite, in Hess Deep, or in layered intrusions found on land. Some of its attributes, including the lack of well-developed layering, and the presence of small 100 m to 500 m intrusions, are similar to the typical structural characteristics of ophiolites believed to have formed in slow-spreading environments, such as the Trinity or Josephine ophiolites, although these on-land ophiolite sequences are believed to be incomplete (Dick et al., 1999). The results from Hole 735B documented a systematic variation in igneous petrology, structure, and alteration with depth, unlike that expected in crust formed in association with large magma chambers or even melt lenses now inferred to exist beneath fast-spreading ridges (Dick et al., 1999). They provide a first assessment of synkinematic igneous differentiation in which the upper levels of the gabbroic crust are enriched in late differentiated melts by means of tectonic processes, rather than the simple gravitationally driven crystallization differentiation often seen in layered intrusions of large terrestrial magma chambers.

ODP Legs 109 and 209: Mid-Atlantic Ridge Rift Valleys

ODP Leg 109, Site 670, on the west wall of the Mid-Atlantic Ridge median valley near 23°10'N targeted the lowermost oceanic crust, and for the first time drilled and sampled serpentinized mantle peridotites (Bryan et al., 1988). In the same area, south of the Kane Fracture Zone, a total of 95 m of serpentinized peridotites were recovered from a 200 m deep hole at Site 920, ODP Leg 153 (Figures 1 and 2; Cannat et al., 1995). Together, these two ODP expeditions demonstrated that the internal stratigraphy of the lower oceanic crust at slow-spreading ridges is governed as much by the dynamic processes of alteration and tectonics as by igneous processes. More recently, ODP Leg 209 (Sites 1268–1275; Figures 1 and 2) returned to drill in the peridotite-rich area around the 15°20'N fracture zone and revealed that the upper oceanic lithosphere in this slow-spreading setting is primarily composed of peridotite and gabbro and that the seafloor is inundated with uncovered fault surfaces (Kelemen et al., 2004). This leads to the conclusion that mantle denudation and plate spreading are accommodated by a combination of high-displacement, low-angle (so-called "rolling hinge") normal faults that lead to the formation of oceanic core complexes and secondary lower-displacement normal faults (Schroeder et al., 2007) that in turn expose the observed ultramafic basement rocks.

IODP Expeditions 304, 305, and 357: Atlantic Massif Ocean Core Complex

IODP Expeditions 304, 305, and 357 specifically targeted those types of denuded fault surfaces and a related ocean core complex, the Atlantis Massif at 30°N, which is located at the inside corner of the intersection between the Mid-Atlantic Ridge (MAR) and the Atlantis Fracture zone. Two holes were drilled during IODP Expeditions 304 and 305 at Site U1309 (Figures 1 and 2) into the footwall of the detachment fault (Blackman et al., 2006, 2011). This work was continued during IODP Expedition 357, which drilled a series of shallow holes into the Lost City hydrothermal field using seabed rockdrills (Früh-Green et al., 2016). Based on the common occurrence of serpentinized mantle peridotite along the south flank of the southern ridge as well as geophysical studies (e.g., Blackman et al., 1998, 2002), fresh mantle peridotite was predicted to occur at reasonably shallow depths (~800 mbsf), allowing drilling to access samples of the mantle for the first time (Canales et al., 2004; Blackman et al., 2011). In stark contrast to geophysical predictions, Hole U1309D sampled a 1,415 m long section of gabbroic rocks in the Central Dome core of the Atlantis Massif, with 75% recovery, but no peridotitic lithologies were encountered (Figure 5). Paleomagnetic data obtained from the IODP core samples indicated that the footwall of the detachment fault

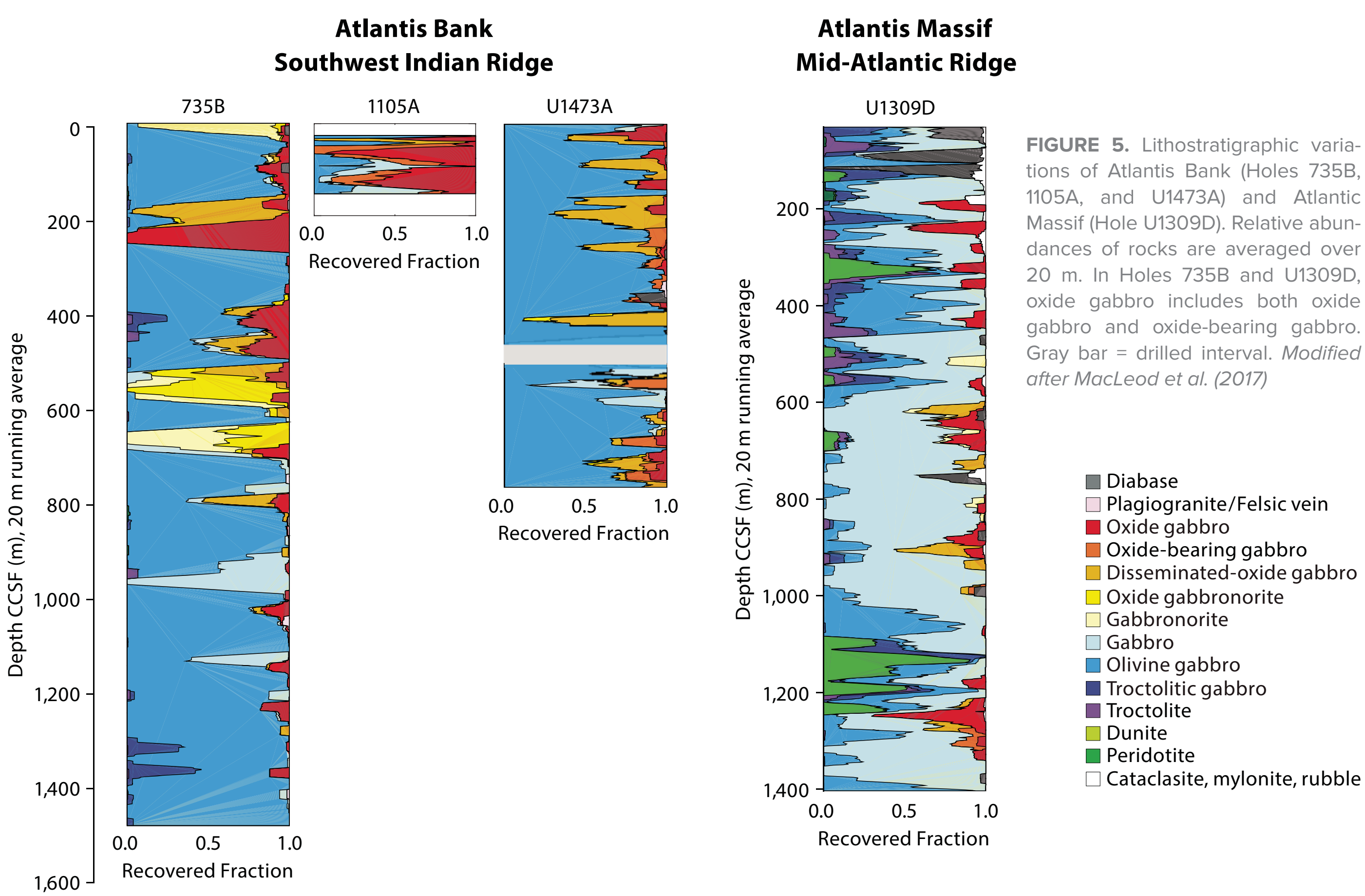


FIGURE 5. Lithostratigraphic variations of Atlantis Bank (Holes 735B, 1105A, and U1473A) and Atlantic Massif (Hole U1309D). Relative abundances of rocks are averaged over 20 m. In Holes 735B and U1309D, oxide gabbro includes both oxide gabbro and oxide-bearing gabbro. Gray bar = drilled interval. *Modified after MacLeod et al. (2017)*

rotated at least 45° around a MAR-parallel horizontal axis (Morris et al., 2009; Blackman et al., 2011), consistent with the "rolling hinge" model (e.g., Wernicke and Axen, 1988; Buck, 1988).

Only three thin (<1 m) intervals of ultramafic rocks, interpreted as residual mantle peridotites, were encountered, and they were intercalated within gabbroic rocks in the upper 225 m of the section (Tamura et al., 2008) in Holes U1309B and U1309D. If the small amount of serpentinized peridotite recovered from Hole U1309D is representative of the bulk makeup of Atlantis Massif, the potential of a bulk expansion during the serpentinization of such altered peridotite is not likely to contribute significantly to the uplift of the Central Dome (Blackman et al., 2011). It is interesting to note that the 16 holes drilled by ODP and IODP into the footwall have reached four different oceanic core complexes, including the Atlantis Massif, and gabbroic sections were encountered exclusively at all holes. These findings indicate that the domal morphology of the core complexes results from the exhumation and unroofing of large gabbroic plutons by the associated detachment faults (e.g., Ildefonse et al., 2007a). Future scientific ocean drilling into both in situ slow-spreading oceanic crust and related oceanic core complexes is needed (1) to fully understand the relationship between tectonics and magmatism in oceanic crust formation, (2) to determine the importance of serpentinization in the lower oceanic crust and upper mantle, and (3) to fully grasp how serpentinization affects the seismic character of the oceanic lithosphere and the nature of the Moho.

MOHO TO MANTLE—FUTURE AND ONGOING DRILLING EFFORTS

Despite the successes of drilling into oceanic crust formed at both fast- and slow-spreading centers, drilling through the Moho and into the upper mantle remains a long-term aspiration, dating to the first Project Mohole operations in 1961. The Mohole-to-Mantle (M2M) proposal (Umino et al., 2012) re-articulated the major planetary science goals that could be achieved by sampling in situ upper mantle peridotite and investigating the nature of the Mohorovičić seismic discontinuity using the riser drilling vessel *Chikyu*. This ambition remains a flagship proposal for future *Chikyu* drilling and would require penetrating at least ~6,000 m of igneous oceanic crust formed at a fast-spreading ridge and an additional ~500 m into the oceanic upper mantle.

To determine the best site for M2M drilling, a large number of factors must be considered (Ildefonse et al., 2010). Any appropriate site should be in the shallowest possible water depths, implying close proximity to the axis of an active fast-spreading mid-ocean ridge. On the other hand, the hole should also be in the coldest possible oceanic lithosphere, implying mature oceanic crust and thus located a significant distance away from an active fast spreading ridge. Balancing those two opposing constraints limits potential M2M sites to three areas off the coasts of Hawaii, Baja California, and Costa Rica (Figure 6; Teagle and Ildefonse, 2011). All potential sites are in the Pacific because the oceanic crust there was created faster than in other ocean basins. As described above, seismic and geologic studies indicate that fast-spreading oceanic crust is relatively uniform and conforms most closely to the end-member Penrose model (Figure 3), making those sites ideal and possibly most representative of the general processes of ocean crust formation. Although a site survey was conducted off the coast of Hawaii in 2017 (Ohira et al., 2018) and funding for future site surveys on the Cocos Plate have been secured, realization of project Mohole continues to require a major funding commitment and political and scientific will. While preparing for eventual M2M drilling, any other scientific ocean drilling expedition, specifically at sites where the Moho is apparently shallower, may provide further insight into ocean crust architecture, the role of serpentinization, and the significance of the seismic Layer 2-3 and Moho boundaries.

IODP Expedition 360 was the first leg of Phase I of SloMo (shorthand for "The Nature of the Lower Crust and Moho

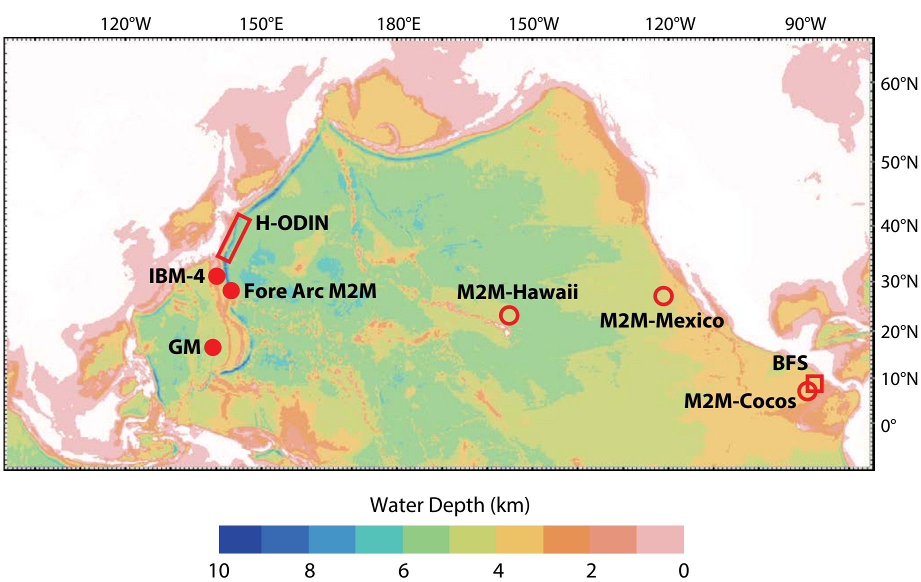


FIGURE 6. Bathymetric map of the Pacific Ocean showing the locations of potential drilling sites for IODP proposals using the riser drilling vessel *Chikyu*: the Mohole to Mantle (M2M) drilling projects (Umino et al., 2012; open circles), bending-fault hydrology of the old incoming plate (H-ODIN; rectangle; Morishita et al., 2015), bending-fault serpentinization (BFS; square; Morgan et al., 2014), direct sampling of forearc peridotite (Fore Arc M2M; solid circle; Michibayashi et al., 2016), Godzilla Megamullion (GM; solid circle; Ohara et al., 2018), and the middle crust in the continent (IBM-4; solid circle; Tatsumi et al., 2010). *Modified after Morishita (2017)*

at Slower Spreading Ridges"), a multiphase drilling project that proposes to drill through the Moho at Atlantis Bank at the ultraslow-spreading Southwest Indian Ridge (MacLeod et al., 2017). By penetrating this fundamental seismological boundary, SloMo is testing the hypothesis that the Moho, at this locality in particular and at slow- and ultraslow-spreading ridges in general, may represent an alteration boundary due to serpentinization within the upper mantle, rather than an igneous crust-mantle transition or a hard physical boundary. If the Moho represents the former and thus is a serpentinization front, the igneous crust/mantle boundary could lie at any depth above the seismic boundary (MacLeod et al., 2017).

IODP Hole U1473A (Figure 2) was drilled on the summit of Atlantis Bank during Expedition 360, 1–2 km away from two previous ODP holes: Hole 735B drilled during ODP Leg 118 in 1987 (Dick et al., 1999; 2000) and Hole 1105A drilled during ODP Leg 179 in 1998 (Casey et al., 2007). While exploring the lateral variability of the stratigraphy in comparison with Holes 735B and 1105A (Figure 5), the principal aim of Expedition 360 was to drill as deep as possible through lower crustal gabbro and leave a hole open and ready to be deepened during a second expedition. A target depth of 1,300 mbsf was estimated, derived from prior experience of drilling conditions at Atlantis Bank; however, Hole 1473A was only drilled to 789.7 mbsf and terminated in massive gabbro cut by isolated dikes (Figures 2 and 5; MacLeod et al., 2017). SloMo next will attempt to reoccupy and deepen the hole with the overall goal of penetrating the crust-mantle transition, which is believed to be as much as ~2.5 km above the Moho; additional drilling, potentially using the riser vessel *Chikyu*, is likely to be necessary to penetrate the Moho itself, at ~5 km below the seafloor (MacLeod et al., 2017).

Another approach to sampling upper mantle materials is to drill and core fresh lower igneous crust and the underlying uppermost mantle peridotite, as accreted during the initiation of a subduction zone. A prime IODP focus has been the study of subduction initiated around ~52–48 million years ago at the Izu-Bonin-Mariana trench (e.g., Ishizuoka et al., 2011; Reagan et al., 2017, 2019; see also Arculus et al., 2019, in this issue), where gabbroic and ultramafic rocks are exposed on the landward slope of the Bonin Trench in the Northwest Pacific (Figure 6). Drilling at this location provides future opportunities to realize a key objective of the M2M mantle drilling (Michibayashi et al., 2016) that differs fundamentally from the M2M itself and SloMo, which both focus on the formation of the oceanic crust during seafloor spreading.

CONCLUDING REMARKS

For 50 years, scientific ocean drilling has contributed significantly to our understanding of the variability in the architecture of oceanic lithosphere. The style of accretion critically depends on the balance between magma production, hydrothermal cooling, and tectonics, which to a first order is related to spreading rate. Seismic, bathymetric, and marine geological observations indicate that oceanic crust formed at fast spreading rates (with full rates >80 mm yr^{-1}) has a relatively constant architecture, compared to crust formed at slow to ultra-slow spreading rates (<40 mm yr^{-1}), and is similar to the Penrose model for ophiolites (Ildefonse et al., 2014). Scientific ocean drilling at ultra-slow spreading centers and at oceanic core complexes has shown that their crustal architectures are very different and that serpentinization likely plays a prominent role in changing the nature of those crustal sections. Deeper drilling efforts to penetrate the core-mantle boundary and the Moho remain the missing piece of the puzzle to help us advance our understanding of ocean crust formation and mantle dynamics. For the upcoming next generation ocean drilling scientists, we end with the following quote by Bahcall (1990): "I believe that the most important discoveries will provide answers to questions that we do not yet know how to ask and will concern objects that we can not yet imagine."

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WHEN HOTSPOTS MOVE

The New View of Mantle Dynamics Made Possible by Scientific Ocean Drilling

By John A. Tarduno and Anthony A.P. Koppers

ABSTRACT. Hotspots tracks—chains of volcanic edifices arising from deep mantle upwellings—were once thought to solely record plate motion. Results of ocean drilling expeditions have led to a transformative change: it is now recognized that these tracks can also reflect the motion of hotspots in Earth's mantle. When hotspots move, their paths can provide insight into the nature of the mantle and the history of convection.

INTRODUCTION

Morgan (1972) surmised that hotspots (Wilson, 1963) were fixed in the deep mantle and hence were suitable as a frame of reference for the motion of tectonic plates. The Hawaiian-Emperor chain was central to this hypothesis. The great 60° bend in the track was the type example of a change in plate motion preserved by a hotspot chain. This simple model was so elegant and powerful that it became a mainstay of introductory textbooks for decades.

Paleomagnetism has inherent capabilities to record paleolatitude and thus can provide critical data to test the fixed hotspot hypothesis. If a hotspot has always been fixed, the volcanic edifices composing an age progressive chain should all record the same latitude, equaling the present-day hotspot location. Yet, to obtain suitable samples requires scientific ocean drilling because the critical volcanic edifices needed for the test have now subsided to great water depths.

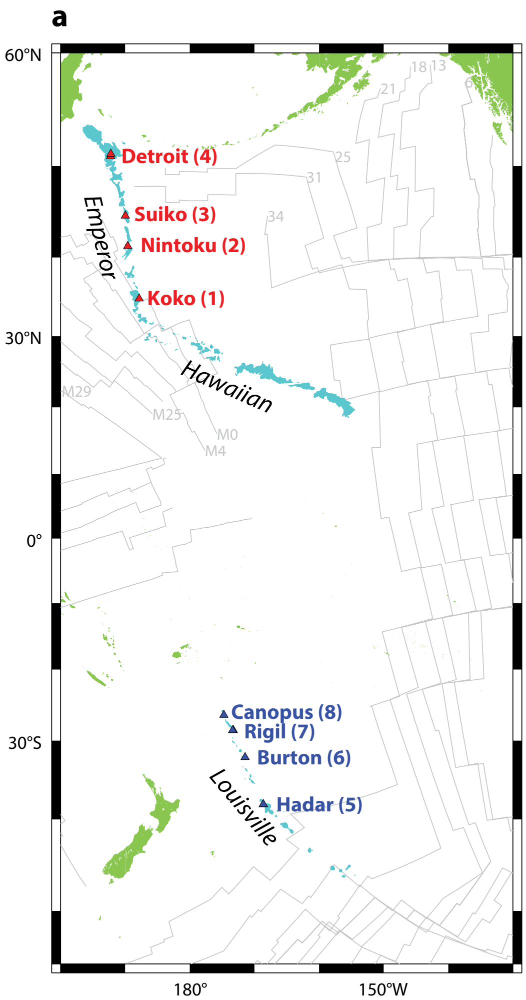
PALEOLATITUDE TESTING OF HAWAII HOTSPOT FIXITY

Ocean Drilling Program Leg 197 in 2001 was the first expedition solely devoted to a paleomagnetic test of hotspot fixity. Through the drilling of seamounts comprising the Emperor track, a trend of decreasing paleolatitude with age was observed (Tarduno et al., 2003). The data are most compatible with southward motion of the hotspot at a rate of ~44 mm yr^{-1} (Figure 1). The Leg 197 results did not just shatter the concept of hotspot fixity. They also suggested that most of the north-south morphology of the Emperor Seamounts was created by hotspot motion (Tarduno et al., 2009). If one subtracts this motion, the great Hawaiian-Emperor bend becomes a minor feature (Figure 2), similar to other wiggles in the chain at times of known plate motion change (Wright et al., 2016). However, based on scientific ocean drilling, we now understand that the bend represents a major change in mantle dynamics, from a rapidly to a more slowly moving hotspot. This realization motivated several additional questions. Had the Pacific hotspots moved as a group? Were local forces involved in driving Hawaiian hotspot motion?

TESTING INTER-HOTSPOT MOTION

Integrated Ocean Drilling Program Expedition 330 investigated the scale of motion in 2010/2011 by drilling the Louisville chain on the southern Pacific Plate. In contrast to the results from Leg 197, age and paleolatitude data showed limited latitudinal motion of the hotspot (Figure 1), establishing that the Hawaii and Louisville hotspots had moved independently (Koppers, et al., 2012). Because the common motion is minor between ~70 and 50 million years ago, these data support global analyses indicating that true polar wander, the rotation of the entire solid Earth, has also been minor (Tarduno, 2007). Moreover, the limited Louisville motion provided the opportunity for another test.

If the Hawaiian hotspot had moved rapidly in Earth's mantle, while Louisville's motion was more limited, we should see a pattern of decreasing distances between seamounts of the same age on the two hotspot tracks with time, because the Hawaiian hotspot moved south and closer to Louisville. Recent advances in radiometric age dating show exactly this pattern (Konrad et al., 2018). Interestingly,



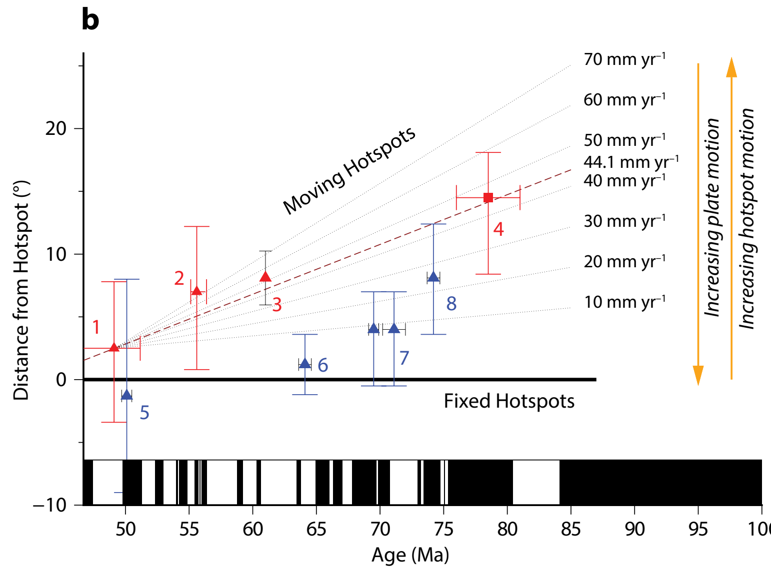


FIGURE 1. Ocean drilling tests of hotspot motion. (a) Hawaiian-Emperor and Louisville Chain seamount and guyot drill sites. (b) Difference between present-day hotspot latitude and paleolatitude determined from paleomagnetic analyses. Results for Hawaiian-Emperor Seamounts from Ocean Drilling Program Leg 197 together with data collected on samples recovered from drilling during Deep Sea Drilling Project Leg 55 and Ocean Drilling Program Leg 145 (in red; see Tarduno et al., 2003, and references therein). Results for Louisville Seamounts from Integrated Ocean Drilling Program Expedition 330 (in blue; Koppers et al., 2012). If hotspots were fixed, paleolatitudes should cluster around the 0° distance line (fixed hotspots). Instead, data indicate rapid movement of the Hawaiian hotspot and more limited motion of the Louisville hotspot.

these data suggest the prior estimate of motion may be conservative. The age-distance data suggest motion rates as high as 60 mm yr^{-1}. We note that this motion also provides a long-sought explanation for geochemical trends seen in the lavas from the Emperor and Hawaiian volcanic chains (Harrison et al., 2017).

GEODYNAMIC IMPLICATIONS

What could have driven this rapid Hawaiian hotspot motion and then led to its cessation? Two mechanisms, which are not mutually exclusive, are current contenders. One explanation invokes "top-down" control. Spreading ridges can migrate across ocean basins and are focused areas of mantle flow that can affect the upwelling pathways of mantle plumes that feed hotspots. Geochemical and paleolatitude data indicate that early in its history the Hawaiian hotspot was situated on a spreading center (Keller et al., 2000; Tarduno et al., 2003, 2009). That spreading waned with time and stopped near the time of the Hawaiian-Emperor bend. The spreading center upwelling could have captured the plume early in its history. As the ridge upwelling diminished, the plume conduit may have returned to a more vertical geometry, resulting in the hotspot motion pattern detected on the surface. Numerical simulations and experimental analogs suggest this is possible (Bunge et al, 1997; Tarduno et al., 2009).

The second explanation invokes a "bottom-up" control. For decades it has been clear that a broad region of deep mantle that is anomalously hot and/or dense underlies the Pacific basin (Tarduno et al., 2009; Garnero et al., 2016). Today, this is called the Pacific Large Low Shear Velocity Province (LLSVP). Could interaction of the Hawaiian plume with the Pacific LLSVP, including deformation of the edges of this province by subducting slabs, have caused the rapid hotspot motion and then a slowdown? Numerical models again suggest this is a viable option (Hassan et al., 2016) and again the geochemical trends support this interpretation (Harrison et al., 2017).

SUMMARY AND FUTURE OBJECTIVES

These new ideas on both top-down and bottom-up geodynamics could not have been possible without evidence collected by scientific ocean drilling. The new data have been transformative, allowing us to see beyond the limited view of fixed hotspots to the actual complexity of mantle convection. Hotspots can move, and when they do, they can move as fast as tectonic plates. Studies using

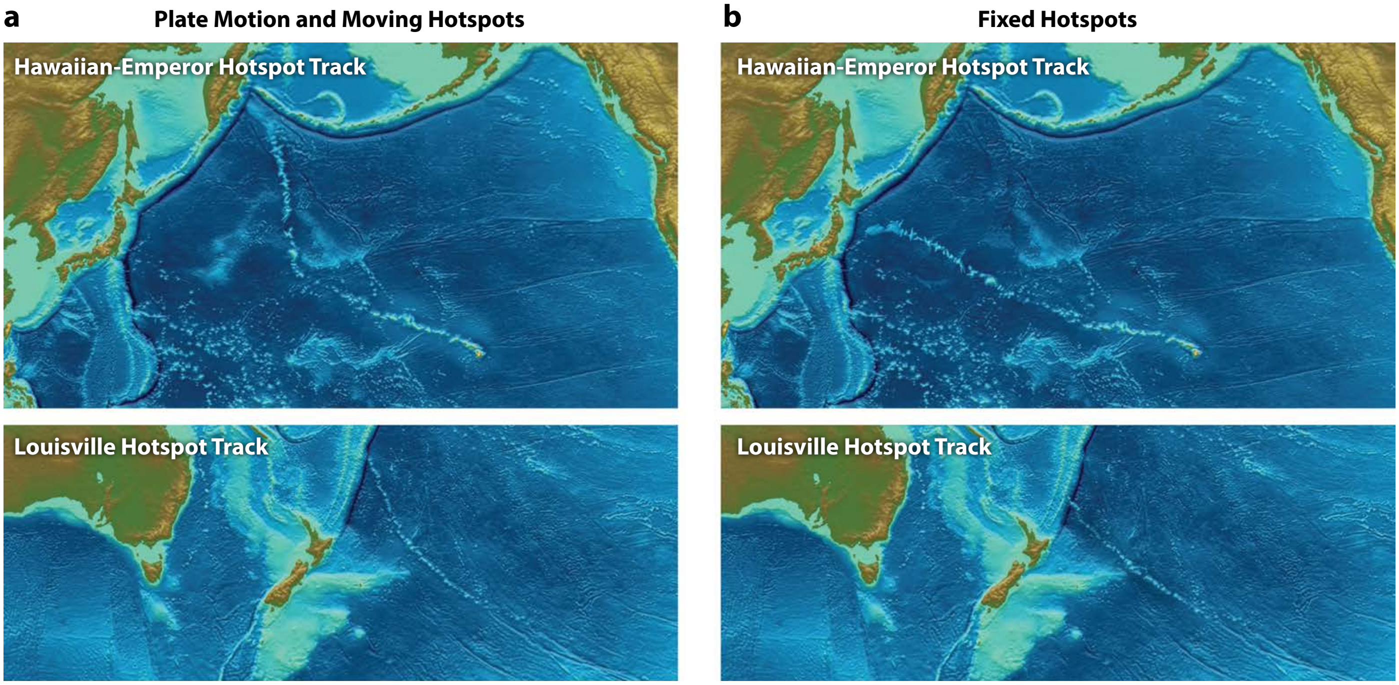


FIGURE 2. Moving versus fixed hotspot tracks. (a) Present-day Hawaiian-Emperor and Louisville hotspot tracks produced by plate motion and moving hotspots. (b) Hotspots tracks that would have been created had the hotspots remained fixed in Earth's mantle, compatible with ocean drilling paleomagnetic data (see Tarduno et al., 2003, and Koppers et al., 2012).

data collected by scientific ocean drilling remain the best means of reconstructing processes that have shaped the oceanic deep mantle over the last 200 million years. The next challenge will be to recover long sequences of lavas in order to construct high-resolution paleolatitude histories (Tarduno et al., 2003) for select sites in other global seamount chains, as well as for submarine volcanic plateaus. These samples are required to further increase the precision of paleolatitude constraints that will allow us to learn even more about Earth's deep interior and overriding lithospheric plates.

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Starting a New Ocean and Stopping It

By Chun-Feng Li, Peter D. Clift, Zhen Sun, and Hans Christian Larsen

ABSTRACT. Small marginal sea basins are often short-lived and typically not older than several to tens of million years, but they play critical roles in global plate tectonic cycles. This paper highlights some recent achievements in answering a range of geodynamic questions stemming from scientific ocean drilling by International Ocean Discovery Program Expeditions 349, 367, 368, and 368X in the South China Sea. Together, results from these expeditions provide new insights into continental breakup in terms of the opening style and time of spreading cessation, magmatism, and sedimentation during the formation of this marginal basin. The outcomes of these expeditions have revealed new challenges and spawned new hypotheses in mantle dynamics and crustal accretion that need to be addressed by future drilling on carefully identified drill targets in the tectonically active western Pacific.

EXTENSION IN A LARGE-SCALE SUBDUCTION REGIME

Beginning in the Mesozoic, subduction of the Paleo-Pacific Plate and the India-Australia Plate in the western Pacific and Southeast Asia, respectively, has left us the largest subduction graveyard to be found worldwide (e.g., C. Li and van der Hilst, 2010). At subduction zones, slab retreat and roll back as well as trench suction are believed to be responsible for the development of many of the region's marginal basins (e.g., Hall et al., 2003; Schellart et al., 2003). However, the mechanism that initiated the opening of the South China Sea basin (SCS) has been much debated because the SCS does not appear to be a typical back-arc basin, but rather may have been formed either by the tectonic extrusion of Indochina triggered by the India-Eurasia collision (e.g., Tapponnier et al., 1982; Briais et al., 1993; Flower et al., 2001) or by the active southeastward slab-pull force in a nearby subduction zone of the proto-SCS. This older basin existed to the south of the present-day SCS. In the latter case, the driving forces for the opening of the SCS may have been similar to those active during the opening of the Tethys Sea, where the closure of an older basin was accompanied by the opening a new one nearby (e.g., Metcalfe, 2013). Recent International Ocean Discovery Program (IODP) Expeditions 349, 367, 368, and 368X did not directly address the mechanisms that triggered SCS development. Instead, these expeditions provided critical constraints on the crustal ages and structures within the continent-to-ocean transition zone, which can help answer fundamental questions concerning the driving forces behind marginal basin opening (C.F. Li et al., 2015; Sun et al., 2018).

SHORT-LIVED MARGINAL BASINS

Unlike in the large open ocean basins, seafloor spreading in the small western Pacific marginal basins occurs over relatively short time periods, mostly over a few tens of millions of years. These short time periods reflect frequent changes in tectonic regimes in a region that is characterized by multiple subduction zones and the complex interplay of numerous plates of various sizes. Subduction is a major factor in marginal basin development because while initiation of a subduction zone can cause back-arc extension, it also alters the regional tectonic stress field, which can terminate seafloor spreading. This scenario might apply to the SCS, where the termination of spreading likely coincided with the initiation of subduction along the Manila Trench to the east (e.g., Hayes and Lewis, 1985). Subduction at the Manila Trench is rather unique, where a very young SCS oceanic lithosphere is being subducted under the relatively old Philippine Sea Plate. Here, it is hypothesized (e.g., J. Li et al., 2004) that the westward movement of the older Philippine Sea Plate, rather than the slab pull force of the younger SCS slab, drove its active obduction over the younger SCS plate. Alternatively, cessation of seafloor spreading in the SCS may be linked to the final southeastward subduction of the proto-SCS under Borneo and the collision of the southern continental margin (Dangerous Grounds) terrane with the trench at that time (e.g., Holloway, 1982; Hutchison, 2004). These complex plate boundary configurations and processes remain poorly understood. The SCS offers an ideal laboratory for testing hypotheses for marginal basin initiation and improving understanding of marginal basin evolution worldwide through the application of scientific ocean drilling.

TESTING MODELS OF CONTINENTAL BREAKUP, OPENING STYLES, AND MARGIN CONJUGATION

Despite its small size, the SCS offers a remarkable diversity of continental margin structures, from wide extended continental margins to the west to very narrow ones to the east. This lateral variability in margin structures coincides with sharp changes in the physical and chemical characteristics of the oceanic lithosphere in the central basin (C.F. Li et al., 2008, 2015). IODP Expeditions 367, 368, and 368X were designed to test how the continent-ocean transition in the SCS differs from classical Atlantic-type volcanic rifted margin models (Larsen et al., 2018; Sun et al., 2018). The small size of the SCS also facilitates comparison of extension structures of the two conjugate margins.

MANTLE DYNAMICS, CRUSTAL ACCRETION, AND MAGMATISM

IODP Expedition 349 recovered mid-ocean ridge basalts and volcaniclastic sediments that are critical to understanding the previously poorly known SCS mantle geochemistry and dynamics (C.F. Li et al., 2015). Carbonated silicate melt, which had only been predicted by experimental studies, was first reported in the SCS (Zhang et al., 2017). Experiments conducted on volcanic rocks recovered during IODP Expedition 349 indicate that a CO_2-rich silicate melt evolved continuously to an alkali basalt that erupted during the later stages of seamount magmatism and was emplaced near the extinct spreading axis in the Late Miocene (Zhang et al., 2017). Distinct trace element and isotope ratios in the volcanic rocks also indicate differences in mantle sources between the southwest and the east sub-basins in the SCS, which are also characterized by a sharp contrast in magnetic anomalies (C.F. Li et al., 2008; Zhang et al., 2017).

Finally, fulfilling the early proposed goals of IODP Expeditions 349, 367, and 368, IODP Expedition 368X in 2018 successfully drilled through the thick sedimentary cover in the SCS and cored over 100 m of basaltic basement near the northern continent-ocean boundary. Samples collected there provide an important reference point between the initial breakup basaltic magmas collected by Expeditions 367 and 368 near the northern margin and basement sections previously cored by Expedition 349 in younger parts of the central basin, near the extinct seafloor spreading centers. Altered and fresh basalts recovered at different locations during these four expeditions provide unparalleled evidence concerning how this marginal sea basin evolved from a continental rift to a mature ocean.

Geochemical analysis and $^{40}Ar/^{39}Ar$ dating of oceanic plagiogranite hint that seafloor spreading in the SCS may have initiated prior to 32 million years ago, as early as 38 million years ago (Zhong et al., 2018). This older age could be possible because the opening of the SCS propagated westward, with the onset of seafloor spreading first occurring in the northeast, meaning that magnetic anomalies within this piece of the extended continental crust must reflect later-stage and thus younger post-spreading volcanism (e.g., Song et al., 2017). Future $^{40}Ar/^{39}Ar$ dating of the Expedition 368 and 368X basement basalts will shed further light on the early stages of SCS continental rifting and evolution during initial breakup.

The role of magmatism in the opening of the SCS remains unclear. Some have attributed the opening of the SCS and extensive post-spreading magmatism to the nearby Hainan hotspot (e.g., Fan and Menzies, 1992; Xu et al., 2012), although deepwater syn-rift sediments and lack of seaward-dipping basaltic sequences indicate that this is not a typical volcanic rifted margin (e.g., Clift et al., 2001; Larsen et al., 2018). Middle Miocene mid-ocean ridge basalts recovered by IODP Expedition 349 record progressive mantle enrichment and possibly signal the (later) contribution of the Hainan mantle plume, which also may have contributed to the latest Oligocene/earliest Miocene ridge jump and propagation in the SCS (Yu et al., 2018). The lack of significant depth anomalies across the SCS, however, implies the absence of a major mantle thermal anomaly (Wheeler and White, 2000). The ridge jump event may be coeval with the onset of the opening of the adjacent southwest sub-basin at around 23.6 million years ago (C.F. Li et al., 2015), as well as with a major far-field event that caused a change in the direction of slip along the Red River Fault ~21 million years ago (e.g., Xie et al., 2006; Zhu et al., 2009).

Post-spreading seamount magmatism, demonstrated in many other basins worldwide, could alternatively be triggered by regional extension and decompression melting related to the cooling and shrinking of the oceanic lithosphere (Song et al., 2017). Although the degree of post-spreading extension measured within the SCS ocean floor is overall too restricted to allow the generation of melt above ambient mantle asthenosphere (McKenzie and Bickle, 1988), extension is expected to be more localized along weak zones, such as the extinct spreading center and extended margins, where the local degree of extension and magmatism may be higher (Song et al., 2017). Late-stage post-spreading magmatism tended to be preferentially emplaced along the extinct spreading center, and in narrow zones subparallel to the continent-ocean boundary along the northern margin, often recognized as linear bathymetric highs (Figure 1).

HIGH SEDIMENTATION RATE IN MARGINAL SEAS

It is not surprising that marginal basins such as the SCS have high sedimentation rates compared to the pelagic open ocean, due to the erosional flux from the adjacent continent. High sedimentation rates along the SCS margin and within the deep basin potentially provide high-resolution records that reflect regional tectonic-climate interactions, as well as provenance changes that are linked to variations in the onshore drainage pattern. IODP Expedition 349 recovered abundant carbonate sediments at a scale not expected in the central basin (C.F. Li et al., 2015). This discovery suggests that marginal basins may play a critical role in global carbon recycling by accumulating rapidly deposited carbonates, which are then transported into the mantle at subduction zones that are responsible for the basins' eventual closures (e.g., along the Manila Trench). Further quantification by scientific drilling in similar basins will be needed to assess the budget for Cenozoic sedimentary carbonate subduction (e.g., Clift, 2017).

Cores recovered during IODP

Expeditions 349, 367, and 368 (C.F. Li et al., 2015; Sun et al., 2018) in the central SCS also include reddish clay-rich layers directly above the basaltic basement in early post-spreading sequences. Similar layers were also found in the nearby Sulu Sea. Are the SCS clays identical to Pacific-type red layers deposited under slow depositional rates and high oxidation conditions? Or did they result from chemical exchange between sediments and cooling basalts, or are they somehow related to unstable water conditions during or soon after the formation of the basin? Isotope work at Site U1433 drilled during IODP Expedition 349 indicates that the clays were not purely volcanic-derived but were also mixed with sediment from Indochina (C. Liu et al., 2017). From current IODP coring, we know they were deposited slowly (C.F. Li et al., 2015). Systematic physical, chemical, and biological characterization of the red layers will shed light on an early critical period of evolution of a young oceanic basin.

FUTURE DRILLING IN THE SCS AND OTHER SIMILAR SETTINGS

Diverse tectonic structures and their complex interplay make the Western Pacific the best active tectonic region for testing a wide range of geodynamic hypotheses. Future scientific ocean drilling could contribute critical information by addressing studies of the following subjects in the SCS and other areas:

1. To further constrain the continental breakup process, the southern conjugate margin of the SCS should remain a target for drilling so that we can compare its symmetry with that of the northern SCS margin (Sun et al., 2016). Seismic data suggest the presence of hyper-extended continental crust (Franke et al., 2011; W.N. Liu et al., 2014) and thick syn-rift sediment near the continent-ocean boundary on the southern margin (Song and Li, 2015).
2. Widespread post-spreading magmatism in the SCS needs to be further sampled in order to understand when and how magmatism and the mantle sources evolved over the entire history of this marginal basin. In addition, the spatial variability in SCS mantle sources observed during formation of two sub-basins offers the possibility to better understand regional-scale mantle heterogeneity in a marginal basin setting.

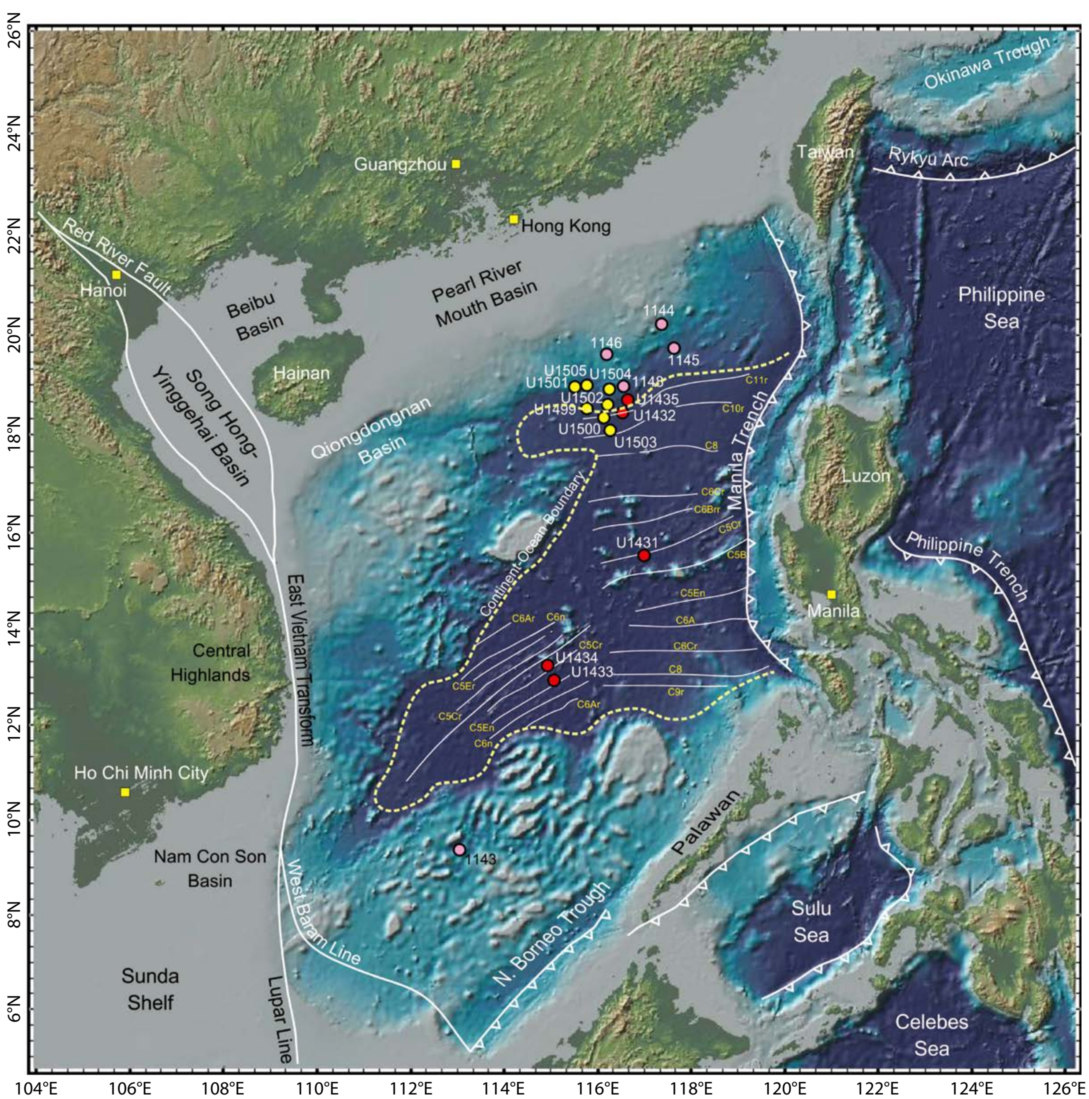

FIGURE 1. Regional geodynamic framework of the South China Sea. Circles mark the drill sites of Ocean Drilling Program Leg 184 (pink), International Ocean Discovery Program (IODP) Expedition 349 (red), and IODP Expeditions 367, 368, and 368X (yellow). The yellow dotted line around the basin marks the continent-ocean boundary. Magnetic isochrons are based on C.F. Li et al. (2014).

3. Similar studies can be carried out in other marginal basins, such as the Caroline Basin, where the nature of various tectonic and volcanic structures, such as intraplate upwellings, juvenile subduction zones, and ridges, along with their links to the nearby Ontong Java large igneous province, are poorly understood.
4. As a partly isolated small ocean basin receiving sediments from the major river systems of Southeast Asia, the SCS has great potential for source-to-sink studies addressing both tectonic and paleo-environmental processes within the last 30 million years.
5. The SCS and adjacent areas are ideal places to study subduction initiation and the development of the early stages of seafloor spreading. Documenting seismogenic behaviors in multiple subduction zones will help us to understand the very wide spectrum of interplate earthquakes.

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SCIENTIFIC DRILLING ACROSS THE SHORELINE

By Sean P.S. Gulick, Kenneth Miller, Peter Keleman, Joanna Morgan, Jean-Noel Proust, and Eiichi Takazawa

ABSTRACT. Shorelines are ephemeral features, yet many science problems cross this ever-moving boundary and require sampling on both its dry and wet sides. The logistics of working on land and at sea are distinct, such that funding agencies in many countries divide their research programs at the shoreline. Similarly, scientific drilling is split between the International Ocean Discovery Program (IODP) in the ocean and the International Continental Scientific Drilling Program (ICDP) on land. Here, we discuss three examples of drilling projects that effectively coordinated activities between IODP and ICDP and highlight the need for increasing cooperation and coordination across the shoreline. We end by casting an eye toward the future of scientific drilling, where truly amphibious projects are now possible.

NEW JERSEY MARGIN

In 2009, IODP-ICDP Expedition 313, New Jersey Shallow Shelf (Mountain et al., 2010) concluded a 20-year planning effort for drilling in shallow water (<100 m) to address sea level changes. It followed onshore drilling by Ocean Drilling Program (ODP) Legs 150X and 174AX and drilling on the outer continental shelf, slope, and rise by ODP Legs 150 and 174A. One goal in moving from ODP to IODP was to be able to drill and log in water depths unattainable with D/V *JOIDES Resolution*, and drilling on the New Jersey shelf provided the first opportunity to unite the work of ICDP and IODP. IODP Expedition 313 used the mission-specific platform (MSP) Liftboat *Kayd* to drill in 35 m of water 45–67 km off the coast of New Jersey. The European Consortium for Ocean Research Drilling (ECORD) contracted the MSP from DOSSEC Exploration Services. Despite challenging borehole conditions that included collapsing sands, a total of 1,311 m of core was recovered at three sites (80% recovery). One of the main objectives of the expedition was to estimate the amplitudes, rates, and mechanisms of sea level change on the eastern United States seaboard. Expedition 313 confirmed the assumption that sequence boundaries are the primary source of impedance contrasts, hence, seismic reflections (Miller et al., 2013a), tested sequence stratigraphic models with core-log-seismic integration (Miller et al., 2013b; Proust et al., 2018), and provided amplitudes of Miocene sea level change, including the influence of mantle dynamic topography (Kominz et al., 2016). Drilling in this New Jersey nearshore setting also identified three groundwater sources: marine seawater, deep-sourced brines, and meteoric freshwater that represents a potential resource for future generations (Lofi et al., 2013; Van Geldern et al., 2013). Integration of nearshore drilling by Expedition 313 with previous onshore and deeper water offshore drilling has established the mid-Atlantic US margin as a natural laboratory for understanding the cause, history, and consequence of sea level change on the sedimentary record and the nearshore distribution of groundwater resources.

CHICXULUB CRATER

In 2016, ECORD conducted IODP-ICDP Expedition 364, Drilling the K-Pg Chicxulub Crater, as an MSP operation aboard Liftboat *Myrtle* (see photo in Spotlight 11) in <20 m water depth. The liftboat was outfitted with an ICDP-provided DOSECC drilling rig to drill into the peak ring of the Chicxulub impact structure (Morgan et al., 2017; Lowery et al., 2019, in this issue). The resultant 835 m of core represented the first offshore drilling into the crater and included basement rocks that were uplifted 8–10 km during crater formation (Morgan et al., 2016; Figure 1). These cores, collected from 500–1,335 meters below the seafloor with almost 100% recovery, were first shipped to Houston to be CT scanned by Weatherford Labs with the data processed by Enthought scientific computing. The cores were then shipped to MARUM, Universität Bremen, for a complete IODP onshore science party analysis from September to October 2016. Science party members for IODP-ICDP Expedition 364 were evenly split between those with IODP experience, those with ICDP knowledge, and those new to scientific drilling, making this expedition not only a resounding success scientifically (Morgan et al., 2016; Christeson et al., 2018; Lowery et al., 2018; Riller et al., 2018) but also a great example of partnership between IODP and ICDP.

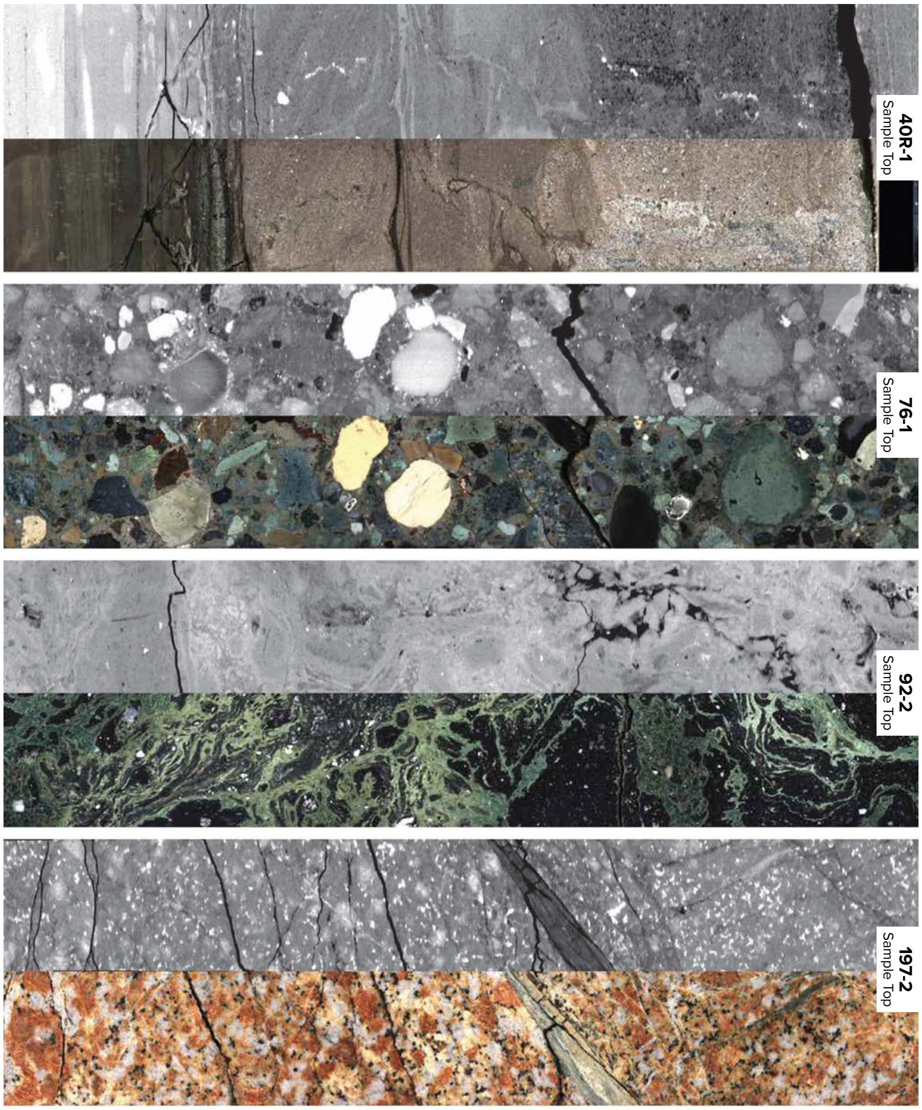

FIGURE 1. Paired images of 1 m long sections of the IODP-ICDP Expedition 364 core. For each pair, a CT scan and photographic line scan image of the same plane through the core is shown. Top to bottom: 40R-1 (618–619 meters below seafloor [mbsf]) shows the top impact breccia (suevite) layer, with evidence of high-energy sand-sized layers with melt particles capped by silt-size carbonate layers containing microfossils; 76-1 (703–704 mbsf) shows suevite with large clasts of the target rock and melt rock; 92-2 (738–739 mbsf) shows impact melt rock (formed at >60 GPa) of two lithologies with schlieren (immiscible) textures; 197-2 (1,018–1,019 mbsf) shows uplifted granitic target rock fractured and deformed during formation of the peak ring of the Chicxulub impact crater, then overprinted by hydrothermal activity.

OMAN DRILLING PROJECT

On-land drilling of Samail ophiolite by the Oman Drilling Project (OmanDP) was undertaken in the two winter seasons of 2016 and 2017 (http://www.omandrilling.ac.uk). OmanDP is an international collaboration involving more than 160 scientists from 30 countries and is supported by ICDP, the Deep Carbon Observatory, the US National Science Foundation, IODP, the Japan Agency for Marine-Earth Science and Technology, and the European, Japanese, German, and Swiss Science Foundations, with in-kind support in Oman from the Ministry of Regional Municipalities and Water Resources, Public Authority of Mining, Sultan Qaboos University, and the German University of Technology. Nine 300–400 m deep holes were drilled (total 3,220 m core) using wireline diamond coring, and six holes of similar depths were drilled using a rotary core barrel (total 3,245 m core) at eight sites with almost 100% core recovery (Figure 2).

Drilling sampled critical sections in the Samail ophiolite stratigraphy, from the dike-gabbro transition and the foliated and layered gabbros (Sites GT1, 2, 3) to the crust-mantle transition, including the Samail paleo-Moho (Sites CM1, 2). Acquisition of such samples had been a long-standing, but unfulfilled, ambition of scientific ocean drilling. In addition, Site BT1 drilled the boundary between the ophiolite and the underlying metamorphic rocks to understand fluid mass transfer and the hydration and carbonation of the upper mantle in an ancient subduction zone. Finally, at Sites BA1 and BA2, drilling has developed a multi-borehole test site in a region where mantle peridotite is undergoing active serpentinization, allowing subsurface hydrogeologic, seismic, and microbiological experiments as well as fluid, gas, and microbial sampling. All drilled cores were transported from Oman to D/V *Chikyu* anchored in the Japanese port of Shimizu. In two Herculean two-month-long campaigns in the summers of 2017 and 2018, the OmanDP cores were described, measured, and analyzed, including complete X-ray CT and infrared scanning. The cores were curated following IODP expedition protocols and the results will be published in IODP-like open-access proceedings of the Oman Drilling Project.

LOOKING TO THE FUTURE

In all three of these examples, drilling was either on land or offshore but with funding or in-kind support provided by the partnering scientific drilling program. Looking ahead, there is now an Amphibious Drilling Project (ADP) policy in place at IODP and ICDP to permit proponents to propose a single expedition to both programs, where the science requires crossing the shoreline. One such ADP proposal is already under evaluation and more are expected. Additionally, major coordinated onshore and offshore efforts are also planned, such as the upcoming Trans-Amazon Scientific Drilling Project that is linked with IODP

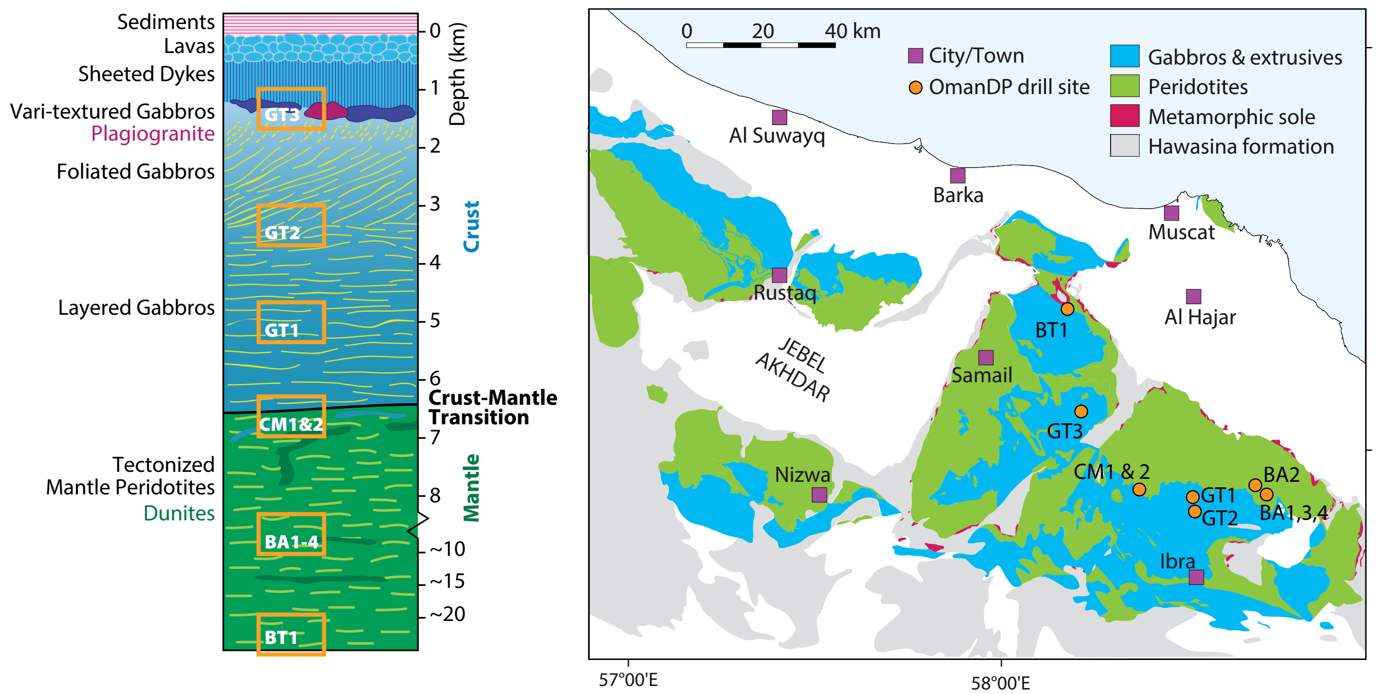

FIGURE 2. Geological map of the southeastern massifs of the Samail ophiolite showing the OmanDP drill site locations and their relative stratigraphic positions. *After Nicolas et al. (2000)*

Expedition 387, Deep Drilling of the Amazon Continental Margin. As discussions are pursued on renewal of IODP into the next decade, post 2023, greater links between IODP and ICDP are being discussed. The successes described above and these future planned drilling projects underline the incredible opportunity for science when we successfully coordinate and cooperate between the vibrant ocean and continental drilling communities.

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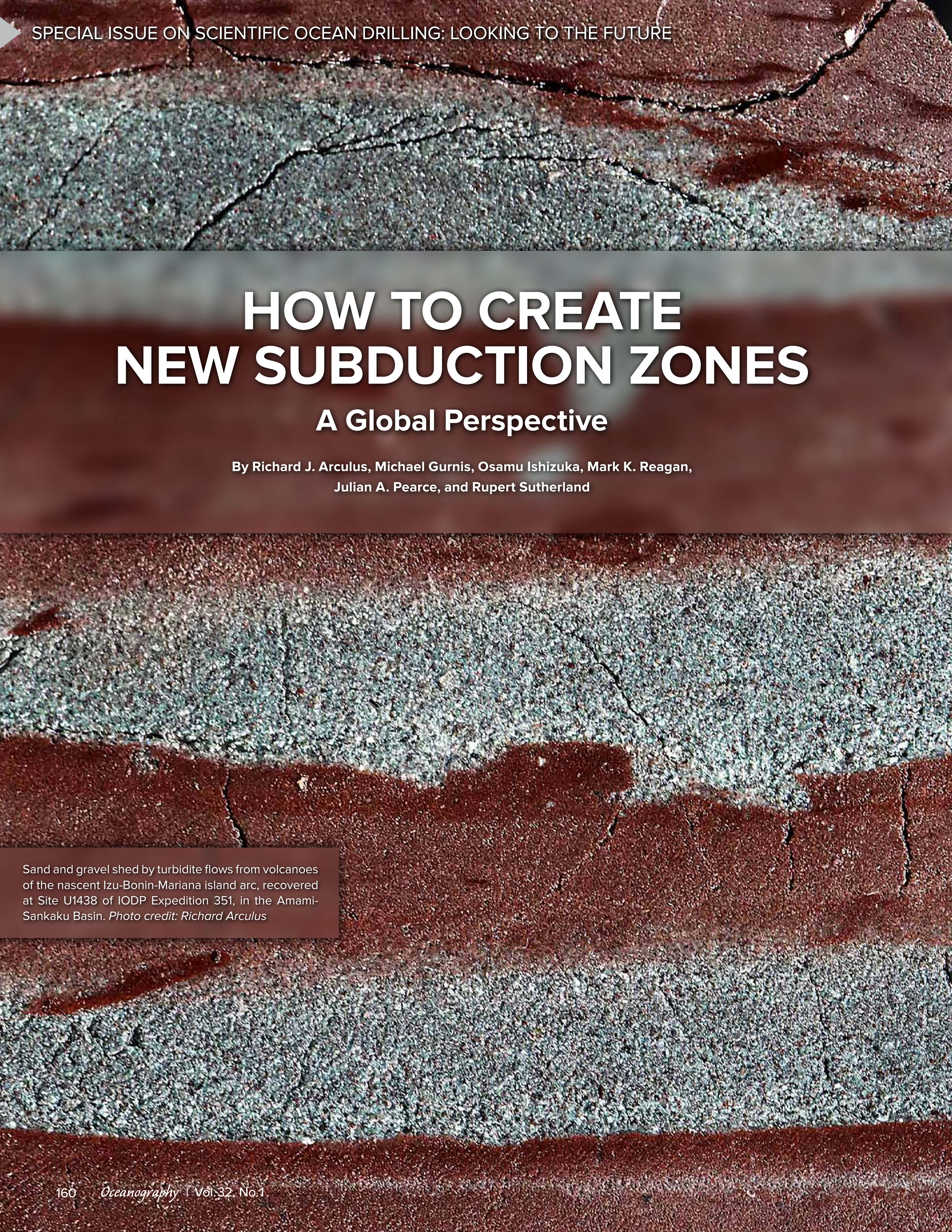
HOW TO CREATE NEW SUBDUCTION ZONES

A Global Perspective

By Richard J. Arculus, Michael Gurnis, Osamu Ishizuka, Mark K. Reagan, Julian A. Pearce, and Rupert Sutherland



Sand and gravel shed by turbidite flows from volcanoes of the nascent Izu-Bonin-Mariana island arc, recovered at Site U1438 of IODP Expedition 351, in the Amami-Sankaku Basin. *Photo credit: Richard Arculus*

ABSTRACT. The association of deep-sea trenches—steeply angled, planar zones where earthquakes occur deep into Earth's interior—and chains, or arcs, of active, explosive volcanoes had been recognized for 90 years prior to the development of plate tectonic theory in the 1960s. Oceanic lithosphere is created at mid-ocean ridge spreading centers and recycled into the mantle at subduction zones, where down-going lithospheric plates dynamically sustain the deep-sea trenches. Study of subduction zone initiation is a challenge because evidence of the processes involved is typically destroyed or buried by later tectonic and crust-forming events. In 2014 and 2017, the International Ocean Discovery Program (IODP) specifically targeted these processes with three back-to-back expeditions to the archetypal Izu-Bonin-Mariana (IBM) intra-oceanic arcs and one expedition to the Tonga-Kermadec (TK) system. Both subduction systems were initiated ~52 million years ago, coincident with a proposed major change of Pacific plate motion. These expeditions explored the tectonism preceding and accompanying subduction initiation and the characteristics of the earliest crust-forming magmatism. Lack of compressive uplift in the overriding plate combined with voluminous basaltic seafloor magmatism in an extensional environment indicates a large component of spontaneous subduction initiation was involved for the IBM. Conversely, a complex range of far-field uplift and depression accompanied the birth of the TK system, indicative of a more distal forcing of subduction initiation. Future scientific ocean drilling is needed to target the three-dimensional aspects of these processes at new converging margins.

INTRODUCTION

In the late nineteenth century, surveying expeditions discovered that there were great depths in the ocean. Their measurements included spot soundings by HMS *Challenger* in 1873 in the Puerto Rico Trench (7,087 m) and in 1875 in the Mariana Trench (8,184 m). The deepest sounding at that time (8,500 m) was reported by Captain George Belknap on USS *Tuscarora*; it marks the first recognition of a linear deep, the Kurile-Kamchatka Trench. By the 1930s and 1940s, it was realized that trenches are associated with all of the volcanic arcs encircling the Pacific, plus those of Indonesia, the Mediterranean, and the Atlantic (Antilles and South Sandwich; Figure 1). The association of these volcanic island chains with ocean deeps, and their positions parallel to one another, had

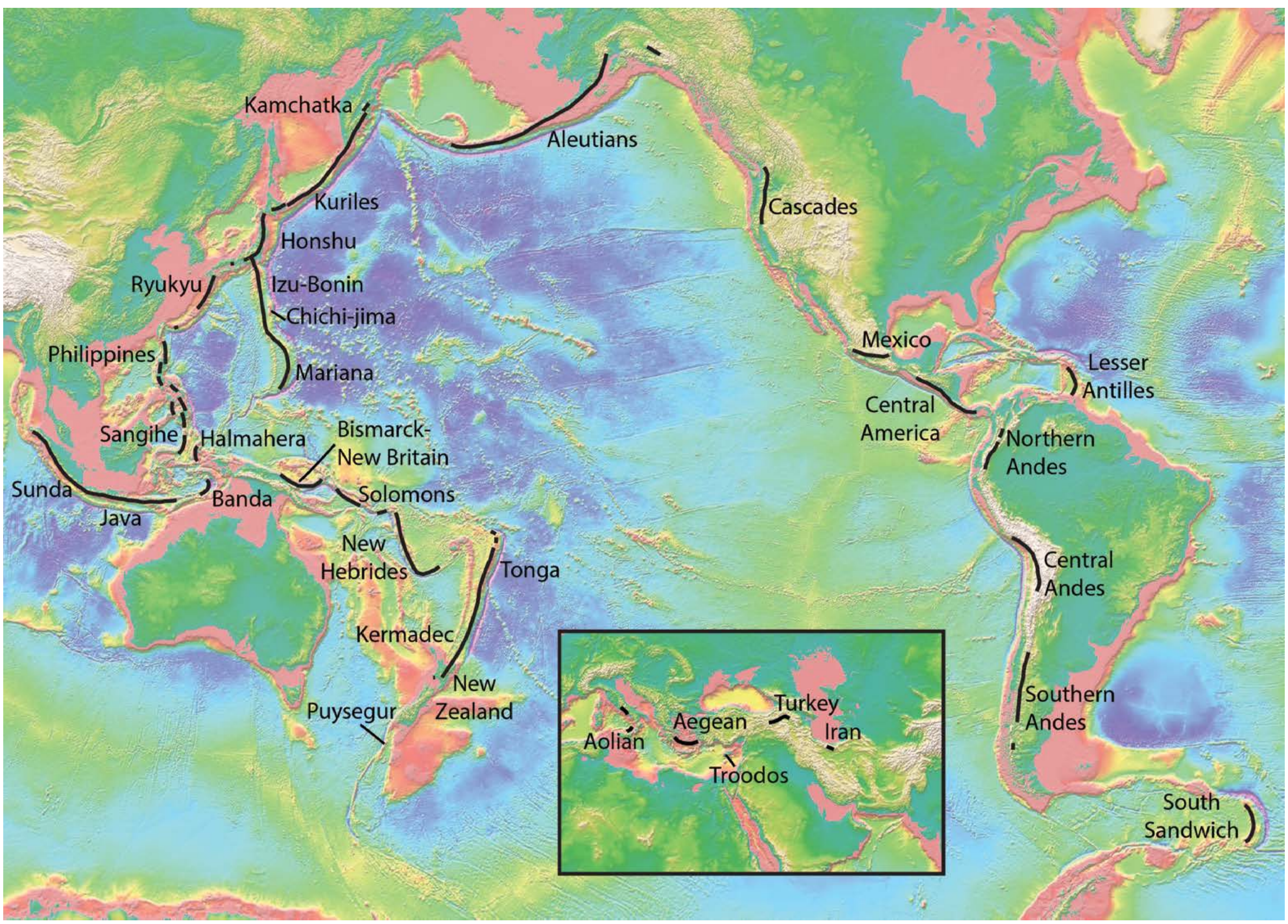


FIGURE 1. Global distribution of island arcs based on the Global Topography base (https://topex.ucsd.edu/marine_topo/). Main panel is centered on the Pacific, with inset showing the Mediterranean and the Middle East.

previously attracted attention. For example, Sollas (1903) demonstrated that an arc of islands could represent the outcrop trace of a planar fault at Earth's spherical surface. Continentward-dipping zones of earthquake foci beneath Japan (Wadati, 1931), the Andes, and Tonga-Kermadec (Benioff, 1949) were recognized as huge thrust faults (Lake, 1931). Benioff (1954) further suggested that the frictional heat generated along these faults was responsible for the volcanism of the island and continental arcs developed above earthquake zones.

In the 1920s to 1930s, submarine-borne gravity measurements in the Indonesian region led by Dutch geophysicist F. Vening Meinesz revealed major negative gravity anomalies along the Sumatra-Java-Banda trenches (Umbgrove, 1945) similar to those subsequently recognized to also exist over other deep-sea trenches. Understanding the significance of radioactive heating of Earth, earthquake and igneous activity, and the characteristics of arc-trench systems was critical in development of a convective hypothesis to account for continental drift (Holmes, 1928). However, it was not until the development of the plate tectonic theory (Hess, 1962; Wilson, 1965; McKenzie and Parker, 1967) that the significance of deep-sea trenches and associated earthquakes and volcanism became generally understood to mark the return (subduction) of tectonic plates (portions of lithosphere) into Earth's interior. Subduction zones can now be defined as locations where two plates converge, as one sinks below the other into Earth's interior. At Earth's surface, the interface between the two plates is typically marked by a deep-sea trench; with increasing depth, subduction zones can be recognized and traced by dipping and planar groupings of earthquakes that are associated both with rocks and sediment in the vicinity of the plate interface, and also brittle failure within the downgoing, colder plate interior.

The paramount importance of subduction zones in terms of overall solid Earth processes is considerable. It has been shown, for example, that most of the driving force behind global plate tectonics derives from subducted plate ("slab") pull rather than "ridge push" (Forsyth and Uyeda, 1975; Conrad and Lithgow-Bertelloni, 2002). The surface of a lithospheric plate carries a carapace of sediment and fluid into Earth's interior that reflects the interactions of rocks with the atmosphere, hydrosphere, and biosphere. Some of these components are returned to the exterior as wedges of sediment that have been scraped off at the trenches, through forearc vents (Fryer, 2012), or via magma genesis within or above the downgoing slab.

All major plate boundaries are ephemeral; they may lengthen or shorten, move relative to one another, or be created and destroyed through time (Dewey, 1975). Subduction zones can vanish, as evident in the Cenozoic demise of the trench associated with the subduction of the Farallon Plate below North America (Atwater, 1970). By using records of paleomagnetic reversals preserved in oceanic crust, observations of seafloor fabric, and a variety of other onshore and offshore data, these events have been reconstructed for the geologic past, with confidence for periods where we have records of the history of plate motions (e.g., back to the Jurassic; Seton et al., 2012), and less so for older times (Matthews et al., 2016a). Knowledge of the processes by which plate boundaries initiate and die is critical to gaining a fuller understanding of how plate tectonics works and how it has shaped our planet through geologic time. And while we have a good understanding of the initiation and development of divergent plate boundaries (i.e., mid-ocean ridges) and straightforward observational opportunities for their study, the same is not true for convergent boundaries and their associated subduction zones. Divergent plate boundaries preserve records of their evolution in the magnetic reversals in the oceanic crust and in the seafloor fabric, but much of the record of subduction initiation is obscured or even destroyed through tectonic erosion, burial, thermal and volcanic overprinting, and other processes at convergent plate boundaries (e.g., Stern, 2004).

The surge in ocean floor exploration of the 1950s–1960s, concurrent with the development of plate tectonic theory, was accompanied by the realization that the compositions of oceanic and continental crust are fundamentally different. The assemblage of rock types (chert-basalt-diabase-gabbro-variably serpentinized peridotite) collectively called an *ophiolite* became key for understanding the origin and development of much more inaccessible in situ oceanic crust (e.g., Gass, 1968). Improvements in analytical techniques for petrological, geochemical, and isotopic studies of magma types led to the realization that subduction zone inputs result in trace element and mineralogical characteristics in convergent margins magmas that are distinct from those of magmas at divergent margins (e.g., Pearce and Cann, 1973). Convergent margin characteristics derive from the input of subducted slab-sourced fluids into the regions of arc magma generation in the wedge of mantle lying between a subducted slab and the overriding plate.

The seminal proposition by Miyashiro (1973) that suggested the Troodos Complex of western Cyprus, an archetypal ophiolite, formed in an island arc rather than at a mid-ocean ridge prompted a torrent of criticism but also a re-examination of the concepts of crustal formation at convergent boundaries. Miyashiro's hypothesis was founded on the similarity of the major element geochemistry of the Troodos Complex with island arcs rather than that of mid-ocean ridges. In particular, the presence of glassy volcanic rocks containing unusually high MgO (>10 wt%) with intermediate (i.e., andesitic) silica (~55 wt% SiO_2) is unlike the basalts and their derivative melts typical of mid-ocean ridges. However, for many geologists, the occurrence on Troodos of a prominent sheeted dike complex represented concurrent magmatism and extension, and the absence of stratovolcanoes with aprons of volcaniclastic debris typical of island arcs seemed incompatible with a convergent margin origin (e.g., Gass et al., 1975).

Two main lines of evidence emerged that have led to current acceptance that most ophiolites formed in convergent margin or so-called "supra-subduction zone" settings (e.g., Pearce, 2003; Dilek and Furnes, 2014). The first, apparently arcane, line of evidence relates to the re-examination (e.g., Kuroda et al., 1978) of the type locality of "boninite" (Petersen, 1891) on the islands of Chichi- and Muko-jima in the Bonin islands located in the modern Izu-Bonin-Mariana (IBM) forearc (Figure 2). Distinctive features of the type boninite are: (1) high MgO (>8 wt%) and low TiO_2 (<0.5 wt%) with intermediate SiO_2 (52–65 wt%) (Le Bas, 2000), and (2) the occurrence of clinoenstatite (Shiraki et al., 1980; Figure 3), an inverted polymorph of high-temperature protoenstatite (Smyth, 1974) that is extremely rare in any other terrestrial igneous rock. Dallwitz et al. (1966) had previously identified clinoenstatite in glassy volcanic rocks on Cape Vogel (Papua New Guinea) but had not realized that they inadvertently discovered boninite (Walker and Cameron, 1983). Cameron et al. (1979) reported boninite on the basis of glass geochemistry in the upper pillow lavas of the Troodos Complex, but noted the absence of clinoenstatite.

The second line of evidence first came from detailed mapping of the IBM forearc islands of Guam (Reagan and Meijer, 1984) and Chichi-jima (Umino, 1985), which revealed igneous basements of near-trench-parallel, boninite sheeted dike-pillow lava complexes. In addition, submarine dredging and examination of the stratigraphy exposed on both trench walls of the current IBM arcs (Dietrich et al., 1978; Ishizuka et al., 2014) revealed a stratigraphy (from deep to shallow) composed of (1) peridotite, (2) minor gabbro, (3) sheeted dikes, (4) low-Ti-K tholeiitic basaltic lava flows, (5) lavas and dikes of boninite, and (6) tholeiitic and so-called "calcalkaline" lavas (see Arculus, 2003). Reagan et al. (2010) reported that the tholeiitic lavas of units 3 and 4 on the trench walls are mid-ocean ridge basalt (MORB)-like in terms of major element and some trace element characteristics but with distinctively lower Ti/V and Yb/V ratios than the latter, interpreted to reflect a significantly different melting environment than that responsible for MORB. The term forearc basalt (FAB) was applied to units 3 and 4 on the basis of their outcrop in the IBM forearc (Reagan et al., 2010). Ishizuka et al. (2011) reported the FAB age range as 52–48 million years old, compared with the oldest boninite at 48.2 million

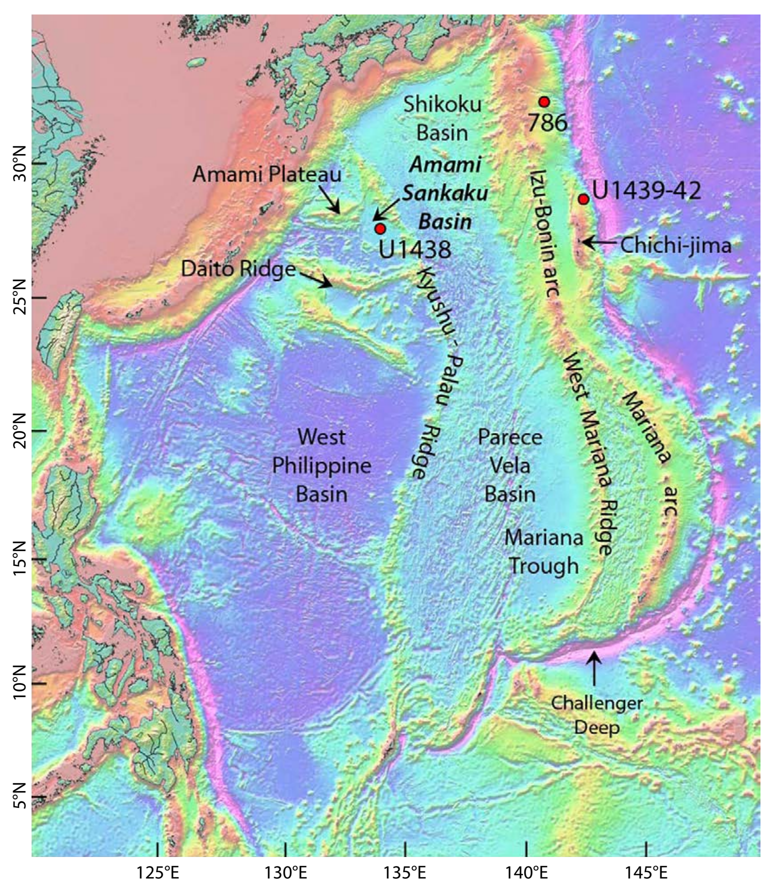


FIGURE 2. Regional context of sites drilled by International Ocean Discovery Program Expeditions (IODP) 351 (Site U1438), 352 (Sites U1439–1442), and Ocean Drilling Program (ODP) Leg 125 (Site 786).

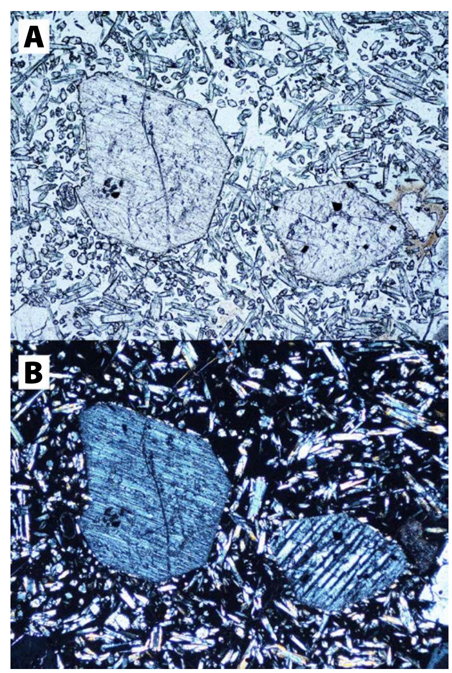


FIGURE 3. Photomicrographs of a thin section of crystal-rich boninite from a pillow lava-dike sequence at Hatsuneura, Chichi-jima. Fields of view are 2.5 mm. (A) Plane-polarized light view with two multiply-twinned clinoenstatite phenocrysts dominating the center of the field in a matrix of clear, isotropic glass and small crystals of pyroxene and olivine. (B) Crossed-polarized light view of the same thin-section.

years old. Thus, the distinctive boninite magma type emplaced under extension in the early growth of the intra-oceanic IBM arcs is convincing evidence that some ophiolites such as the Troodos Complex might have similar origins. Whattam and Stern (2011) interpreted the sequence of early FAB overlain by later boninites or similar lavas to be strong evidence that an ophiolite sequence formed during subduction initiation.

Realization of the significance of subduction zone initiation has stimulated multidisciplinary field, laboratory, and modeling studies to understand the process (Stern and Gerya, 2018). While McKenzie (1977) suggested that "ridges start easily, but trenches do not," Gurnis et al. (2004) pointed out that half of all extant subduction zones initiated in the Cenozoic, and concluded that forces resisting subduction can be overcome in a diversity of settings. Two end-member situations have been identified: spontaneous and induced (Stern, 2004; Gurnis et al., 2004; Figure 4). The former occurs when large density differences exist across lithospheric boundaries (e.g., transform fault conversion; circum-mantle plume head), and the latter when pre-existing plate motions force the development of a new subduction zone (e.g., subduction polarity switch).

One of the largest changes in global plate motions during the Cenozoic may have occurred at ~50 million years ago, as marked by a change in the orientation of the Hawai'i-Emperor seamount chain formed by the Hawai'i mantle plume (Sharp and Clague, 2006; O'Connor et al., 2013). Assuming that plate motion (at least partially) explains this Hawai'i-Emperor Bend, several explanations could be advanced for this change in Pacific Plate motion from NNW to WNW, including (1) the subduction of the Izanagi-Pacific Ridge along eastern Asia (Seton et al., 2015), (2) collision of an intraoceanic arc with southern Asia prior to the arrival of Indian continental crust (Aitchison et al., 2007; Matthews et al., 2016b), (3) the separation of Australia from Antarctica (Whittaker et al., 2007), and (4) the Pacific Plate began to move

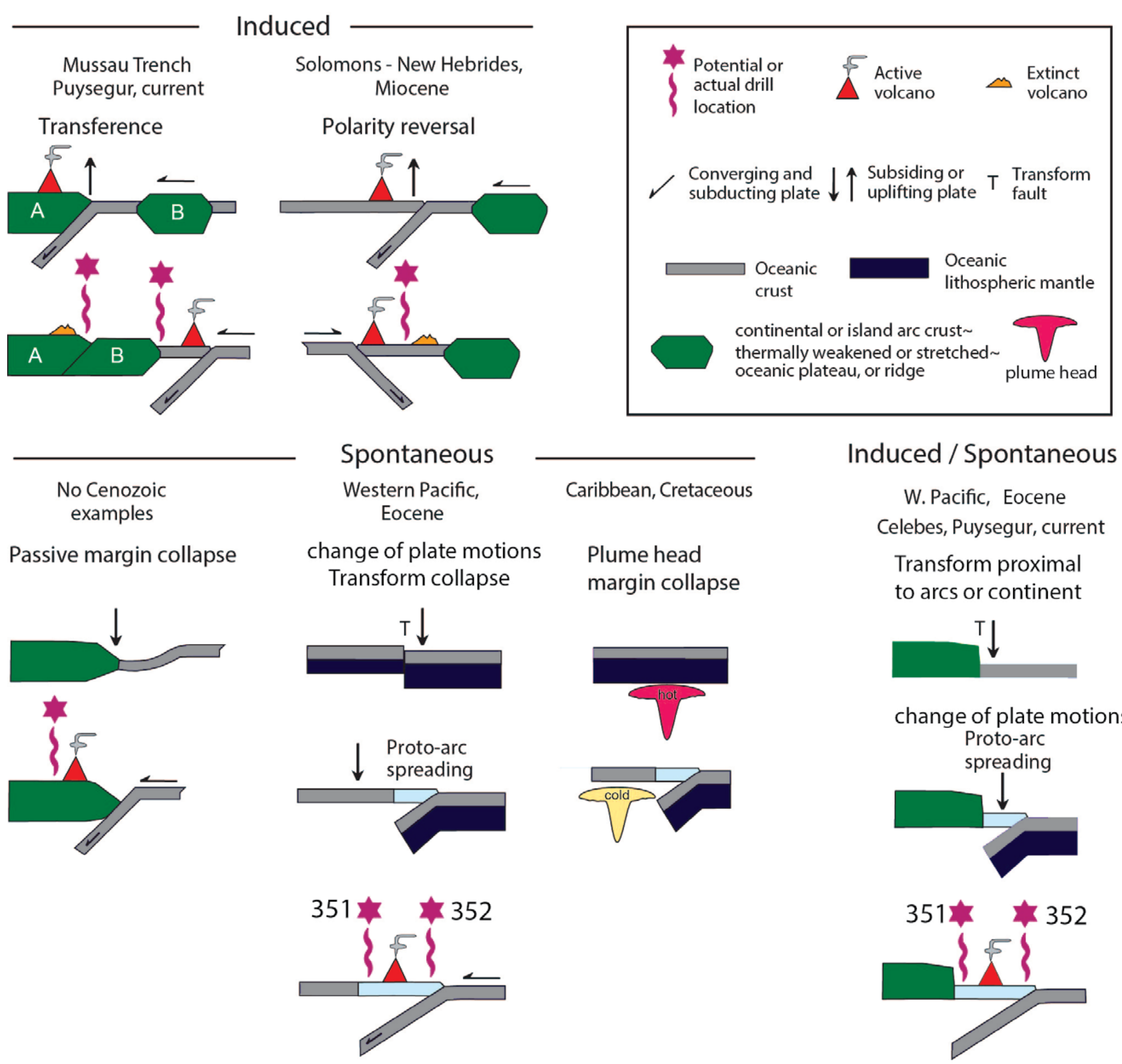


FIGURE 4. Representation after Stern and Gerya (2017) of types of subduction initiation, with specific geographic examples, past and present. Locations of IODP 351 and 352 drill sites are schematically indicated under two types of settings.

toward another or new convergent margin. It is known that subduction zones developed in the western Pacific along a line that extends from Japan in the north, southward through the IBM (Ishizuka et al., 2011; Reagan et al., 2013), to the Tonga-Kermadec (TK) system, albeit with local complications (Meffre et al., 2012; Wu et al., 2016). Seismic tomography (subsurface images made using knowledge of seismic wave propagation) reveals an immense wall of subducted Pacific Plate along this great length of convergent boundaries (Ritsema et al., 2004; C. Li et al., 2008;). Uyeda and Ben Avraham (1972) first proposed conversion of pre-existing transform fault(s) to a transpressional regime at the locus of IBM arc initiation consequent to the change in Pacific Plate motion. Taking into account along-arc strike extension by continued arc-parallel spreading in the West Philippine Basin, Dewey and Casey (2011) developed a model for arc initiation as a trench-ridge-trench triple junction and for formation of a forearc ophiolite complex as now outcrops in the IBM trench walls (Bloomer et al., 1995). The contrast between the settings at subduction initiation of the IBM versus TK systems is significant. For example, while many depict subduction initiation at the IBM as intra-oceanic (e.g., Hall, 2002; Whittaker et al., 2007), it developed at TK at the eastern margin of the rifted fragments of Australia (e.g., Whittaker et al., 2007; Schellart and Spakman, 2012; Meffre et al., 2012; Matthews et al., 2015, 2016b; Figure 5).

A multitude of studies involving extensive geophysical surveys, coring, dredging, and data from previous scientific ocean drilling expeditions provided the stimulus for a campaign by the International Ocean Discovery Program (IODP) to resolve some of the major issues concerning subduction inception and arc initiation in the IBM and TK systems. These issues were identified as first-order research problems in the IODP Science Plan for 2013–2023 (http://www.iodp.org/about-iodp/iodp-science-plan-2013-2023). In 2014, two IODP expeditions targeted the distal rear-arc (Expedition 351) and forearc (Expedition 352) of the Izu-Bonin system (Figure 2) to discover the nature of the arc basement, the spatial and temporal distribution of the earliest magmatism, and the early evolution of the arc. The primary goal of IODP Expedition 371 in 2017 was to date and quantify the deformation and uplift/subsidence of continental ribbons and intervening basins

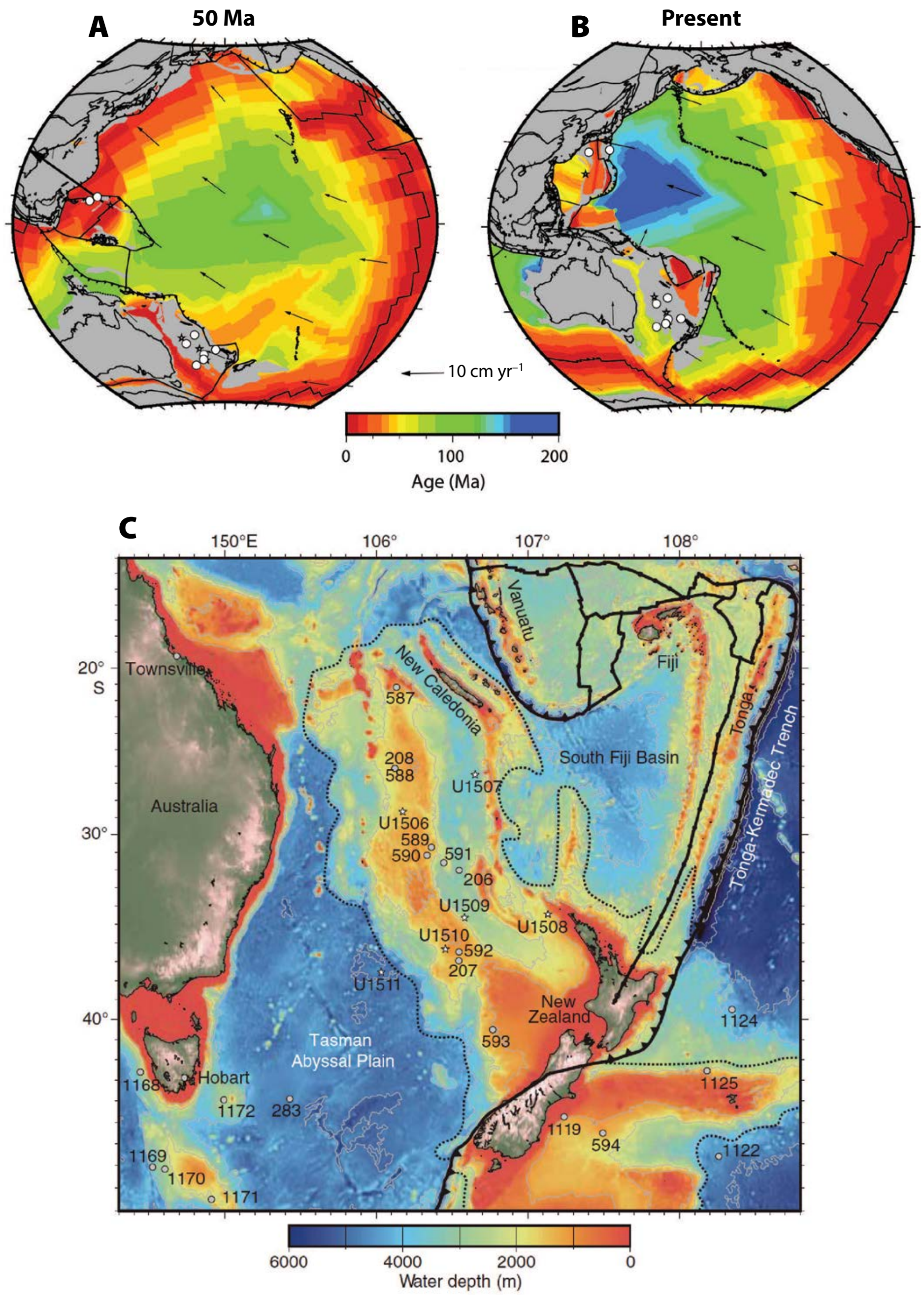


FIGURE 5. Drilling sites, topography, and bathymetry in the Western Pacific. Tectonic features are shown (A) at 50 million years ago (Ma), and (B) at the present day, using the plate tectonic reconstruction of Seton et al. (2012). Velocities are in a moving hotspot frame of reference. The Izanagi-Pacific Ridge at this time had just been subducted beneath Japan and East Asia. Sites from IODP Expeditions 351, 352, and 371 discussed in the text are indicated with larger circles, while selected sites from earlier Deep Sea Drilling Project and ODP legs are marked with stars. This reconstruction does not account for the many discoveries from these recent IODP Expeditions. In this reconstruction, the Pacific Plate has an approximate northwest-trending motion at 50 Ma, which trends to a more westerly motion at 47 Ma. (C) Locations of Expedition 371 sites (stars) along the Tasman Frontier (Sutherland et al., 2017), together with previous deep-sea drilling sites (circles).

between Australia and the TK convergent margin (Figure 5, Tasman Frontier; Sutherland et al., 2017) in order to test the predictions of alternative geodynamic models for subduction inception. In the following sections, we provide some suggestions for future drilling targets to resolve outstanding problems related to western Pacific Eocene subduction initiation and more recently developing systems.

IODP EXPLORES SUBDUCTION INITIATION

Expedition 351: Evidence for the Earliest Evolution of the IBM

The Kyushu-Palau Ridge (KPR) is the oldest remnant arc in the Izu-Bonin-Mariana system, separated 30–25 million years ago from the volcanic IBM front by seafloor spreading in the Parece Vela and Shikoku backarc basins. At its northern end, the KPR strikes across the Amami-Sankaku Basin and forms the eastern boundary of the east-west-striking Mesozoic arc fragments of the Amami Plateau and Daito Ridge (Figure 2). Taylor and Goodliffe (2004) emphasized that the KPR (and hence the inferred juvenile trench) trended at high angles to the Amami Plateau, Daito Ridge, and bounding faults of the Amami-Sankuku Basin. Accordingly, they argued against the inception of the subduction zone and earliest arc at a pre-existing transform fault that was linked to, for example, the Izanagi-Pacific Ridge.

The original aims of IODP Expedition 351 drilling at Site U1438 in the Amami-Sankaku Basin were to explore the pre-arc basement underlying the IBM arc and to recover the history of the early development of the arc preserved in volcaniclastic-rich sediments shed from the growing KPR that, when active, was part of the IBM arc. Prior to IODP Expedition 351, two hypotheses had been put forward for the origin of the reconstructed IBM arc, one in which subduction nucleated spontaneously due to a difference in plate age across a former fracture zone (Stern and Bloomer, 1992) and the other through forced convergence (Gurnis et al., 2004). The two models predicted different histories and ages of the sediments immediately overlying the Amami-Sankaku basement. The simple layered structure of the Amami-Sankaku Basin is composed of ~1.5 km of sediment overlying a normal oceanic crustal thickness of ~6 km (Arculus et al., 2015). The seismic structure of the basement persists eastward beneath the KPR and forms a significant portion of its total thickness. IODP Expedition 351 successfully recovered the targeted sequences—and generated some major surprises (Arculus et al., 2015). The basement (Unit 1) is composed of low-Ti-K tholeiitic basalts ~49 million years in age (Ishizuka et al., 2018) and not Paleocene (66–56 million years old) or older as hypothesized pre-Expedition 351. These basalts overlap in age with the Bonin Ridge boninites (Ishizuka et al., 2006) but are younger than the overall basalt-to-boninite sequence recovered from the present-day IBM forearc by dredging and submersible sampling (Ishizuka et al., 2011) and by IODP Expedition 352 drilling at Sites U1439–U1442 (Reagan et al., 2019).

Conclusions drawn from studies of the petrologic and geochemical characteristics (including radiogenic isotopes) of the Expedition 351 basement basalts (Hickey-Vargas et al., 2018; Yogodzinski et al., 2018) are: (1) they are derived from mantle peridotite source(s) that were highly depleted by melt extraction prior to IBM arc inception ~52 million years ago; (2) the basalts lack the fluid-mobile trace element enrichments typical of most island arc basalts, boninites, or high-Mg andesites (e.g., Schmidt and Jagoutz, 2017); (3) the compositional characteristics of the (micro)phenocrysts of olivine-clinopyroxene-plagioclase-spinel comprise a globally unique data set, reflecting generation of the magmas at relatively high pressures and temperatures under low-redox conditions, followed by rapid transfer to the surface likely under seafloor spreading conditions.

Expedition 352: IBM Forearc Architecture and Construction Timescale

Over a distance of about 13 km, IODP Expedition 352 drilled four sites in the forearc orthogonal to the strike of the Bonin Trench, and recovered a high-fidelity record of crustal generation related to subduction initiation in the Bonin forearc. This was the first expedition dedicated entirely to exploration of the stratigraphy of the IBM forearc. Previous drilling during Ocean Drilling Program (ODP) Leg 125 recovered a sequence of boninite and derivative rocks (e.g., Arculus et al., 1992) at Site 786, located ~270 km north and along the strike of the forearc from those drilled during IODP Expedition 352. A sequence of FABs overlying dikes was recovered at Sites U1440 and U1441, closest to the trench; they were emplaced during near-trench seafloor spreading that accompanied subduction initiation. The basalts are petrologically similar to the FABs retrieved by submersible, dredging, and drilling along the entire length of the IBM forearc (see DeBari et al., 1999; Reagan et al., 2010; Ishizuka et al., 2011). The FABs recovered from the drill cores, together with a compositionally related gabbroic rock collected nearby, have ages of ~51.9–51.3 million years (Reagan et al., 2019). Forearc basalt lavas are generally aphyric, with rare plagioclase and augite phenocrysts. Like the basalts from Site U1438, FABs are highly depleted in incompatible trace elements as a result of ancient melt extraction events (Shervais et al., 2018).

Boninites were drilled furthest from the trench at sites U1439 and U1442. The oldest boninites have compositions that are transitional toward FAB (termed "low-Si boninites," or LSB) and erupted while seafloor spreading continued. These lavas are beneath "high-Si boninites" (HSB) that erupted atop the new oceanic crust and have compositions resembling the boninites on the nearby island of Chichi-jima. HSB ages span 51.3 to 50.3 million years old

(Reagan et al., 2019), placing eruption of the LSB near the age of the nearby FAB. All boninites are formed by flux melting of depleted mantle that involves fluids derived from dehydration and melting of subducted materials. LSB were generated in the presence of melts/fluids from subducting altered Pacific MORB, whereas melts/fluids from subducting sediments were involved with the genesis of HSB (H.Y. Li et al., 2017).

Expedition 371: Exploration of TK Subduction Initiation

IODP Expedition 371 drilled six sites across some of the major structural elements of the Tasman Frontier, including the northern and southern New Caledonia Trough, Reinga Basin, Lord Howe Rise, and Tasman Abyssal Plain (Figure 5). The variable but persistently moderate bathymetry of the Tasman Frontier has ensured preservation of depth-sensitive, fossil-rich records both pre- and post-subduction initiation at ~50 million years ago along the TK arc. Seismic reflection data across the Tasman Frontier reveal episodes of compression, uplift, and subsidence (Sutherland et al., 2017). Results from IODP Expedition 371 show regionally dramatic, Eocene-age vertical motions, with evidence for Eocene-Oligocene faulting and folding (Sutherland et al., 2018). Subduction inception along the proto-TK Arc may have involved elements of both spontaneous and induced elements.

DISCUSSION

Complementing the past multidisciplinary and collaborative approaches to the study of the IBM and TK arcs, the recent IODP scientific ocean drilling expeditions have confirmed some hypotheses regarding crustal architecture, but also produced novel and surprising results. For example, one of the most important conclusions of the collective studies of the IBM system is that the structure and magmatic output of a nascent arc is unlike that of established systems. The latter can be defined as "a chain of concurrently or potentially active volcanic islands, consistently associated but displaced spatially more than 100 km from a deep-sea trench. Much of the eruptive activity is typically explosive. Adjacent to many island arcs in the western Pacific are backarc basins, floored by crustal spreading centers. Some arcs have associated non-volcanic islands between the volcanic arc and trench comprising uplifted basement or trench-accreted sediments" (Arculus, 2009; Figure 6). Implicit in this definition is the notion of a volcanic front marking the trenchward limit of volcanic edifices, a forearc region lacking volcanism, and backarc basins wherein new basaltic ocean crust forms by seafloor spreading. For many arcs, there are also isolated edifices or chains of rear-arc volcanoes not formed through seafloor spreading, such as the Chokai Zone of Japan (Tatsumi, 1989; Tamura et al., 2002), or the cross-chains of the northern IBM arc (Machida et al., 2008). The volcanic front is dominated by subaerial and submarine stratovolcanoes, with extensive aprons of volcaniclastic debris (e.g., Pope et al., 2018).

A persistent chain of stratovolcanoes, geometrically stationary with respect to an adjacent trench and likely fed from plugs or radial dikes (Nakamura, 1977), nevertheless seems incompatible with the presence of an underlying sheeted dike complex. This observation, together with the absence of aprons of volcanic debris, were prime factors in the initial rejection of Miyashiro's (1973) hypothesis that the Troodos Complex formed in an island arc. In fact, the earliest stages of "supra-subduction zone" magmatism might well be unrecognized in the absence of tectonic and geophysical constraints. It turns out that both Miyashiro and his critics were right: the Troodos Complex formed by seafloor spreading but at a convergent plate margin; whether this spreading was in a near-trench setting during subduction initiation remains controversial (Woelki et al., 2018). The accumulating

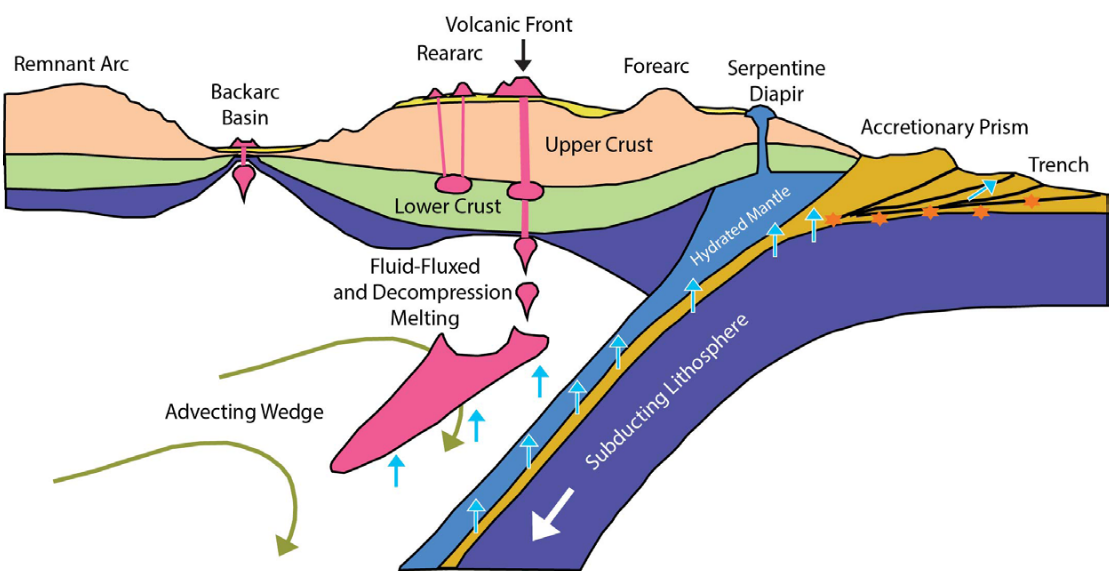


FIGURE 6. Schematic cross section of an island arc from trench to backarc basin. Orange stars represent great earthquakes in the seismogenic portion of the Wadati-Benioff zone. Blue arrows represent movement of hydrous fluids/melts.

evidence clearly supports the model initially proposed by Stern and Bloomer (1992) and recently extended by Stern and Gerya (2018) for the earliest development of the IBM arc. Simply stated, the tholeiitic basalts forming the earliest crust in the IBM arc, sampled at the present-day forearc (Sites U1440 and U1441), were emplaced at one or more spreading ridges underlain by sheeted dike swarms. The architecture of this oceanic crust suggests the basalts formed at a ridge on the overriding plate during subduction initiation (Ishizuka et al., 2014). At this stage, there was no chain of stratovolcanoes, and the concept of a forearc, rear-arc, and backarc for the earliest situation as delimited by a volcanic front cannot be applied. Seen in this context, the basalts drilled at U1438 are younger than FAB and erupted at the same time as boninites along the Bonin Ridge. Reagan et al. (2017, 2019) propose the Amami-Sankaku Basin basement formed through trench-distal magmatism, possibly as a type of later backarc activity, after trench-proximal seafloor spreading ceased, rather than as a continuation of the seafloor spreading that produced the FAB.

Restoring the geometry of the initial stages of magmatism in the proto-IBM arc by closing the backarc basins and forearc rifts places the Amami-Sankaku Basin ~250 km across strike from the Bonin Ridge adjacent to Expedition 352 Sites U1439–1442 (Figure 2). The duration of the earliest period of tholeiitic basalt eruption was less than 1.2 million years at the present location of the Bonin forearc (FAB, 52–48 million years ago; Ishizuka et al., 2011; Reagan et al., 2019), with perhaps two additional million years in the Amami-Sankaku Basin (49–47 million years ago; Ishizuka et al., 2018). The period of boninitic magmatism endured at least from 51 to 44 million years ago on the Bonin Ridge, possibly associated, during the later stages of high-silica boninite eruption, with individual topographically prominent volcanic edifices (Reagan et al., 2017), before transitioning to eruption of the more usual basalts associated with stratovolcanoes (so-called island arc tholeiitic and calcalkalic suites; Ishizuka et al., 2011; Reagan et al., 2019). We note that a slab dipping at ~45° and subducting at 60 mm yr^{-1} (Whittaker et al., 2007; Figure 5) takes ~2.4 million years to reach a depth of 100 km below a volcanic front that is characteristic of mature arcs. This is a relatively short period of time compared with a duration of ~7 million years from the earliest tholeiitic to boninitic magmatism in the case of drill recovery from the present-day forearc to the outcrops on the Bonin Ridge. The processes that drive the transition from seafloor spreading during the nascent arc stages to establishment of the archetypal magmatic arc with a forearc-volcanic front-rear/backarc geometry are not yet understood. However, the processes must reflect the transition from hinged subsidence of the old seafloor, with asthenospheric upwelling into the space created, to true downdip subduction and a reversal of asthenopheric flow (Stern and Bloomer, 1992). A corollary is that the strike of the KPR is related to the establishment of the volcanic front of a mature magmatic arc, and does not necessarily bear any simple relationship to preexisting ridge-transform segments and their orientations.

Comparison of petrological and geochemical characteristics of the tholeiitic basalts erupted during the initial stages of convergent margin formation with those from mid-ocean ridges and backarc basins is critical for understanding the respective petrogenetic processes involved. We require distinguishing compositional parameters to recognize tholeiitic magmatism associated with subduction inception events in the Mesozoic and older eras (e.g., Buchs et al., 2010). For comparative purposes, we need to know the absolute abundances of major and trace elements allied with isotopic characteristics and constituent mineral compositions of these nascent subduction-related basalts. In this framework, abstracting the most significant results published to date from the IODP expeditions, in combination with previous studies (see references cited earlier), we emphasize five issues.

1. Inception of the IBM system was adjacent to a series of Mesozoic-aged arc-basin systems (Arculus et al., 2015; Leng and Gurnis, 2015). Inception of the TK system was adjacent to a welt of continental crustal ribbons, intervening basins, and older arcs (Meffre et al., 2012; Sutherland et al., 2017). These two systems were not intra-oceanic in the sense of birth surrounded solely by oceanic lithosphere.
2. The earliest lavas accompanying subduction initiation were basalts erupted in a seafloor spreading environment, above sites of asthenospheric upwelling.
3. These early basalts have extremely low abundances of the light (L) relative to the heavy (H) rare earth elements (REE) and small to insignificant enrichment in the most subduction-mobile elements; hence, they lack the large negative Nb anomalies that characterize almost all arc lavas.
4. These early basalts are strikingly radiogenic $^{176}Hf/^{177}Hf$ (εHf ≤ 22.1) at given $^{143}Nd/^{144}Nd$ compared with ocean floor basalts from the Pacific Plate.
5. Clinopyroxene-bearing phenocryst/microphenocryst assemblages in the early basalts reflect rapid transfer from mantle source depths (~30 km) to the surface without the extensive staging that is characteristic of sub-mid-ocean ridge chambers and mush zones.

Elaborating on the significance of the set of geochemical and petrologic characteristics, Figure 7 plots the slopes and curvatures of the chondrite-normalized REE abundances for global MORBs (gray or white circles; O'Neill, 2016) compared with the nascent arc tholeiitic basalts (colored symbols). Quantification of the total shapes of the usual chondrite-normalized abundance plots (see the three insets) is the great advantage of this type of figure. It shows the Amami-Sankaku Basin basalts from IODP Site U1438 define a LREE-depleted limit of the global MORB array. While also highly depleted, FABs are distinct compared with the Amami-Sankaku Basin basalts in having less concave-downward curvatures of the chondrite-normalized LREE abundances and more diverse REE patterns (Shervais et al., 2018). Nevertheless, both the Amami-Sankaku Basin basalts and FABs have Hf-Nd isotopic characteristics requiring mantle source(s) that were more depleted by prior melting than any equivalents tapped beneath the global network of mid-ocean ridges. Development of very high $^{176}Hf/^{177}Hf$ requires an increase in the Lu/Hf ratio of the mantle sources above that of the MORB source(s) and must result from basalt melt extraction combined with the passage of time. There can be a trade-off between the extent of Lu/Hf fractionation and the melting events subsequently associated with subduction, but development of radiogenic Hf must precede the subduction initiation event (Reagan et al. 2010; H.Y. Li et al., 2017; Yogodzinski et al., 2018).

After careful filtering for post-eruptive seawater alteration, Hickey-Vargas et al. (2018) show the abundances of the fluid-mobile trace elements (alkali, alkaline earth, Pb, U, and Th) in the Amami-Sankaku Basin basalts are typical of the most highly depleted MORBs with no evidence of subducted-slab derived inputs. After similar filtering, Shervais et al. (2018) conclude that most FABs lack a subduction influence in their genesis, although some FABs from Site U1441 with elevated Sr (fluid-mobile)/Zr(fluid immobile) (~3.2) likely require some subducted slab-derived water inputs to their mantle sources (Reagan et al., 2017). The presence of negative high-field-strength element anomalies in island arc basalts is commonly interpreted to result from enrichments in La and other LREE of the mantle wedge sources by slab-derived fluids (e.g., Pearce and Peate, 1995). The abundances of elements such as Nb and Ta are then assumed to reflect the pre-enrichment values of the unmodified mantle. The absence of negative anomalies for Nb and Ta in the case of the Amami-Sankaku Basin basalts and FABs can therefore be interpreted as precluding slab-derived additions of the LREE to the mantle sources, therefore ruling out modification of the intrinsic, pre-subduction inception Nd and Hf isotopic characteristics of this sample set.

The mineralogy of IBM FABs and Amami-Sankaku basalts is also distinctive compared with the overwhelming majority of MORBs. The presence of phenocrystic clinopyroxene, for example, is highly unusual compared with the persistent lack of this phase as a phenocryst in primitive (Mg-rich) MORBs (Francis, 1986; Herzberg, 2004). We know that clinopyroxene is involved in the generation of the global MORB compositional array (O'Neill and Jenner, 2012) and is a major constituent of gabbros recovered by scientific ocean drilling, dredging, and submersible sampling of the oceanic crust. Herzberg (2004) notes the so-called "clinopyroxene paradox" is in fact consistent with phase relationships of effectively anhydrous MORB magma. Decompression of a melt saturated with olivine, plagioclase, and clinopyroxene from a crustal magma (melt-crystal mush) chamber at ~2–4 km depth below the seafloor will eliminate clinopyroxene as a near-liquidus phase. The persistence of clinopyroxene in the nascent IBM basalts might be accounted for by more rapid ascent from such depths allied with higher water contents. Clinopyroxenes in the Amami-Sankaku Basin basalts and FABs have lower Na and Ti compared with the rare phenocrysts in MORBs and the abundant compositional data for MOR gabbros; the Amami-Sankaku Basin clinopyroxenes range to more aluminous compositions, whereas the FAB clinopyroxenes are less aluminous than MORB. Spinel compositions in the Amami-Sankaku Basin basalts range from Fe^{3+}-poor, aluminous-chromian

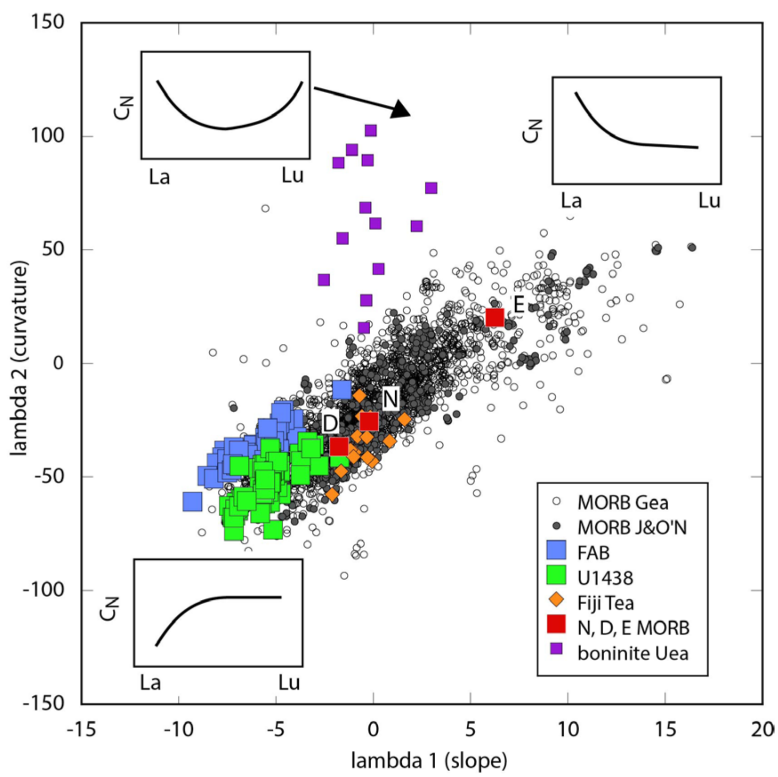


FIGURE 7. Comparison of the curvature (lambda 2) vs. slopes (lambda 1 values) of chondrite-normalized (C_N), rare earth element abundances (O'Neill, 2016) for subduction-inception related magmas compared with mid-ocean ridge basalts. Insets show where representative types of patterns project in the main figure. D = Depleted. E = Enriched. N = Normal. Gea = From Gale et al. (2013). J&O'N = Jenner and O'Neill, 2012. Tea = Todd et al. (2012). Uea = Umino et al. (2015).

to ferrian (magnetite), exceeding the range known in MORBs (Sigurdsson and Schilling, 1976; Barnes and Roeder, 2001), and consistent with higher pressures (or greater depths) of derivation of the Amami-Sankaku Basin basalts than for most MORBs.

Based on the results of Expedition 352, Reagan et al. (2017, 2019) outlined the progression from subduction inception at a transform margin through seafloor spreading and the development of the first chain of individual stratovolcanoes or "typical" arc (Figure 8). Rapid collapse or sinking of the subducting slab leads to decompression of asthenosphere, generating FAB magma with minimal or no material transfers from the slab. Progression to slab-derived flux melting of the wedge proceeds through the generation of the most depleted FAB to boninite over less than 1.2 million years and must reflect changes in the motion of the sinking lithosphere and the advecting mantle above it. This early and fast igneous outpouring of FAB, LSB, and HSB forms the basement of the present-day IBM arc and forearc, and a portion of the welts of remnant arcs, such as the Kyushu-Palau and West Mariana ridges. In terms of crustal growth rates in arcs, this conclusion is important because the flux in the first few million years approached that of mid-ocean ridges (~1,000 km^3 per million years per kilometer of ridge), but diminished once the mature arc, backarc spreading, and the KPR became established.

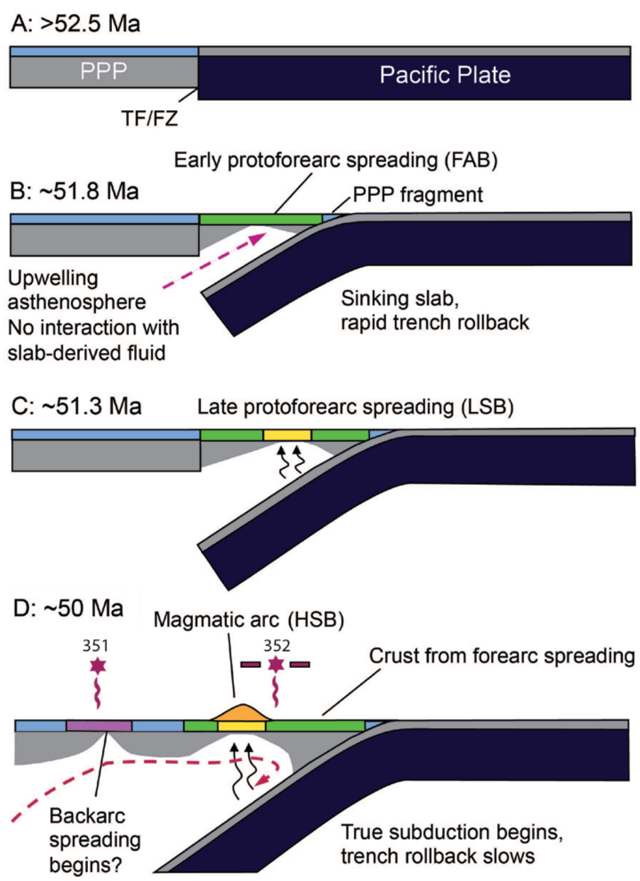


FIGURE 8. Cartoon with time slices after Reagan et al. (2019) of creation and evolution of the Izu-Bonin-Mariana (IBM) crust after subduction initiation. (A) Philippine Sea Plate (PPP)-Pacific Plate in contact prior to subduction initiation along a transform fault/fracture zone (TF/FZ). (B) Subduction inception between 52.5 and 51.9 million years ago (Ma), with asthenospheric upwelling and decompression melting with trench-proximal seafloor spreading and forearc basalt (FAB) generation. (C) Continued Pacific Plate subduction and seafloor spreading generating FAB followed by slab-derived fluid fluxing generating low-silica boninite (LSB). (D) Embryonic arc (chain of stratovolcanoes, advecting wedge, and possibly early trench-distal [backarc] seafloor spreading). IODP Expedition 351 and 352 sites indicated.

The development of the TK system differed from that of the IBM in a number of ways. Crustal elements developed above an eastward–dipping subduction zone in the 57–35 million year old Loyalty-Three Kings arc were thrust over the Norfolk Ridge and are now exposed in New Caledonia (e.g., Cluzel et al., 2018). Meffre et al. (2012) argue that the oldest (~52–48 million years old) igneous rocks (plagiogranites) now in the TK forearc were originally created in a backarc-arc setting. Subduction polarity reversal and collision of the Loyalty-Three Kings arc with New Caledonia placed the 52 million year-aged rocks into the forearc of the TK system. Todd et al. (2012) reported the earliest subaerially exposed magmatic products of the Fiji-TK arc, including island arc tholeiite, boninite, and "early-arc tholeiite" interbedded in outcrops on Viti Levu and Eua (Fiji). The authors interpret these to be products of decompression and flux-enhanced melting of a proto-mantle wedge following subduction inception. For comparison with the forearc and Amami-Sankaku Basin basalts of the IBM system, Figure 7 shows the shapes of the chondrite-normalized abundance patterns of the early arc tholeiites from Fiji. A number of these samples extend into the more LREE-depleted range of global MORB, but are not as extreme as those from the Amami-Sankaku Basin or the IBM forearc.

OUTSTANDING QUESTIONS

We have learned much concerning the creation of new subduction zones over the past five years from a variety of multidisciplinary approaches and focused IODP scientific ocean drilling, but what are the outstanding problems, and what future drilling projects might be undertaken to solve them?

Noting that oceanic lithosphere >10 million years old is unstable gravitationally compared with the underlying mantle (Cloos, 1993), there is broad agreement that Stern's (2004) fundamental division of subduction initiation into spontaneous and induced types is a useful way to approach the issues surrounding creation of convergent margins. Nevertheless, individual examples may well involve a combination of these end members, and it is abundantly clear that subduction inception is intrinsically a three-dimensional process (Zhou et al., 2018). Building on regional geophysical surveys and tectonic syntheses, localized but extensive rock and sediment cores have been recovered that record the operation of fundamental structural and magmatic processes. Identifying the localized as opposed to regional-scale factors then becomes important in overall understanding of these processes. Leng and Gurnis (2015) point out that extensional events in the relatively buoyant Cretaceous-aged arcs (Amami Plateau-Daito Ridge; Figure 2) and, hence, thermal rejuvenation of the region, were important factors leading to subduction initiation along an adjacent transform fault bounding the Mesozoic arcs and comparatively dense Pacific oceanic lithosphere. There is considerable disagreement over whether spontaneous subduction initiation can occur at an old fracture zone absent any other factors (Leng and Gurnis, 2015; Stern and Gerya, 2018). However, the juxtaposition of old Pacific Plate to reheated buoyant relic arcs provides sufficient driving forces for spontaneous initiation (Leng and Gurnis, 2015). In broad terms, the same situation prevailed in the TK system. Other complexities of regional geology in the case of the IBM system concern the impact of the Oki-Daito plume and initiation of spreading in the West Philippine Basin (Ishizuka et al., 2013). There is general agreement that the potential change in azimuth of Pacific Plate motion ~52–50 million years ago coincided with initiation of subduction of the IBM and the TK systems, but the ultimate causal factors are not yet known. Localization of subduction initiation along transform faults bordering preexisting arc terranes and stretched continental ribbons followed. This event can potentially be viewed as a hybrid that included induced processes exploiting along-strike variations in local buoyancy forces.

In the specific case of the IBM system, exploration of the foundations and earliest magmatic products is demonstrably incomplete. We have minimally explored the three-dimensional aspects of the Amami-Sankaku Basin, both in terms of probing the lateral and vertical structure and composition of the basement, as well as through exploring the early stage of arc growth via the KPR output as recorded in the overlying sediments (Straub et al., 2015; Brandl et al., 2017). Combining sample recovery from Deep Sea Drilling Project Leg 60, ODP Leg 125, and IODP Expedition 352 with those from diving and dredging along the IBM forearc, we have the beginnings of an along-strike recovery of crustal sequences associated with subduction initiation. The crust clearly has all of the lithologies found in ophiolites, but the structural and compositional relationships between the units remain poorly known. Penetration to the gabbros that must underlie the sheeted dikes, and ultimately to the underlying mantle remains a priority for understanding the development of the nascent crust after subduction initiation and the precise link between the results of drilling forearc crust and the genesis of supra-subduction ophiolites. Sites closer to the trench than those drilled by Expedition 352 and shown schematically in Figure 8 are the obvious locations.

> "Knowledge of the processes by which plate boundaries initiate and die is critical to gaining a fuller understanding of how plate tectonics works and how it has shaped our planet through geologic time."

The early IBM basalts are a global end member with respect to the degree to which they are depleted in highly incompatible elements, and isotopic compositions convincingly show that this depletion occurred in their mantle sources long before subduction initiation (Yogodzinsky et al., 2018). This opens the possibility that subduction initiation occurred along some sort of geochemical boundary in the mantle, like that represented by the Australia-Antarctic Discordance to the south (Gurnis and Müller, 2003). However, basalts from ophiolites generally are not unusually depleted in incompatible trace elements (e.g., the Samail Ophiolite; Alabaster et al., 1982). Thus, if our conclusion that the IBM forearc is the in situ equivalent of an ophiolite is correct, then strong prior depletion of the mantle is not required for subduction initiation to proceed.

For the TK system, ODP Leg 135 primarily targeted the evolution of the Lau Basin. It is clear, however, from the success of Expedition 352, in combination with the dredging recoveries from the Tonga Trench wall (Bloomer and Fisher, 1987; Meffre et al., 2012), that deep-sea drilling of the TK forearc is of fundamental importance to further understanding of the development of the system.

Globally, there is much interest in further exploring the current tectonism and geophysical characteristics of the

Puysegur-Fiordland boundary between the Australian and Pacific Plates south of New Zealand (e.g., Meckel et al., 2003). This transpressional margin appears to be transitioning from induced (forced) to self-sustained (spontaneous) subduction (Gurnis et al., 2004; Mao et al., 2017). Particular advantages of this region in terms of studying subduction initiation is that the processes are active, the plate kinematics are well constrained, and the geological record is not obscured. Drilling targets will emerge from a number of regional geophysical surveys that have recently been completed.

Also in the Southwest Pacific, the polarity of subduction at the boundary between the Australian and Pacific Plates reversed (Papua New Guinea-Solomon Islands-Vanuatu) following collision of the Ontong Java Plateau with the Vitiaz Trench ~10 million years ago (Petterson et al., 1999). This setting was a target for ODP Leg 134, and is a specific example of a type of induced subduction identified by Stern (2004; Figure 4). A series of multinational geophysical surveys under the auspices of the Circum-Pacific Council for Energy and Mineral Resources in the 1980s revealed much of the fundamental tectonic architecture and geology of this region. There are obvious targets for study of the consequences of polarity reversal such as the sediment record preserved within intra-arc troughs exemplified by the New Georgia Basin.

Exploration of subduction initiation has not yet targeted the many active and developing systems of the Indonesia-Philippines region. Hall (2018) identified many examples of the process from the earliest stages of downward flexure of the oceanic crust to the development of an observable Wadati-Benioff zone. He noted specific cases of subduction initiation propagating along strike from existing subduction zones, as invoked in part by Arculus et al. (2015) for the IBM system, and there are other examples at isolated deeps developed in extensional settings.

In summary, it is clear that we have a multiplicity of global targets for drilling and a potentially coherent ensemble of different examples and stages of subduction initiation. Scientific ocean drilling is the best way to recover the records of subduction initiation, which can potentially be tied to on-land studies of ophiolites. Progress in this field has the potential to transform our understanding of plate tectonics.

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SPOTLIGHT 11. Mission-Specific Platforms

The Integrated Ocean Drilling Program adopted mission-specific platform (MSP) expeditions in 2003 to extend the program's capabilities for a new generation of scientific drilling projects in areas inaccessible to *JOIDES Resolution*, for example, ice-covered seas, waters shallower than 100 m, and areas with hard rock exposed at the seabed or with unconsolidated sediments.

MSP expeditions are implemented by the European Consortium for Ocean Research Drilling (ECORD) Science Operator (ESO) through a partnership with the British Geological Survey (BGS), the German Center for Marine Environmental Sciences (MARUM, Universität Bremen), and the European Petrophysics Consortium (which includes the University of Leicester in the UK and the University of Montpellier in France).

Since its inception, ESO has successfully staged eight MSP expeditions from the Arctic to the South Pacific. The expeditions have provided new insights into the Arctic's Cenozoic paleoenvironmental and climatic evolution, new data on the paleoceanographic evolution of the tropics as recorded in coral reefs, new knowledge of the role of serpentinization in driving hydrothermal systems that sustain microbiological communities, and new information on the mechanics and effects of large meteorite impacts.

The platforms and drilling services used in MSP expeditions are typically contracted from the commercial sector. In addition, the majority of International Ocean Discovery Program (IODP) standard measurements are not collected at sea, but instead during onshore science gatherings hosted by the IODP Bremen Core Repository. In this respect, MSPs give the community access to leading-edge as well as alternative technologies without the need to maintain a permanent drilling infrastructure. This creates the opportunity to redefine what constitutes a scientific drilling platform and encourages "high risk" proposals in new areas of science.

One of the most successful MSP approaches has been to adapt shore-based mining technologies for use on traditional offshore platforms. This approach was successfully implemented for Expedition 310 (Tahiti Sea Level), Expedition 313 (New Jersey Shallow Shelf), and Expedition 364 (Chicxulub Impact Crater). The smaller cutting surface area of the drill bits and coring tools used by these systems, in combination with a raised platform (Expeditions 313 and 364 only) standing on the seabed (photo), makes possible higher core recovery and better core quality in lithologies that otherwise are challenging to drill by wider-diameter systems deployed from floating platforms.

More recently, the introduction of seabed robotic drilling is yielding promising results. During Expedition 357 (Atlantis Massif Serpentinization and Life), when these drills were first applied for IODP, they achieved a new record in core recovery (up to 75%) for the uppermost 15 m in exposed hard rock environments. The robotic drills provide a future vehicle for other technologies and experiments to be developed and implemented in support of scientific ocean drilling. For example, using such a drill, Expedition 357 deployed novel water sensor and sampling assemblies to study in situ ephemeral fluid properties and installed borehole plug systems that offer the opportunity to repeatedly revisit these sites to resample equilibrated borehole fluids.

The flexibility of using MSPs offers the scientific community opportunities to take advantage of new technologies or employ existing technologies in innovative ways. Using the MSP approach will be critical for future scientific ocean drilling projects that require both onshore and offshore experiments. MSPs remain the only way for the scientific ocean drilling community to investigate areas where no drilling platform has gone before.

— David McInroy and Gilbert Camoin

Platforms such as Liftboat *Myrtle* that sit on the seabed provide a stable environment for drilling and coring, resulting in higher core recovery. *Credit: D. Smith*

MISSION SPECIFIC PLATFORMS STATISTICS

Number of expeditions	8
Number of sites	80
Number of holes	137
Number of cores	3,547
Number of expedition operational days	609*
Total distance drilled	10,241 m
Total distance cored (attempted)	8,424 m
Length of core recovered	6,672 m
Average core recovery (all expeditions)	79%
Most core recovered on a single expedition	1,645 m (Exp. 381)
Highest recovery on a single expedition	100% (Exp. 364)
Deepest borehole	1,335 mbsf (Exp. 364)
Deepest water depth	1,568 m (Exp. 357)
Shallowest water depth	19.8 m (Exp. 364)
Highest latitude	87°56.0'N (Exp. 302)
Distance traveled	38,745 nm

*Offshore and Onshore Science Party

Contributions of Scientific Ocean Drilling to Understanding the Emplacement of Submarine LARGE IGNEOUS PROVINCES and Their Effects on the Environment

By Clive R. Neal, Millard F. Coffin, and William W. Sager

Thin section production in progress, Integrated Ocean Drilling Program Expedition 324, Shatsky Rise. *Photo credit: John Beck, IODP/TAMU*

ABSTRACT. The Ontong Java Plateau (OJP), Shatsky Rise (SR), and Kerguelen Plateau/Broken Ridge (KP/BR) represent three large igneous provinces (LIPs) located in oceanic settings. The basement lavas have been investigated through scientific ocean drilling and, in the case of the OJP, fieldwork on the emergent obducted portions of the plateau in the Solomon Islands. Such studies show that these three LIPs have very different characteristics. For example, the KP/BR still has an active hotspot, whereas the OJP and the SR do not. The OJP is remarkable in its compositional monotony across the plateau (the Kwaimbaita geochemical type), with minor compositional variation found at the margins (the Kroenke, Singgalo, and Wairahito types). Shatsky Rise shows more compositional variation and, like the OJP, has a dominant lava type (termed the "normal" type) in the early stages (Tamu Massif), but subsequent eruptions at the Ori and Shirshov massifs comprise isotopically and trace element enriched lavas, likely reflecting a change in mantle source over time. The KP/BR has highly variable basement lava compositions, ranging from lavas slightly enriched above that of normal mid-ocean ridge basalt in the northern portion (close to the South East Indian Ridge) to more enriched varieties to the south and on Broken Ridge, with a continental crust signature present in lavas from the southern and central KP/BR. The OJP and the KP/BR appear to have formed through punctuated magmatic events, whereas the SR was formed by one relatively long, drawn out event. The formation of oceanic LIPs has in many (but not all) cases been synchronous with oceanic anoxic events. This paper focuses on three oceanic plateaus to emphasize the debate surrounding the environmental impact such LIPs may have had, and also highlights the contributions of scientific ocean drilling to our knowledge of oceanic LIP formation and evolution. This new knowledge allows planning for future oceanic LIP drilling.

INTRODUCTION

Volcanic plateaus on the ocean crust represent the oceanic equivalents of continental flood basalts. Some of these formed in nascent ocean basins (e.g., Kerguelen Plateau/Broken Ridge in the southern Indian Ocean), and the earliest outpourings contain the geochemical signature of continental crust contamination (e.g., Storey et al., 1992; Neal et al., 2002; Kinman et al., 2009). Others formed within an oceanic setting and are free from the contamination of continental crust, which allows an examination of the deeper mantle source regions for these voluminous eruptions (e.g., Shatsky Rise, Ontong Java Plateau, Hikurangi Plateau, and Manihiki Plateau in the Pacific Ocean; Heydolph et al., 2014; Fitton et al., 2004; Hoernle et al., 2010; Timm et al., 2011). This paper outlines scientific ocean drilling contributions to understanding the origins, evolution, and environmental impacts of three oceanic LIPs—the Ontong Java Plateau and the Shatsky Rise in the Pacific Ocean, and the Kerguelen Plateau/Broken Ridge in the Indian Ocean.

Ontong Java Plateau

The Ontong Java Plateau (OJP) is situated in the Southwest Pacific and covers an area of 1.86×10^6 km^2 (Coffin and Eldholm, 1994; Table 1), about the size of Alaska, Greenland, or Western Europe (Fitton and Goddard, 2004). However, OJP-like basalts also have been recovered from the Nauru, East Mariana, and Pigafetta basins that surround the OJP (e.g., Saunders, 1986; Castillo et al., 1992, 1994), more than doubling the area of these basalts to ~4×10^6 km^2. Based on a variety of geophysical data, the crustal thickness of the OJP is estimated to be between 30 km and 43 km, with an average around 36 km (e.g., Furumoto et al., 1970, 1976; Murauchi et al., 1973; Hussong et al., 1979; Miura et al., 1996; Richardson and Okal, 1996). Gladczenko et al. (1997) estimated the volume of the OJP to be between 44.4×10^6 km^3 and 56.7×10^6 km^3; the lower estimate is assuming the plateau formed on preexisting older oceanic crust and the higher assumes it formed on young crust at a spreading center. The OJP consists of two parts: the main, or High Plateau in the west and north and the Eastern Salient to the east, the latter having been split during the opening of the Stewart Basin (e.g., Neal et al., 1997; Figure 1a). The OJP lies generally between 2 km and 3 km water depth, although the central High Plateau region rises to ~1,700 m below sea level. The OJP is isostatically compensated (e.g., Sandwell and McKenzie, 1989), with much of the plateau surface being relatively smooth, but the top of the plateau is punctuated by several large seamounts, including Ontong Java atoll,

TABLE 1. Sizes of oceanic large igneous provinces.

Name	Area (10^6 km^2)	Volume (10^6 km^3)	References
Ontong Java Plateau	1.86	44–57	1,2,3
Manihiki Plateau	0.77	9–14	1,4
Hikurangi Plateau	0.4–0.8	6.4–18.8	5
Shatsky Rise	0.48	6.9	6
Kerguelen Plateau/Broken Ridge	2.3	15–24	1

1 = Coffin and Eldholm (1994) 2 = Neal et al. (1997)
3 = Gladczenko et al. (1997) 4 = Eldholm and Coffin (2000)
5 = Hoernle et al. (2010) 6 = J. Zhang et al. (2016)

Tauu atoll to the west, and Nukumanu atoll to the north (Figure 1a). The plateau has been considered the product of plume volcanism, formed through the pressure release melting of a large packet of mantle material rising from the deep interior as a bulbous plume head with a long tail that extends back to the source region (e.g., Richards et al., 1989; Campbell and Griffiths, 1990). In this scenario, the impact of the plume head on the rigid lithosphere should induce uplift (e.g., Griffiths et al., 1989; Hill, 1991), but the lack of subaerial volcanism at the thickest part of the OJP High Plateau, coupled with a lack of any identifiable plume tail evidence, has called the origin of the OJP via a surfacing plume head into question (e.g., Korenaga, 2005).

The OJP collided with the Solomon Arc along its southern and southwestern borders (Figure 1a), which promoted a change in subduction direction from the southwest to the northeast around 27–23 million years ago (Ma; Coleman and Kroenke, 1981; Cooper and Taylor, 1985; Petterson et al., 1997, 1999). Consequently, subaerial outcrops of OJP basalt are present on the islands of Malaita, Santa Isabel, Makira,

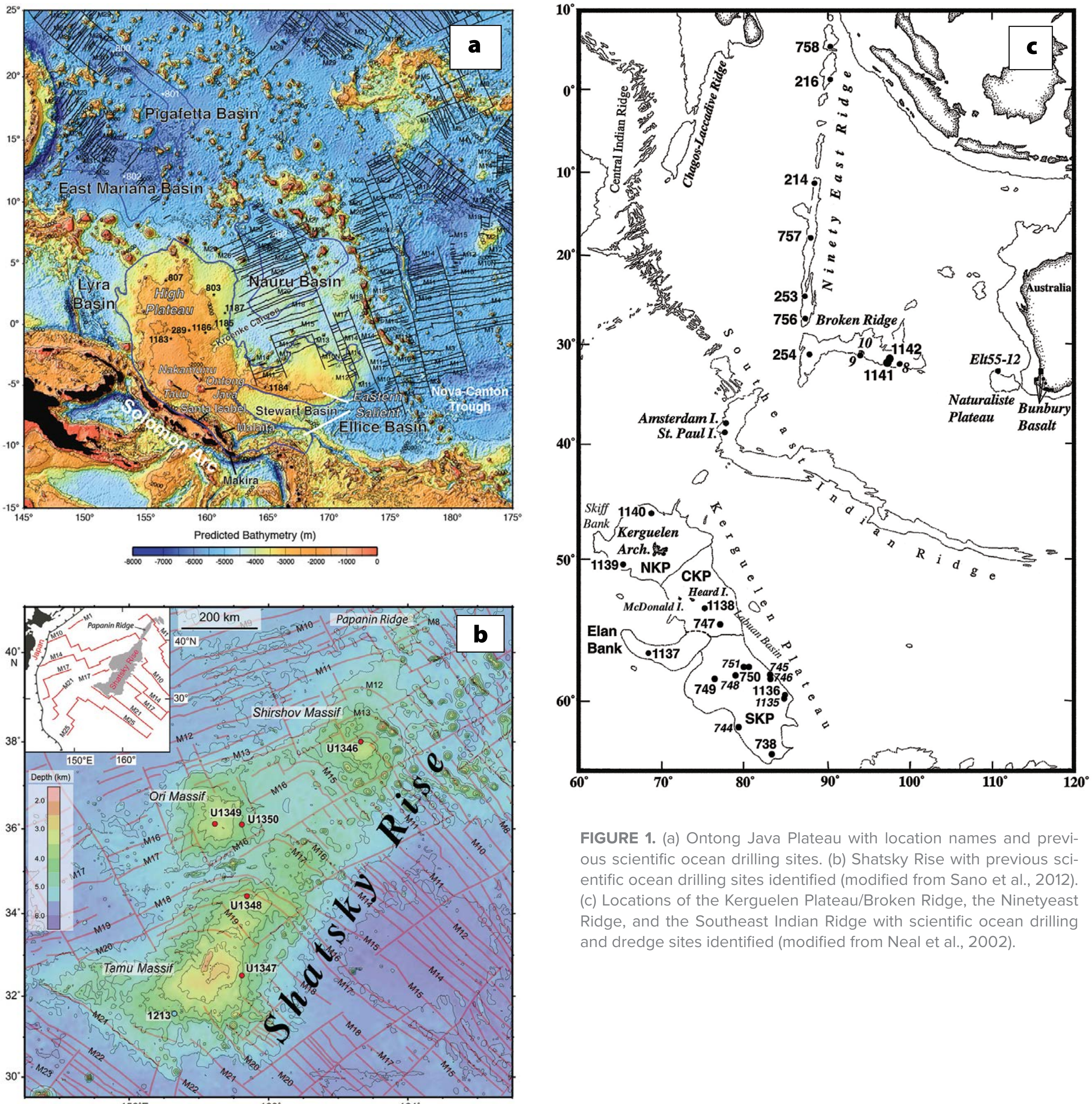

FIGURE 1. (a) Ontong Java Plateau with location names and previous scientific ocean drilling sites. (b) Shatsky Rise with previous scientific ocean drilling sites identified (modified from Sano et al., 2012). (c) Locations of the Kerguelen Plateau/Broken Ridge, the Ninetyeast Ridge, and the Southeast Indian Ridge with scientific ocean drilling and dredge sites identified (modified from Neal et al., 2002).

and Ramos, which have been examined through a number of field seasons (e.g., Petterson et al., 1997, 1999, 2009; Petterson, 2004; Tejada et al., 1996, 2002). Recently, it has been argued that the OJP may be much bigger than previously thought, as the Manihiki (~0.8×10^6 km^2; Coffin and Eldholm, 1994. Table 1) and Hikurangi (~0.5×10^6 km^2; Hoernle et al., 2010; Table 1) plateaus have been hypothesized to have formed with the OJP, but were subsequently rifted apart (Taylor, 2006; Chandler et al., 2012, 2015; Hochmuth et al., 2015).

Shatsky Rise

Shatsky Rise (SR), located ~1,500 km east of Japan, stretches over ~1,700 km and covers an area of ~0.5×10^6 km^2 (about the size of California), with an estimated igneous volume of 6.9×10^6 km^3 (J. Zhang et al., 2016; Table 1). It is proposed to have erupted at a triple junction of divergent plate boundaries due to the convergence of magnetic lineation groups at Shatsky Rise (e.g., Sager et al., 1988, 1999; Nakanishi et al., 1989). It is comprised of three principal volcanic massifs, Tamu, Ori, and Shirshov (Figure 1c; Sager et al., 1999). Tamu was built on oceanic crust of Late Jurassic-Early Cretaceous age, while the Ori and Shirshov massifs were built on progressively younger crust. The Tamu Massif, with a volume of 2.5×10^6 km^3, is thought to have erupted at flood basalt rates of ~1.7 km^3 yr^{-1} (Sager and Han, 1993), which is three orders of magnitude greater than the eruption rate of Kilauea (~0.002 km^3 yr^{-1}). This massif represents a shield volcano that could be the largest on Earth, rivaling the size of the largest such edifice in the solar system, Olympus Mons on Mars (Sager et al., 2013), with a maximum thickness of ~30 km (Korenaga and Sager, 2012). The size, morphology, and trend of decreasing edifice volume over time appears to fit the plume head hypothesis, with a transition from voluminous plume head eruptions at Tamu Massif to smaller-scale eruptions from the narrower plume tail farther along the plateau (Nakanishi et al., 1999; Sager, 2005). However, Shatsky Rise is unique among the large western Pacific oceanic plateaus because it formed during a time of magnetic reversals (Late Jurassic and Early Cretaceous, ~145–125 Ma) so that spreading ridge magnetic anomalies were recorded within the plateau, promising to allow the connection with mid-ocean ridges to be examined (Sager, 2005). This is corroborated by geochemical evidence pointing to a system with strong mid-ocean-ridge basalt characteristics.

Kerguelen Plateau/Broken Ridge

The conjugate Kerguelen Plateau/Broken Ridge (KP/BR) in the southern Indian Ocean (Figure 1b) together cover a vast area (~2.3×10^6 km^2—a little over three times the size of California; Coffin and Eldholm, 1994; Table 1), stand 2 km to 4 km above the surrounding ocean floor, and have thick mafic crusts of 15 km to 25 km (Charvis et al., 1995; Operto and Charvis, 1995, 1996; Borissova et al., 2003) and an estimated volume of 15–24 × 10^6 km^3 (Coffin and Eldhom, 1994; Table 1). In addition, it has been estimated that in total ~2.5×10^7 km of mafic crust has been produced from the Kerguelen hotspot source(s) since ~130 Ma (Coffin et al., 2002). The Cretaceous Kerguelen Plateau/Broken Ridge large igneous province (LIP) is interpreted to represent voluminous volcanism associated with arrival of the Kerguelen plume head below young Indian Ocean lithosphere (e.g., Coffin et al., 2002; Whittaker et al., 2015). Subsequently, rapid northward movement of the Indian Plate over the plume tail formed a 5,000 km long hotspot track from ~82 to 38 Ma, the Ninetyeast Ridge (e.g., Seton et al., 2012). The KP itself is divided into distinct domains: the southern (SKP), central (CKP), and northern Kerguelen Plateau (NKP); Elan Bank; and the Labuan Basin (Figure 1b). Multichannel seismic reflection data show that numerous dipping intra-basement reflections interpreted as subaerial flood basalts form the uppermost igneous crust of the Kerguelen Plateau/Broken Ridge (Coffin et al., 1990; Schaming and Rotstein, 1990). Magma output has varied significantly through time, beginning with low volumes contemporaneous with or postdating continental breakup in Early Cretaceous time, extending through at least one and possibly two peaks in Early and Late Cretaceous time into a preexisting and growing ocean basin, and finally tapering to relatively steady state output in Late Cretaceous and Cenozoic times.

At ~40 million years ago, the newly formed Southeast Indian Ridge (SEIR) intersected the Kerguelen plume's position. As the SEIR migrated northeast relative to the plume, hotspot magmatism became confined to the Antarctic Plate. From ~40 Ma to the present, the Kerguelen Archipelago, Heard and McDonald Islands, and a northwest-southeast trending chain of submarine volcanoes between these islands were constructed on the northern and central sectors of the Kerguelen Plateau/Broken Ridge. Taken together, a ~130 million-year long record of volcanism is attributed to the Kerguelen plume.

COMPOSITIONAL AND AGE DATA

Ontong Java Plateau

The OJP basement has been studied through Deep Sea Drilling Project (DSDP) Leg 30 (Site 289; Stoeser, 1975) and Ocean Drilling Program (ODP) Leg 130 (Sites 803 and 807; Kroenke et al., 1991; Mahoney et al., 1993a,b) and Leg 192 (Sites 1183–1187; Fitton et al., 2004). In addition, fieldwork has been conducted on the obducted portions of the OJP where they outcrop in the Solomon Islands on Santa Isabel, Malaita, Ulawa, Ramos, and San Cristobal (Makira) (Tejada et al., 1996, 2002; Birkhold-VanDyke et al., 1996; Neal et al., 1997; Petterson et al., 1997, 1999, 2009; Birkhold-VanDyke, 2000; Petterson, 2004). Four very similar basalt formations have been recognized: Kroenke, Kwaimbaita, Wairahito, and Singgalo, with the Kwaimbaita basalts being the most voluminous. The basalt compositions are similar (Figure 2a), but there are key differences in the incompatible trace element (ITE) abundances, ratios, and observed isotopic ratios, which give insights into magma chamber processes underlying OJP formation, as well as subtle differences in mantle source regions for these different basalt formations. The Singgalo and Wairahito basalts sit on top of the Kwaimbaita Formation, as do the Kroenke basalts (as demonstrated at Site 1185; Mahoney et al., 2001). The Kroenke Formation basalts are the most primitive (and ITE depleted; Figure 2a,d) recovered from the OJP, being magnesian tholeiites containing 11.8–13.2 wt.% MgO and relatively low abundances of ITEs (Fitton and Goddard, 2004). The Kwaimbaita and Singgalo Formations are named after type locality rivers on the island of Malaita (Tejada et al., 2002). Singgalo basalts correspond to the Unit A basalts and Kwaimbaita to Units C–G basalts (Unit B is a 1–2 m limestone interbed) from ODP Leg 130, Site 807, in the north of the High Plateau (Figure 1a; Mahoney et al., 1993a,b), and the Singgalo composition is also present at ODP Leg 192, Site 1183, as a vitric tuff in the sediment above the Kwaimbaita basalts (Tejada et al., 2004). The Wairahito Formation basalts are named after the type locality, Wairahito River, on the island of Makira (San Cristobal). The Kwaimbaita basalts are the most abundant type, found across the High Plateau and the Eastern Salient (Mahoney et al., 2001). They are evolved tholeiites containing generally 6–8 wt.% MgO, although the Kwaimbaita Formation basalts from the island of Ulawa are more primitive (9.8–11.2 wt.% MgO), but all Kwaimbaita type have higher abundances of ITEs than those from the Kroenke Formation (Figure 2a). The Wairahito Formation contains basalts that are even more evolved with higher ITE abundances (notably Nb) than the Kwaimbaita basalts (Figure 2a) and 4.5–7 wt.% MgO (Birkhold-VanDyke, 2000; Shafer et al., 2004; Petterson et al., 2009). Basalts from the Kroenke, Kwaimbaita, and Wairahito formations are isotopically indistinguishable from each other, indicating they were derived from similar mantle sources (e.g., Shafer et al., 2004; Tejada et al., 2004), and at least the Kroenke and Kwaimbaita basalts have been related by crystal fractionation of olivine (Fitton and Goddard, 2004). The Singgalo Formation

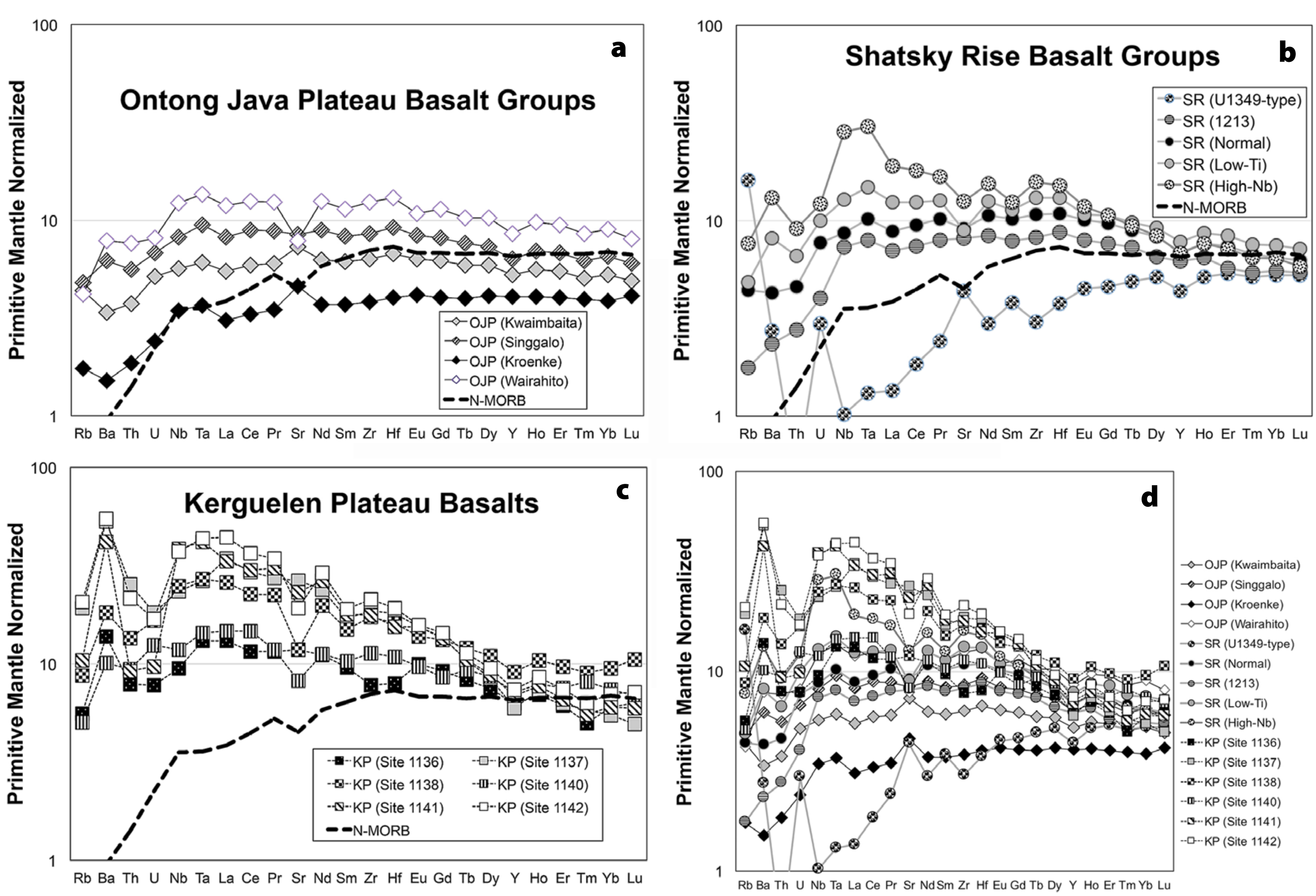

FIGURE 2. Primitive mantle normalized (Sun and McDonough, 1989) trace element plots of average basalt compositions from: (a) the Ontong Java Plateau (OJP; Birkhold-VanDyke et al., 1996; Birkhold-VanDyke, 2000; Petterson et al., 2009; Tejada et al., 1996, 2002, 2004; Fitton and Goddard, 2004; Shafer et al., 2004); (b) Shatsky Rise (SR; Mahoney et al., 2005; Sano et al., 2012); (c) Kerguelen Plateau/Broken Ridge (KP/BR) ODP Leg 183 data (Neal et al., 2002; Weis and Frey, 2002); and (d) all data on the same plot. Normal mid-ocean ridge basalt (N-MORB) composition taken from Sun and McDonough (1989).

is stratigraphically higher than the Kwaimbaita Formation and has similar MgO contents (6.3–7.8 wt.%), but higher abundances of the ITEs (Figure 2a). This is seen across the plateau from the islands of Malaita, Makira, and Santa Isabel in the south of the OJP to ODP Leg 130 Site 807 in the north, and since the Singgalo basalts are isotopically distinct, they must have been derived from a different source region than the Kroenke, Kwaimbaita, and Wairahito basalts (Mahoney et al., 1993a,b; Tejada et al., 1996, 2002; Birkhold-VanDyke, 2000).

The bulk of the OJP formed around 122 Ma with vast outpourings of submarine lava flows that are remarkable for the overall homogeneity of their basalt compositions (e.g., Tejada et al., 1996, 2002; Chambers et al., 2002, 2004; Fitton and Goddard, 2004). Kwaimbaita Formation basalts are found across the plateau, including from the Solomon Islands in the south (Santa Isabel, Malaita, Ulawa, Makira) and at all cored sites (except Site 1187 that recovered only Kroenke basalts). Distinct plagioclase-rich cumulate xenoliths are also found in some Kwaimbaita flows across the plateau (Kinman and Neal, 2006). Although the Singgalo Formation basalts are stratigraphically above those of the Kwaimbaita formation, the $^{40}Ar/^{39}Ar$ ages of the former are indistinguishable within the relatively large (±1–2 million year) analytical age uncertainties (e.g., Mahoney et al., 1993a,b; Tejada et al., 2002). The Kroenke Formation basalts, potentially the parent to the Kwaimbaita basalts (Fitton and Goddard, 2004), are found only at Sites 1185 and 1187 from ODP Leg 192, and a few basaltic clasts from Site 1184 have the Kroenke basalt signature (Shafer et al., 2004). The Wairahito Formation basalts are known only from Makira in the Solomon Islands and again as clasts in the volcaniclastic sequence from Site 1184 (Birkhold-VanDyke, 2000; Shafer et al., 2004). The unaltered basaltic glass in the lower portion of the Site 1184 core is of Kwaimbaita composition (White et al., 2004). Thus, from what we know so far about the OJP, the variation in basaltic types occurs around the margins of the plateau. There were also periodic eruptions subsequent to the main ~122 Ma outpouring of magma, again concentrated around the edge of the plateau, that produced Kwaimbaita-type lavas. This could occur through periodic remelting of the Kwaimbaita source at progressively lower degrees of partial melting (Birkhold-VanDyke et al., 1996; Birkhold-VanDyke, 2000). Compiling the Ar-Ar ages for OJP basalts yields the following eruption periods (all uncertainties are 1 sigma of the mean):

- 121.1 ± 3.8 Ma, n = 26 (ODP Sites 289, 807, 1183, 1184, 1185, 1886, 1187; islands of Malaita, Ramos, Santa Isabel). Data from Mahoney et al. (1993a,b), Chambers et al. (2002, 2004), Tejada et al. (1996, 2002).
- 90.5 ± 3.3 Ma, n = 13 (ODP Site 803; islands of Makira, Santa Isabel). Data from Mahoney et al. (1993a,b), Tejada et al. (1996), Birkhold-VanDyke et al. (1996), Birkhold-VanDyke (2000).
- 61.1 ± 4.6 Ma, n = 8 (islands of Makira and Santa Isabel). Data from Tejada et al. (1996), Birkhold-VanDyke et al. (1996), Birkhold-VanDyke (2000).
- 36.6 ± 1.2 million years ago, n = 4 (island of Makira). Data from Birkhold-VanDyke et al. (1996), Birkhold-VanDyke (2000).

Shatsky Rise

This oceanic plateau was drilled sporadically by DSDP and ODP, principally for paleoceanographic data from its carbonate sediment cap (e.g., Bralower et al., 2006). The basement of Shatsky Rise was drilled during ODP Leg 198 (Site 1213 on Tamu; Shipboard Scientific Party, 2002; Mahoney et al., 2005) and Integrated Ocean Drilling Program (IODP) Expedition 324 (Sites U1346 on Shirshov; U1347, U1348 (volcaniclastics only) on Tamu; U1349, U1350 on Ori; Expedition 324 Scientists, 2010; Sano et al., 2012). Cores recovered both pillow lavas and massive flows, with a trend from thick, massive flows at Tamu Massif to mainly pillow lavas at Shirshov Massif. The core interval recovered at Site U1347, with intervals of massive flows separated by pillow lavas, appears much like that from Leg 192 Sites 1185 and 1186 on the OJP (Shipboard Scientific Party, 2001), implying similar volcanic emplacement. The shift in volcanic style with time is consistent with the expected waning of volcanism from high effusion (thick, massive flows) to lesser effusive outpourings (pillow lavas) with the transition from plume head to tail (Sager et al., 2011, 2016).

The picture that emerged was that Shatsky Rise, although a large LIP, has strong links to and geochemical similarities with mid-ocean ridges (Mahoney et al., 2005; Sager, 2005). Five magma types have been described from the plateau: normal, low-Ti, high-Nb, and U1349 types (Figure 2b; Sano et al., 2012). Additionally, the basalts from Site 1213 (Leg 198) are also distinct, being depleted relative to the normal-type (Figure 2b). The normal type basalt composition is the most abundant in volume, appears on all three massifs, and is similar to normal mid-ocean ridge basalt (N-MORB) composition, but with a slight relative enrichment of the highly ITEs. The low-Ti type is distinguished from the normal type basalt by slightly lower Ti contents at a given MgO, and slight enrichment of the more incompatible ITEs (Figure 2b). The compositions of high-Nb basalts are characterized by distinctively higher contents of the ITEs relative to the other types. U1349 type basalts are composed of more primitive and depleted compositions compared with other SR basalts (Figure 2b). Modeling demonstrates that compositions of the normal-, low-Ti-, and high-Nb-type basalts evolved through fractional crystallization of olivine, plagioclase, and augite in shallow magma chambers (Sano et al., 2012; Heydolph et al., 2014), akin to mid-ocean ridge volcanism.

Ages (Ar-Ar plateau) for Shatsky Rise were derived from two samples of basalts from Tamu Massif Site 1213 (Leg 198) by Mahoney et al. (1995) of 143.7 ± 3.0 Ma and 144.8 ± 1.2 Ma. A longer section of cored basalt was recovered by Expedition 324 at Tamu Massif and yielded basalt ages of 143–144 Ma in the lower portion, but a significantly younger age of 133.9 ± 2.3 Ma was obtained in the upper section (Geldmacher et al., 2014). Compiling of $^{40}Ar/^{39}Ar$ (Mahoney et al., 2005; Koppers, 2010; Geldmacher et al., 2014; Heaton and Koppers, 2014; Tejada et al., 2016) and magnetic anomaly (Sager et al., 1999; Nakanishi et al., 1999) ages shows an age progression to the northeast from Tamu Massif (~144–129 Ma) and the Ori Massif (142–134 Ma) to Shirshov Massif (137–136 Ma), with the Papanin Ridge yielding ages of 128–121 Ma.

Kerguelen Plateau/Broken Ridge

Basement material has been recovered through drilling on Broken Ridge and each part of the Kerguelen Plateau during ODP Legs 119 (Site 738), 120 (Sites 747, 749, 750), and 183 (Sites 1136-1142). Only Leg 183 recovered basalt from Broken Ridge (Sites 1141–1142), with scientific dredging on Broken Ridge affording additional samples from this part of the KP/BR (e.g., Mahoney et al., 1995). Compositions are dominantly tholeiitic, but are highly variable across the Kerguelen LIP (Figure 2c), with alkali basalts sitting atop Broken Ridge, and trachytes, dacites, and rhyolites found at Sites 1137 (as clasts in conglomerate horizons) and 1139 on Skiff Bank (Frey et al, 2000). The latter is interpreted to be part of a later shield volcano constructed on top of the basaltic plateau (Kieffer et al., 2002). The geochemical data show that a continental component must be present in some of the KP/BR basement lavas (e.g., Frey et al., 2002; Ingle et al., 2002a; Neal et al., 2002), perhaps derived from the Eastern Ghats of eastern India for Site 1137 (Nicolaysen et al., 2001; Ingle et al., 2002a,b). Continental remnants must therefore have occurred at shallow depths within the Indian Ocean lithosphere and contaminated the rising mantle-derived melts. The basalts recovered from CKP Site 1138 and NKP Site 1140, however, do not contain the continental crustal signature (Neal et al., 2002).

Duncan (2002) reported basement ages for the Leg 183 basalts, and Whitechurch et al. (1992) for Leg 120 basalts. Their basalt $^{40}Ar/^{39}Ar$ plateau ages from SKP Sites 749, 750, and 1136 are 109 ± 0.7 Ma, 118.2 ± 5 Ma, and 118.99 ± 2.11 Ma, respectively; from Elan Bank Site 1137, the age is 107.53 ± 1.04 Ma; from CKP Sites 1138 and 1139, the ages are 100.51 ± 1 Ma and 68.57 ± 0.61 Ma, respectively; from NKP Site 1140 is 34.34 ± 1.22 Ma, and from Broken Ridge Sites 1141 and 1142, the ages are 95.17 ± 0.77 Ma and 94.87 ± 0.91 Ma, respectively. On the basis of these data, the Kerguelen Plateau/Broken Ridge has been built in several stages over the last ~130 million years.

Paleolatitudes of Kerguelen Plateau/Broken Ridge and Ninetyeast Ridge basalts suggest 3°–10° southward motion of the hotspot relative to the rotation axis, a finding that can be modeled by large-scale mantle flow influencing the location of the plume conduit (Antretter et al., 2002). At ~40 Ma, the newly formed SEIR intersected the plume's position. As the SEIR migrated northeast relative to the plume, hot spot magmatism became confined to the Antarctic plate. From ~40 Ma to the present, the Kerguelen Archipelago, Heard and McDonald Islands, and a northwest-southeast trending chain of submarine volcanoes between these islands were constructed on the northern and central sectors of the Kerguelen Plateau/Broken Ridge.

Combined with the above results and age determinations for basalt from the Ninetyeast Ridge (Duncan, 1978, 1991), age determinations from basalt and lamprophyre attributed to the Kerguelen hotspot in India, Western Australia, and Antarctica (Coffin et al., 2002; Kent et al., 2002) make the ~130 million-year-long record of Kerguelen hotspot activity the best documented of any hotspot trace on Earth. Magma output has varied significantly through time, beginning with low volumes contemporaneous with or postdating continental breakup in Early Cretaceous time, extending through at least one and possibly two peaks in Early and Late Cretaceous time into a preexisting and growing ocean basin, and finally tapering to relatively steady state output in Late Cretaceous and Cenozoic time. The 25 million-year-long duration of peak hotspot output at geographically and tectonically diverse settings is challenging to reconcile with current plume models. Coffin et al. (2002) proposed two alternatives to the standard Hawaii model for hotspots, one involving multiple mantle plume sources and the other a single, but dismembered, plume source. Alternatively, Lin and van Keken (2005) proposed a model of secondary instabilities resulting from the interaction between thermal and compositional buoyancy forces in a thermochemical mantle plume.

LIP PETROGENESIS

The three oceanic LIPs described here represent three different examples of flood magmatism. The OJP and SR contain basalts that have ~MORB-like compositions, but both have a "high-Nb" magma type ("Wairahoito-type" on the OJP; "high-Nb-type" on the SR) that is distinct from MORB (Figure 2a,b). No basalt from the OJP or SR contains any evidence of a continental signature in their basalt compositions. The KP/BR does contain a continental crustal signature in some of the basalts so far recovered, predominantly in the southern and central portions. The basalt ages for the different LIPs also suggest differences: the OJP appears to have erupted regularly every ~30 million years after the ~122 Ma eruption (which was the largest), whereas SR basalt ages indicate that the main edifices were created near the time of surrounding lithosphere formation (Geldmacher et al., 2014; Heaton and Koppers, 2014; Tejada et al., 2016), implying that volcanism occurred at or near the spreading ridges (consistent with the MORB-like character of the lavas). The KP was initiated at the breakup of India, Antarctica, and Australia, with trapped continental selvages at least in the SKP and CKP.

It also appears that magmatic flux waxed and waned in that the KP/BR was built in stages (Duncan, 2002). Explaining the origin of these three LIPs through a unified model has proven difficult.

Ontong Java Plateau

Much of the OJP was erupted in deep water, which was used to argue against a plume head origin for the plateau (e.g., Korenaga, 2005). The central portion of the OJP was taken to be on the High Plateau (Figure 1a) where the crust is thickest, but lavas recovered here at Site 1183 still showed deepwater eruptions, as did other sites on the high plateau (Fitton and Goddard, 2004; Roberge et al., 2004, 2005). Evidence for subaerial eruptions, as expected from a surfacing thermal plume (Campbell, 2007), surprisingly came from the only Eastern Salient drilling, at Site 1184 (Figure 1a), where the volcaniclastic sediment contain glass shards indicating shallow eruption (Roberge et al., 2005), and several horizons of carbonized wood were recovered in the volcaniclastic sequence (Shipboard Scientific Party, 2001; Thordarson, 2004). Neal et al. (1997) predicted there was between 1 km and 4 km of uplift if the OJP formed from a surface plume head. As noted above, this was not over the thickest part of the OJP, as Site 1183 gave an eruption depth of over a kilometer (Roberge et al., 2005), but actually in the Eastern Salient at Site 1184. Using the basalt compositions, estimates of partial melting for the OJP range from ~23%–30% of garnet peridotite (Fitton and Goddard, 2004) or melting over a pressure range (i.e., polybaric melting) that started in garnet peridotite and ended shallower in spinel peridotite (Neal et al., 1997). These melting conditions are consistent with a rising plume head to explain the OJP, but there is no evidence of a long-lived hotspot track associated with the OJP, as plate reconstructions show that the nearby Louisville seamount chain is not a viable candidate (e.g., Yan and Kroenke, 1993).

Taylor (2006) suggested that, based upon seafloor fabric data, three oceanic plateaus in the western Pacific (Ontong Java-Manihiki-Hikurangi; Figure 3) were all formed by a singular huge magmatic event and subsequently rifted apart. For example, comparison of seafloor fabric data between the Hikurangi and the Manihiki plateaus shows they have conjugate margins separated by a former spreading center, the Osbourn Trough (Billen and Stock, 2000; Figure 3) that opened up and separated them (Taylor, 2006). Ages of Integrated Ocean Drilling Program Expedition 329 basalts collected just north of the Osbourn Trough indicate that rifting of the Hikurangi and Manihiki plateaus was "superfast" (~190 mm yr^{-1}), and that the ocean floor basalts produced by this now extinct spreading center were akin to basalts from the Ontong Java and Manihiki plateaus (G.-L. Zhang and Li, 2016). Subsequent kinematic plate reconstructions also show the plausibility of this hypothesis (Chandler et al., 2012, 2015; Hochmuth et al., 2015), which has been termed the Ontong Java Nui or Greater Ontong Java event. These three plateaus sit on ocean crust of similar ages, show similarities in their basalt compositions (Figure 4) and seismic velocity structures, and formed at roughly the same time (Ingle et al., 2007; Hoernle et al., 2010; Timm et al., 2011; Chandler et al., 2012, 2015; Hochmuth et al., 2015; Golowin et al., 2018). Interestingly, reconstruction of these oceanic plateaus to when they were conjoined shows the central portion located around the Eastern Salient of the OJP, the only part that once was subaerial. While this is consistent with the plume model, the lack of a plume tail for these plateaus is not. Also,

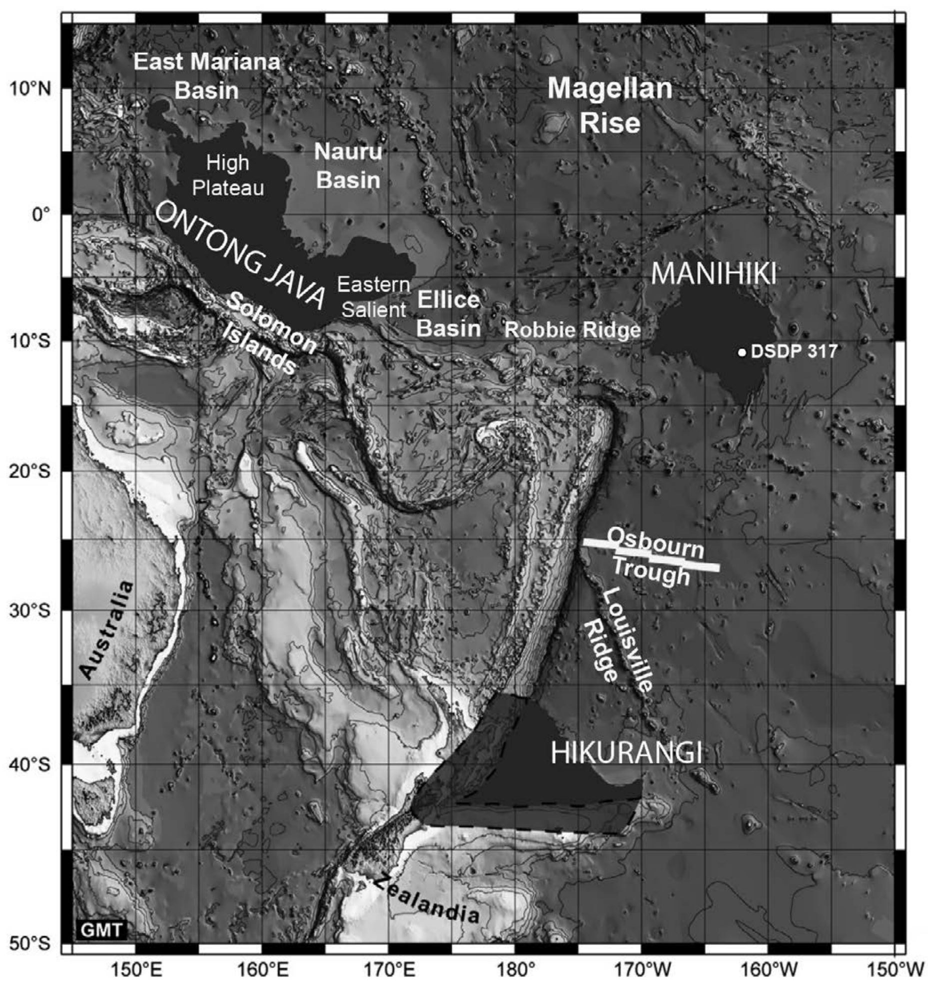

FIGURE 3. Map of the Western Pacific with Ontong Java, Manihiki, and Hikurangi Plateaus and location names. *Map modified from Hoernle et al. (2010)*

if the three plateaus formed at the same time, it would represent the largest magmatic event recorded (~59–90 × 10^6 km^3 of magma production; Table 1).

Shatsky Rise

Geochemical data from most cored lavas give major element ratios that are near normal MORB but trace elements that imply deeper melting than at normal mid-ocean ridges (Sano et al., 2012). Both major element geochemistry and immobile trace element geochemistry indicate 15%–23% partial melting, greater than normal mid-ocean ridge values (Sano et al., 2012; Husen et al., 2013) but less than the 30% estimated for the OJP (Neal et al., 1997; Fitton and Goddard, 2004). The degree of melting implies slightly (~50°C) higher mantle temperatures than normal (Sano et al., 2012; Sager et al., 2016).

IODP Expedition 324 was envisioned as a test between competing hypotheses for the formation of oceanic plateaus: a thermal mantle plume head (Richards et al., 1989; Coffin and Eldholm, 1994) versus shallow, plate-controlled volcanism (Foulger, 2007). Many of the results from the expedition can be framed by the plume head model (e.g., Heydolph et al., 2014). Physical characteristics, including crustal thickness, large magmatic emplacement, apparent rapid emplacement, and possible formation at the edge of the Pacific LLSVP (Large Low Shear-wave Velocity Province; Burke et al., 2008) are all consistent with the plume head hypothesis. Deeper melting than normal MORB, greater percentage of partial melt, and greater than normal temperature are also consistent with this model. Other characteristics can be similarly interpreted. Whereas Tamu Massif lavas are homogeneous in composition with nearly normal MORB chemistry, those from the other massifs are more heterogeneous, including some that are enriched both isotopically and in incompatible trace elements, interpreted as evidence that the source contained recycled oceanic crust, possibly brought up from the lower mantle (Heydolph et al., 2014). The shift to more heterogeneous geochemistry with the lesser volcanic flux of smaller Shatsky Rise edifices was suggested to be indicative of a plume head to plume tail transition because modeling indicates that lower mantle chemical heterogeneities can be preserved in plumes with predominantly vertical motion and limited stirring and at lower degrees of melting (Farnetani et al., 2002; Heydolph et al., 2014). Shatsky Rise samples are also anomalous in $^3He/^4He$ ratios, which were found to be lower than MORB values (Hanyu et al., 2015). Similarly, vanadium isotopes were also found to be different than those found in MORB (Prytulak et al., 2013).

Despite the seeming preponderance of evidence pointing toward a plume source, the connection with ridge volcanism was also strengthened, and some of the plume indications are unequivocal. For example, while the predominant lava type is close to MORB in major element and isotopic chemistry (Sano et al., 2012), some characteristics interpreted as favoring a plume origin, including volume, flux, volume and flux variations over time, and high degrees of partial melting, could also occur from shallow melting of a fertile source (e.g., King and Anderson, 1995; Foulger, 2007). However, geochemical modeling indicates a shallow source could not have generated the erupted basalt compositions (Sano et al., 2012; Husen et al., 2013).

Other indicators are equivocal. Although basal sediments cored on Expedition 324 were deposited in shallow water (Sager et al., 2011), in accord with evidence from volatiles that eruptions were in water <1 km deep (Shimizu et al., 2013), there is little core or geophysical evidence of significant subaerial exposure (Sager et al., 2013, 2016). This does not support the prediction of significant uplift by a thermal plume (Campbell, 2007). Furthermore, the inferred anomalous temperature is much less than expected (~100°–200°C) for a strong thermal plume. Other inferences are model-dependent. Compositional heterogeneity, although indicative of source heterogeneity, does not necessarily imply a deep plume. Likewise, recycled crust can be found at shallow depths (Foulger, 2007), and is not necessarily material recycled to the deep mantle. Moreover, the Jurassic position of Shatsky Rise is probably

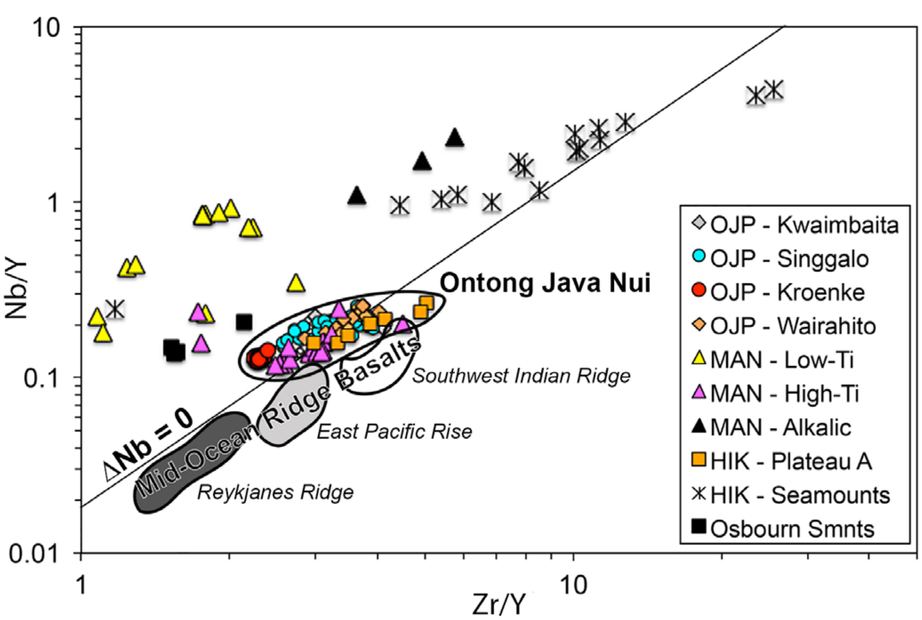

FIGURE 4. Zr/Y vs. Nb/Y plot for Ontong Java, Manihiki, and Hikurangi basalts after Fitton et al. (1997). Data sources as in Figure 2 plus Ingle et al. (2007), Hoernle et al. (2010), Timm et al. (2011), Golowin et al. (2018). OJP = Ontong Java Plateau. MAN = Manihiki. HIK = Hikurangi.

uncertain by ~1,000 km because of poor constraint on the total northward drift of the Pacific Plate during the Cretaceous. As a result, its reconstructed position relative to the LLSVP is also not well known.

Recent research into improving the mapping of magnetic anomalies over Shatsky Rise provides a stronger link to mid-ocean ridge volcanism, indicating that all of the massifs record linear anomalies and thus were formed by spreading (Huang et al., 2018). These results suggest that whatever the source of the Shatsky Rise volcanism, it occurred through a spreading center (which was the path of least resistance), and this may be why many oceanic plateaus apparently formed near spreading ridges. The reason that Expedition 324 research was unable to separate plume from plate mechanisms may be that they are inextricably intertwined (Sager et al., 2016).

Kerguelen Plateau/Broken Ridge

The uppermost basement lavas forming the LIP range widely in Sr, Nd, and Pb isotopic ratios, and each scientific ocean drilling site has distinctive isotopic characteristics (Frey et al., 2003). This points toward differences in source materials and their proportions in the Kerguelen mantle source(s). Site 1140 basalt erupted within 50 km of the SEIR axis at 34 Ma, and the geochemical characteristics of Site 1140 lavas can be explained by mixing, in varying proportions, components derived from the Kerguelen plume and the source of SEIR MORB (Weis and Frey, 2002). In contrast, lavas from Site 738 on the SKP (Mahoney et al., 1995), and from Site 1137 on Elan Bank have radiogenic isotopic ratios that reflect a small and variable but significant role for continental crust in their petrogenesis (Weis et al., 2001; Ingle et al., 2002b). The isotopic evidence indicating a role for continental crust correlates with a relative depletion in abundance of Nb. As to the origin of the continental components contributing to the LIP lavas, intercalated within the basaltic flows at Site 1137 is ~26 m of fluvial conglomerate with clasts of garnet-biotite gneiss containing zircon and monazite (Frey et al., 2000) of Proterozoic age (Nicolaysen et al., 2001). This constitutes the first and only unequivocal evidence of the presence of continental crust within the Kerguelen Plateau/Broken Ridge and in any other oceanic plateau drilled so far. The geochemical data indicate that the signature of continental crust is widely distributed in Cretaceous basalt forming the uppermost basement of the LIP. The most compelling examples are at Site 738 (SKP), Site 1137 (Elan Bank), and Site 747 (CKP) (Mahoney et al., 1995; Ingle et al., 2002b; and Frey et al., 2002, respectively).

A plume source, but more complex than a single plume head and tail model, for the basalt forming the Kerguelen Plateau/Broken Ridge remains a viable hypothesis. Like the active plumes of Hawaii, Iceland, and the Galápagos, lavas forming the Kerguelen Plateau/Broken Ridge are isotopically heterogeneous. Challenging questions posed here are: to what extent is this heterogeneity intrinsic to the plume, and to what extent does the heterogeneity reflect mixing between quite different components, such as oceanic and continental lithosphere. For lavas from some of the Kerguelen Plateau/Broken Ridge sites, the isotopic heterogeneity undoubtedly reflects mixing of plume-related components with components derived from depleted asthenosphere (Site 1140) or continental lithosphere (Sites 738, 747, and 1137; Frey et al., 2003).

Evidence from ODP Legs 119, 120, and 183 clearly demonstrates that large parts of the SKP and CKP that are now submarine were originally subaerial during at least the final stages of plateau construction (Coffin et al., 2000; Mohr et al., 2002). Subsidence estimates for ODP drill sites indicate that the various parts of the Kerguelen Plateau/Broken Ridge subsided at a rate comparable to that for normal Indian Ocean lithosphere (Coffin, 1992; Wallace, 2002). Hence, the original maximum elevations would have been 1 km to 2 km above sea level, and much of the SKP's ~500,000 km^2 area would at one time have been above sea level (Coffin, 1992). The SKP and CKP supported a dense conifer forest with various fern taxa and early angiosperms in late Albian to earliest Cenomanian time (Francis and Coffin, 1992; Mohr et al., 2002). By latest Cenomanian time, the CKP had subsided to a depth that allowed open marine sediments to accumulate.

On Broken Ridge, the vesicularity and oxidative alteration of basement basalts at Sites 1141 and 1142, which formed close to the CKP (Figure 1), are also consistent with a subaerial environment (Keszthelyi, 2002). At SKP Site 1136, inflated pāhoehoe lavas lack features of submarine volcanism (e.g., pillows and quenched glassy margins), suggesting subaerial eruption. The igneous basement complex of Elan Bank (Site 1137) includes basaltic lava flows that erupted subaerially, as indicated by oxidation zones and the presence of inflated pāhoehoe flows. Some interbedded volcaniclastic rocks were deposited in a fluvial environment, consistent with subaerial eruption of the basalt. The NKP (Site 1139) was also subaerial during its final stages of formation, as indicated by a succession of variably oxidized volcanic and volcaniclastic rock. After volcanism ceased, paleoenvironments changed from intertidal (beach deposits) to very high-energy, nearshore (grainstone and sandstone), to low-energy offshore (packstone), to bathyal pelagic (ooze) (Coffin et al., 2000).

ENVIRONMENTAL IMPACT

It has been hypothesized that eruption of flood basalts affected the surface environment (e.g., Self et al., 2005, 2008) and potentially prompted mass extinctions (e.g., Keller, 2005). The extent of environmental impact related to LIP volcanism depends on whether eruptions were subaerial or submarine, and whether the magma passed through coal, petroleum, and/or evaporite deposits on the way to the surface, supplementing the magma's volatile content (Neal et al., 2008; Svensen et al., 2009). The other important factor in assessing the environmental impact of LIP formation is determining the flux of volcanism. It is unfortunate that many of the erupted lavas are low-K tholeiites, as the uncertainty of $^{40}Ar/^{39}Ar$ ages is usually between one and two million years. This uncertainty makes it impossible to assess the flux of volcanism during LIP formation and to determine how many eruptive episodes there were, though these topics remain top priorities in understanding LIP formations and their impacts on the environment (Neal et al., 2008).

Evidence indicates a link between LIP formation and environmental crises. For example, the largest mass extinction at the Permo-Triassic boundary was synchronous with the eruption of the Siberian and Emeishan Traps (Wignall, 2005; Wignall et al., 2009). Oceanic LIP formation would have had a more subtle environmental impact, given the general submarine nature of the eruptions (e.g., Ernst and Youbi, 2017). In order for submarine LIP formation to generate a global impact on the ocean, the ocean needs to be well mixed, but LIP volcanism alone could not have released enough CO_2 to have a global environmental impact (e.g., Kerr, 2005; Kerr and Mahoney, 2007; Naafs et al., 2016). However, it is likely that a complex positive feedback mechanism triggered by the volcanically derived CO_2 led to increased CO_2 and elevated temperatures associated with submarine oceanic plateau volcanism (e.g., Kerr, 2005). The initial emissions from oceanic plateau volcanism were probably a mixture of CO_2, SO_2, and halogens (Self et al., 2005), which would have made the ocean at least more anoxic and acidic locally. This increased acidity would have led to the dissolution of shallow-water carbonates, thus releasing more CO_2 to the ocean and the atmosphere (Kerr, 2005). In addition, the main phase of Ontong Java Plateau formation (~120 Ma) appears to correlate with a massive release of methane, which may have come from warming of methane hydrate that had been stored beneath the ocean floor (Jahren, 2002; Naafs et al., 2016). As CO_2 solubility decreases, the warmer the ocean water becomes. Kerr (1998) proposed that such a scenario would relatively rapidly result in the establishment of a runaway greenhouse effect. Also contributing to oceanic anoxia is the fact that a warmer ocean dissolves less O_2 (de Boer, 1986).

The reaction of O_2 with trace metals and sulfides in hydrothermal fluids as well as enhanced phytoplankton growth also decrease the amount of oxygen in seawater (Sinton and Duncan, 1997). Injection of a large hydrothermal plume could easily rise through the water column and spread laterally over a significant proportion of the ocean's surface. The metal-rich waters of such massive hydrothermal plumes may well have stimulated increased levels of organic productivity (e.g., increased iron can stimulate phytoplankton productivity) in nutrient-poor surface waters (Coale et al., 1996; Sinton and Duncan, 1997). Such productivity could have led to further oxygen reduction in ocean waters as organic material decayed and sank through the water column.

While there is evidence for the subaerial eruption of parts of the KP/BR and OJP, most of these plateaus (and SR) formed through submarine eruptions. If the Ontong Java, Manihiki, and Hikurangi plateaus formed from a "superplume" event (see Larson, 1991), the environmental impact may have been immense. A global oceanic anoxic event (OAE-1a or the "Selli" event at 124–122 Ma; Coccioni et al., 1987; Méhay et al., 2009) was coincident with the initial (and largest) eruption of the OJP at ~122 Ma. Tejada et al. (2009) show a causative link between OJP emplacement and OAE-1a using osmium isotopes, where two large influxes of non-radiogenic osmium were observed within a period of ~2 million years starting in the lower Aptian and ending just above OAE-1a. These Os influxes are consistent with huge outpourings of mantle-derived submarine basalts though major eruptions at the formation of the Ontong Java Nui. While the formation of the OJP (and potentially the formation of the Manihiki and Hikurangi Plateaus) had global implications for the surface environment, this event also changed the nature of the upper mantle in the western Pacific. The oceanic crust that pre-dates this event is different in composition from that which post-dates it (Janney and Castillo, 1997).

Shatsky Rise erupted prior to the OJP over a period of ~24 million years, from 145 Ma to 121 Ma, with the largest eruptions occurring earlier and volcanism waning thereafter (e.g., Sager et al., 2016; Tejada et al., 2016). Two OAEs over this period have been reported: the Weissert Event (late Valanginian at ~140.5 Ma) and the Faraoni Event (late Hauterivian at ~131 Ma) (e.g., Erba et al., 2004; Jenkyns, 2010). OAEs were also forming during the construction of the KP/BR (OAE-1b,c,d occurring at approximately 111.5 Ma, 103–104 Ma, and 100 Ma, respectively; e.g., Erba, 2004). This suggests that all three LIPs studied here had major effects on ocean chemistry, although the links between the SR and the KP/BR with OAEs are not as compelling as the link between the OJP and OAE-1a (e.g., Tejada et al., 2009).

FUTURE OCEANIC LIP DRILLING

In 2007, a multidisciplinary group of 80 scientists met July 22–25 at the University of Ulster in Coleraine, Northern Ireland, to discuss strategies for advancing our understanding of LIP formation, evolution, and environmental impacts (Neal et al., 2008). This workshop produced a series of questions that could be addressed, at least in part, by scientific ocean drilling:

- To what extent do melting anomalies reflect excess fertility in the mantle rather than excess mantle temperature?
- Do thermo-chemical plume models account for the observations of uplift and basalt chemistry around oceanic plateaus?
- What is the internal architecture of an oceanic LIP?
- Do LIPs initiate continental breakup, or does continental breakup initiate LIP development?

- What was the mode(s) of LIP emplacement? Fissure eruptions (e.g., OJP)? Large volcanic centers (e.g., SR)?
- Was there more than one pulse of voluminous volcanism associated with LIP formation or were there a series of smaller magmatic pulses?
- How long did the pulse(s) of LIP volcanism last?
- What were the environmental impacts of such voluminous volcanism?
- Are there differences between subaerial and submarine LIP emplacement?
- What is the overall architecture of an oceanic plateau sequence?
- What is the nature of seaward-dipping reflectors that are highly significant components of several LIPs (e.g., North Atlantic, Kerguelen)?
- What is the relationship between felsic LIP magmas and the more common mafic (basaltic) varieties?
- Are environmental perturbations, including mass extinctions, directly caused by LIP emplacement?

While it can be argued that in the ~12 years since the last LIP workshop, progress has been made in addressing at least some of these questions, they still remain valid for developing future scientific ocean drilling strategies. Neal et al. (2008) highlighted a number of ways scientific ocean drilling could advance our understanding of LIPs:

- Obtaining deep sections within multiple LIPs to examine magmatic (and therefore mantle source) variability through time
- Defining the nature of melting anomalies (i.e., compositional vs. thermal) that produce LIPs
- Defining precise durations of oceanic LIP volcanic events
- Defining modes of eruption-constant effusion over several million years or several large pulse events over the same time interval
- Establishing relationships among oceanic LIPs, OAEs, and other major environmental changes (e.g., ocean acidification and fertilization)

> “It is evident that large igneous provinces can have global environmental impacts, and understanding their origin and evolution is important for understanding how our planet has evolved, potentially from the core-mantle boundary to the surface environment.”

Obtaining a continuous record of syn-LIP sediments may be one of the most important endeavors for the future. With such materials, we will be able to address the last three points above. Potential sites include the sediments on top of the Magellan Rise in the Southwest Pacific, which could be used to examine the duration of volcanic events, modes of eruption, and environmental impacts of the Ontong Java, Hikurangi, and Manihiki oceanic plateaus. Mercury may be a promising new tracer for fingerprinting major volcanic events recorded in sediment (Font et al., 2016; Jones et al., 2017).

An example of what has changed since 2007 is provided in work on the OJP, beneath which there was reported to be an anomalous seismically slow region that extends to 300 km beneath the plateau (Richardson et al., 2000). This had been interpreted to represent the depleted mantle root that remained after a superplume (see Larson, 1991) formed the OJP, and that is now (still) moving with the plateau (Klosko et al., 2001). Subsequent seismic data have questioned this interpretation. For example, Covellone et al. (2015) used a combination of Rayleigh wave data extracted from ambient noise and earthquakes (and an iterative finite-frequency tomography method) to show that shear wave speeds were actually faster beneath the OJP, rather than slower as found in earlier work (Richardson et al., 2000; Klosko et al., 2001). This was interpreted as being consistent with eclogite entrainment by the surfacing plume head, which also retarded surface uplift. The fast seismic signature in the mantle beneath the OJP down to ~300 km was also supported by Japanese ocean bottom seismometer data (Isse et al., 2018; Obayashi et al., 2018). However, the geochemistry of erupted OJP basalts is not consistent with eclogite in the mantle sources (e.g., Tejada et al., 2004). Further research is required to resolve this issue.

It is important to realize that the last scientific ocean drilling conducted on the OJP was 19 years ago (Leg 192 to the OJP in 2000), 10 years ago for the SR (Expedition 324 in 2009), and 20 years ago for the KP/BR (Leg 183 in 1998/1999). Since that time and based upon the data already obtained through drill cores, new questions can be asked that can be only or best addressed by scientific ocean drilling. Examples include:

- What is (are) the possible interaction(s) of LIP emplacement and the plate tectonic cycle (continental breakup, the subduction process, enhancement of mid-ocean ridge spreading)?
- What, if any, is the temporal relationship between LIP events and changes in the reversal frequency of Earth's magnetic field (e.g., the formation of the OJP is approximately synchronous with the beginning of the Cretaceous Normal Superchron; e.g., Granot et al., 2012, and references therein)?

- What role do LIPs have in initiation of continent formation and continental growth (e.g., Wrangellia and OJP; Samson et al., 1990; Wignall, 2001; Kerr, 2003; Miura et al., 2004)?
- Do all LIPs have the chemical inventory of LIPs to produce ore deposits, such as those associated with the Siberian Traps (e.g., Naldrett et al., 1996; Malitch et al., 2014)?
- Can the magnitude of the environmental effects induced by LIP eruption be quantified?

The first 50 years of scientific ocean drilling have informed us about the formation, evolution, and environmental impacts of oceanic LIPs. Based upon previous results, the next 50 years will see new expeditions to investigate oceanic LIPs that will address more sophisticated questions. Such investigations would also inform us of similar volcanic constructs on the Moon, Mars, Mercury, and Venus (e.g., Head and Coffin, 1997; Hansen, 2007; Head et al., 2011; Neal et al., 2017).

SUMMARY

Scientific ocean drilling has given us major insights into the origin and evolution of the three LIPs highlighted here. However, the data thus far collected show each has unique characteristics that are difficult to reconcile with a unifying petrogenetic model. For example, the KP/BR still has an active hotspot, whereas the OJP and SR do not. The OJP is remarkable in that its compositional homogeneity is transitional between normal (N-)MORB and enriched (E-)MORB across the plateau, whereas SR in the early stages (Tamu Massif) is similar to N-MORB, but subsequent eruptions at the Ori and Shirshov massifs include both geochemically more enriched and depleted compositions. The KP/BR has highly variable basement lava compositions, with a continental crust signature present in lavas from the southern and central KP, and there is strong evidence of subaerial eruptions across the plateau. The OJP and KP/BR appear to have formed through punctuated volcanic events, whereas SR was formed by one relatively long event.

Neal et al. (2008) summarized future LIP drilling targets that are still valid today. One issue, however, that could be resolved by future LIP drilling (and not included in the compilation by Neal et al., 2008) is that the OJP may be much larger than originally thought, as the Manihiki and Hikurangi plateaus are hypothesized to have formed from the same magmatic event that formed the OJP. Only one site has been drilled on Manihiki (DSDP Leg 33, Site 317) and none have been drilled on Hikurangi. Most of the data we have for each of these plateaus are from dredged samples. This huge magmatic event also affected the Pacific upper mantle as MORB prior to the OJP was of a different composition than MORB that post-dates its formation.

What is common among the OJP, the SR, and the KP/BR is that coincident with or shortly after their emplacements, a crisis in the world ocean resulted in an unprecedented die-off that is highlighted by global black shale horizons representing oceanic anoxic events. It is evident that LIPs can have global environmental impacts, and understanding their origin and evolution is important for understanding how our planet has evolved, potentially from the core-mantle boundary to the surface environment.

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SPOTLIGHT 12.

Future Opportunities in Scientific Ocean Drilling: Deep Earth

Innovations in engineering and adaptations of mining technologies over the last 50 years have enabled scientific ocean drilling to reveal much about the deep Earth that would have been impossible using any other methods. However, this so-called "deep" drilling has not penetrated more than the top few hundred meters into igneous basement in most holes, and even when applying multi-expedition approaches, it has only reached as far as two kilometers into in situ oceanic crust (Hole 504B in the eastern equatorial Pacific). Many challenges and questions remain, and new areas need to be pursued through continued drilling efforts. We still have not answered the fundamental Earth science question: Is the Mohorovičić Discontinuity a lithological transition, a geophysical boundary, a serpentinization front, or a combination of those?

Other important questions about the deep Earth that can be answered through scientific ocean drilling include: How does oceanic crust mature over tens of millions of years? How does alteration of deep oceanic crust contribute to microbial life in shallower habitat (and vice versa)? Has Earth experienced true polar wander via a sudden tilt of its rotation axis? How does the chemistry of the mantle and its related oceanic volcanism evolve over geological time? And how does mantle convection work not only at large scales but also at smaller scales, when mantle plumes form at the core-mantle boundary? What have been the environmental effects of large outpourings of magma during the formation of large igneous provinces? Do these eruptions indeed prompt global anoxic events and potentially extinction events? What are the roles of plate tectonics, far-field changes in plate motion, and the impingement of mantle plumes in triggering the formation of new subduction zones and new ocean basins?

To continue making headway in answering these questions requires additional advancements in drilling and coring techniques that permit faster drilling to greater depths into igneous basement over several two-month expeditions. In this scientific ocean drilling field, technological improvements will lead the way.

– Anthony A.P. Koppers

Shipboard scientist Marco Maffione (Utrecht University, The Netherlands) prepares a core for paleomagnetic study aboard *JOIDES Resolution*, IODP Expedition 351, Izu-Bonin-Mariana Arc Origins. *Photo credit: William Crawford, IODP JRSO*

SPOTLIGHT 13.

Reaching Out and Preparing the Next Generation

Outreach in scientific ocean drilling over the last five decades has taken many forms and has targeted diverse audiences, including the lay public, students and educators, and the Deep Sea Drilling Project, Ocean Drilling Program, Integrated Ocean Drilling Program, and International Ocean Discovery Program (IODP) communities themselves. The primary objectives are to raise awareness of scientific ocean drilling and its benefit to society, to encourage global scientific literacy and foster enlightened stewardship of the planet, and to inspire students and attract them to the general field of Earth sciences and to scientific ocean drilling in particular. To achieve these goals, evidence-based outreach components are strategically employed, including ship-to-shore video events, collaborations with museums, lecture programs, graduate student fellowships, training schools for early career scientists, web-based educational materials for teachers, and traditional and social media activities.

Recent high-profile IODP expeditions have sparked significant media and public interest. The British Broadcasting Corporation (BBC) and the US Public Broadcasting System (PBS) aired documentaries on Expedition 364 (Chicxulub Impact Crater), and Expedition 371 (Tasman Frontier Subduction Initiation and Paleogene Climate) engendered more than 100 television stories and a viral social media response. In addition, Expedition 343 (Japan Trench Fast Drilling Project) was featured in the museum exhibit *Deep-Ocean 2017* (Tokyo, Japan) and attracted 617,062 visitors in 79 days.

One of the more novel IODP-related outreach initiatives is a traveling exhibit, *In Search of Earth's Secrets*. Funded by the US National Science Foundation, this project involves "pop-up" science events at various venues that target traditionally underserved communities and features a 13.7 m inflatable replica of *JOIDES Resolution*. A multi-screen array inside the replica displays a looped video that highlights IODP's major scientific achievements. Six interactive kiosks, each focusing on a different scientific or engineering aspect of the program, and a large floor map of the world's ocean bottom complete this immersive educational experience.

In addition to producing content for the general public, IODP strives to reach out to young scientists to ensure a continuous supply of new participants and novel ideas to sustain the program's cutting-edge scientific ambitions and achievements into the future. In the aggregate, approximately one-fourth of all IODP science parties are composed of graduate students who are mentored at sea by experienced program participants from all IODP nations. In addition, the European Consortium for Ocean Research Drilling organizes shore-based "virtual drillship" training schools at the Bremen Core Repository in Germany, and workshops are organized across the program for early career scientists to help "demystify" the IODP proposal process. In early 2018, Japan also conducted a successful "Core-Log-Seismic Investigation at Sea" aboard *Chikyu* that brought 14 international early career scientists together with a multidisciplinary group of scientific mentors as an adjunct to IODP Expedition 380 (Nankai Trough Seismogenic Zone Experiment).

While the immediate goal of scientific ocean drilling is to expand our knowledge of Planet Earth, it is communication of the program's discoveries and achievements to public stakeholders, future generations of IODP scientists, and society at large that completes the IODP mission.

– Carl Brenner, Nobu Eguchi, and Antony Morris

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YEARS OF OUTREACH
ON D/V *CHIKYU* 2016–2018

Expedition Videography for 2016–2018:

7 Videos for Expedition 365
2 Videos for Expedition 370
1 Videos for Expedition 358

Exhibition in Museum in 2017:

617,062 visitors (7,811/day)

Media Coverage for 2018:

128 for internets
15 interviews for TV and radio
71 newspapers
4 books and magazines

Social Media for 2018:

22,431 Twitter followers

W. Crawford, IODP JRSO

A YEAR OF OUTREACH
ON *JOIDES RESOLUTION* 2017

Onboard Outreach Officers:

14 officers from 8 countries

Ship to Shore Video Events:

344 broadcasts to 17,132 viewers in 17 countries

Record-Setting Media Coverage (Expedition 371):

98 television stories
24 radio reports
27 online news features

Social Media:

902 new Facebook followers
768 new Twitter followers
305 new Instagram followers

L. Perez-Cruz, ECORD-IODP

YEARS OF OUTREACH
ON MISSION SPECIFIC PLATFORMS 2016–2018

MSP Expedition Web-based Outreach:

21,200 visitors from > 70 countries to the Expedition 381 blog site
16,893 blog views during Expedition 364
6,198 participants in Expedition 364 Reddit AMA sessions

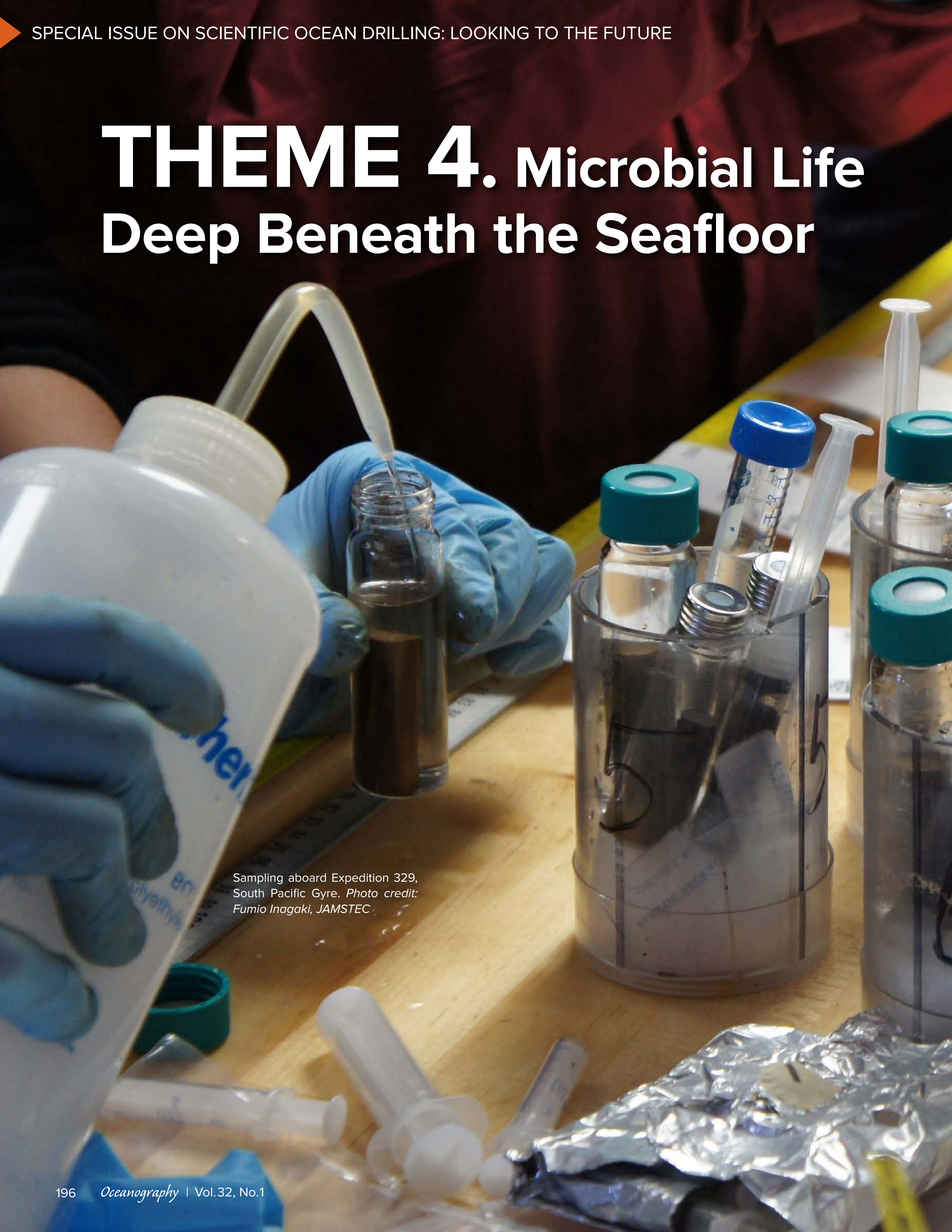
Museum Exhibition on Expedition 381:

7,000 visitors to exhibit at Our Dynamic Earth, Edinburgh UK

Social Media:

1,615 Twitter followers
1,043 Facebook followers
6,300 ECORD YouTube channel views

THEME 4. Microbial Life Deep Beneath the Seafloor



Sampling aboard Expedition 329, South Pacific Gyre. *Photo credit: Fumio Inagaki, JAMSTEC*

During the initial phases of scientific ocean drilling 50 years ago, it was tacitly assumed that the deep subsurface was devoid of life, an environment where only buried fossils were preserved as remnants of past surface biosphere activity. The subsurface, characterized by harsh conditions, was seen as too old and too dark for any known life forms to flourish. Over the last two decades, this view has been fully reversed as scientific ocean drilling has enabled the discovery of a rich, deep subseafloor biosphere.

Since the first deep biosphere-dedicated expedition—Ocean Drilling Program Leg 201 in 2002 aboard *JOIDES Resolution* off Peru and the eastern equatorial Pacific—many microbiologists and biogeochemists, including new generations of graduate students and early career scientists, have participated in and spearheaded deep biosphere scientific ocean drilling expeditions. Their work has vastly expanded our knowledge of this least-explored frontier deep beneath the ocean floor. Accumulating evidence and new discoveries from offshore expeditions and laboratory-based analyses show that a wide array of microorganisms indeed thrive in the sediment and underlying oceanic crustal habitats, even in energetically and geophysically challenging environments. However, key questions related to the origins, limits, evolution, and functionality of deep subseafloor life and its biosphere remain unanswered, requiring enhanced systematic and transdisciplinary explorations, big data integration analyses, and new imaginative experimentation through future scientific ocean drilling projects and post-drilling investigations.

This special issue of *Oceanography* reviews and highlights several representative achievements of deep biosphere research enabled through scientific ocean drilling and discusses the fundamentally significant issues and mysteries that remain to be solved.

– Fumio Inagaki

IODP ADVANCES IN THE UNDERSTANDING OF SUBSEAFLOOR LIFE

By Steven D'Hondt, Fumio Inagaki, Beth N. Orcutt, and Kai-Uwe Hinrichs

CORK borehole observatory deployment on *JOIDES Resolution* during IODP Expedition 336 Mid-Atlantic Microbiology. *Photo credit: William Crawford, IODP-USIO*

ABSTRACT. The most recent decadal phase of scientific ocean drilling through the International Ocean Discovery Program (IODP) has resulted in paradigm-shifting understanding of life below the seafloor. Enabled by new drilling and coring approaches, cutting-edge methodologies, and novel observatory science, IODP expeditions have significantly advanced understanding of the amount and diversity of subseafloor life, the metabolic strategies that this life uses to survive under extreme energy limitation, and consequences of this life for the Earth system. Here, we summarize highlights from recent IODP expeditions focused on life beneath the seafloor and emphasize remaining major science challenges in investigating the form and function of life in this environment.

INTRODUCTION

Study of subseafloor life is a central objective of the International Ocean Discovery Program (IODP) and its immediate predecessor, the Integrated Ocean Drilling Program. Exploration of "Biosphere Frontiers," one of four guiding themes of the IODP Science Plan 2013–2023 (IODP, 2011), includes three challenges: What are the origin, composition, and global significance of subseafloor communities? What are the limits of life in the subseafloor? How sensitive are ecosystems and biodiversity to environmental change?

The first two challenges focus solely on subseafloor life. They guide the biological objectives of individual drilling expeditions. They also guide IODP decisions about shipboard facilities, sampling procedures, and shipboard measurements. Within the context of the current IODP Science Plan, the ultimate objective is to use scientific ocean drilling to advance understanding of:

- The composition and diversity of subseafloor communities, the processes by which they are established, and the ease by which they disperse and find new resources
- The physical and chemical limits to life in the subseafloor, including mechanisms that microbes use to generate energy and fix carbon far from the influence of Earth's surface (photosynthetic) environments (IODP, 2011).

A wide range of projects has used Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and IODP samples and data to address these challenges. Most have been scientific ocean drilling expeditions dedicated to study of subseafloor life and the deep biosphere. A few have been ancillary programs on expeditions with other central foci (such as paleoceanography). Other projects have used archived data and/or samples from DSDP, ODP, and IODP to identify global patterns of subseafloor life and habitability. Here, we describe some of the major discoveries that have resulted from these scientific ocean drilling projects, beginning with dedicated expeditions and ending with studies that mined samples or data.

PRE-IODP EXPLORATION OF SUBSEAFLOOR LIFE

Deliberate exploration of subseafloor life began during DSDP. A serious program of DSDP porewater chemical measurements began with DSDP Leg 15 (Caribbean Sea) in 1970 (Broecker, 1973). Within a few years, concentration profiles and stable isotopic signatures of methane (CH_4) and sulfate (SO_4^{2-}) provided the first evidence that microbial activity occurs deep in marine sediment, even at burial depths as great as 800 m and in sediment that has been buried for tens of millions of years (Claypool and Kaplan, 1974). Subsequently, direct measurements of CH_4 concentrations in incubations of DSDP Leg 64 (Gulf of California) sediment showed that methane is produced in sediment recovered from depths as great as 12 meters below seafloor (mbsf) (Oremland et al., 1982). This demonstration was bolstered by the discovery of organic molecules typical of methanogens in the sediment of a Leg 64 site (Thomson et al., 1982). On the last two DSDP expeditions (Legs 95 and 96), radiotracer incubations were introduced to the shipboard scientific arsenal to identify sulfate-reducing and methanogenic activity in sediment recovered from depths as great as 167 mbsf in the Gulf of Mexico (Whelan et al., 1986) and the New Jersey Margin (Tarafa and Whelan, 1987). A deliberate objective of these DSDP radiotracer studies was to develop methodology for microbiological experiments on future ODP expeditions (Whelan et al., 1986).

Early in ODP, direct counts on core samples from multiple expeditions showed microbial cells to be ubiquitous in subseafloor sediment throughout much of the ocean (Parkes et al., 1994). ODP radiotracer studies showed that SO_4^{2-} reduction, CH_4 production, and CH_4 oxidation occur in continental margin sediment throughout the world ocean (Parkes et al., 2000). Research with contamination tracers during Leg 185 (Izu-Mariana Margin) showed the influence of drilling contamination to be so low that the vast majority of cells in ODP piston cores are indigenous to the sediment (D.C. Smith et al., 2000).

Other studies of ODP core samples suggested that microbial life and activity might be ubiquitous in the igneous crust that underlies marine sediment. Fisk and colleagues (1998) showed that altered surfaces of subseafloor basalt from DSDP and ODP core samples from the Atlantic, Pacific, and Indian Oceans display textures suggestive of microbial colonization. Torsvik and coauthors (1998) found evidence of DNA in the altered surfaces of subseafloor lava from ODP Hole 896A (Costa Rica Rift). Cowen and colleagues (2003) sampled the hydrologic observatory at ODP Hole 1026B (Juan de Fuca Ridge flank) to discover that bacteria and archaea are abundant in warm water flowing through subseafloor basalt. Other studies of the same site documented connectivity between microbial communities in the sediment and communities in the underlying basement (Engelen et al.,

2008) and identified the predominant origin of dissolved organic carbon in the basaltic aquifer from microbial communities that subsist on inorganic chemicals (McCarthy et al., 2011).

ODP Leg 201, the first ocean drilling expedition dedicated solely to study of subseafloor life, occurred late in ODP (2002). It laid the foundation for IODP studies of subseafloor life by bringing large numbers of microbiologists and biogeochemists into the field and advancing understanding on multiple fronts. Leg 201 explored the subseafloor sedimentary ecosystems of the Peru margin and the equatorial Pacific. The expedition showed that subseafloor sedimentary communities are characterized by diverse metabolic activities (D'Hondt et al., 2004), including previously unknown activities (microbial production of ethane and propane; Hinrichs et al., 2006), and by diverse bacterial and archaeal taxa (D'Hondt et al., 2004; Inagaki et al., 2006). Most of the sedimentary cells were found to have been active recently enough that they contained detectable RNA concentrations (Schippers et al., 2005). Study of the bulk RNA pool in sediment samples from Peru margin Site 1227 indicated that the active community in the subseafloor sulfate-reducing methane-oxidizing zone is very different than the active communities in the sediment above and below that zone (Sørensen and Teske, 2006). Both Bacteria (Schippers et al., 2005; Schippers and Neretin, 2006) and Archaea (Biddle et al., 2006, 2008; Lipp et al., 2008) are abundant in Leg 201 sediment. Although cell abundance and community metabolic activity generally decrease exponentially with sediment depth, cell concentrations and rates of potential activities can be much higher at subseafloor sulfate-methane transitions than in the overlying or underlying sediment (Parkes et al., 2005).

For more than a decade, study of archived samples and data from Leg 201 has continued to advance understanding of subseafloor life. For example, organic geochemical study of Leg 201 samples stored at −80°C showed that endospores (compositionally distinct dormant bacterial cells) are as abundant as vegetative (metabolically active) cells in Peru margin sediment, and amino-acid racemization (molecular handedness) data indicate that microbial biomass turnover times range from centuries to millennia (Lomstein et al., 2012). Study of community RNA signatures in archived Leg 201 samples indicated that subseafloor sedimentary microbes engage in a wide range of metabolic activities, repair DNA, undertake some degree of cell division, and span all three domains of life (Bacteria, Archaea, Eukarya) (Orsi et al., 2013).

A few studies used data or samples from many DSDP and ODP expeditions to advance understanding of subseafloor life. D'Hondt and colleagues (2002) integrated chemical and microbiological data from DSDP and ODP expeditions through ODP Leg 182 to show that most subseafloor catabolic activity occurs in a relatively narrow zone of sulfate-reducing methane oxidation along continental margins, that methane is produced in anoxic sediment throughout the world ocean (whether dissolved sulfate is present or absent), and that per-cell respiration rates are orders of magnitude lower in subseafloor sediment than in the surface world. Bach and Edwards (2003) analyzed data from multiple DSDP and ODP sites to infer that most oxidation of subseafloor igneous crust occurs within 10–20 million years following crust formation at mid-ocean-ridge spreading centers. Their quantification of basaltic-crust oxidation rates indicates that water-rock reactions may support a significant quantity of microbial life within mid-ocean-ridge flank systems. Inagaki and colleagues (2006) used genomic techniques to identify bacterial and archaeal taxa in subseafloor sediment samples from three different regions of the ocean—the eastern equatorial Pacific (ODP Leg 201), the Peru margin (Leg 201) and the Cascadia margin (ODP Leg 204). Their results significantly advanced understanding of subseafloor biogeography by demonstrating that (1) similar subseafloor sedimentary environments in distant parts of the ocean contain similar microbial communities, and that (2) the communities of different subseafloor environments (hydrate-bearing sediment vs. hydrate-free sediment) differ significantly.

MAJOR IODP SUBSURFACE LIFE DISCOVERIES

Life in Subseafloor Sediment

There are many good reasons to study microbial life in subseafloor sediment. Although the community structure, metabolic interactions, and origin of subseafloor sedimentary communities are poorly known, sediment chemistry studies show that they strongly influence Earth's near-surface biogeochemical cycles (Bowles et al., 2014). In affecting these cycles, subseafloor sedimentary communities directly affect Earth's climate and surface oxidation state. These communities provide an accessible model for subsurface sedimentary life on other worlds. The environmental variation in subseafloor sediment provides exciting opportunities to test limits to life on Earth (Morita and Zobell, 1955; LaRowe et al., 2017).

During IODP, several expeditions dedicated to the study of subseafloor life, some expeditions of opportunity, and several post-expedition syntheses of IODP data and samples have focused on (1) documenting the composition, global significance, and origin of microbial life in subseafloor sediment; and (2) testing the limits to life in subseafloor sediment. We briefly describe some of these scientific ocean drilling expeditions and their primary discoveries below.

The Origin and Composition of Subseafloor Sedimentary Communities (Terrestrial Life Deep Beneath the Seafloor)

IODP Expedition 337 in 2012 discovered the most deeply buried subseafloor microbial communities to date (Inagaki et al., 2015; Figure 1). Using the riser drilling technology of D/V *Chikyu*, Expedition 337 cored more deeply than any previous scientific ocean drilling expedition—2,466 mbsf—to study microbial life and biogeochemical processes in terrigenous coal and shale underlying marine sediment off Shimokita, Japan (Inagaki et al., 2015). In doing so, the expedition yielded fundamental insight about the origin and persistence of deep subseafloor communities.

The microorganisms that inhabit the ~20 million-year-old subseafloor coalbeds are most closely related to lineages found in peat or modern tropical forest soil (Inagaki et al., 2015). Furthermore, diverse fungal species (Ascomycota and Basidiomycota) related to terrestrial wood-rotting fungi were isolated from a thin layer of soft brown coal at 2,457 mbsf, interbedded with sand (Liu et al., 2016). These coal-associated microbial communities are highly distinct from commonly observed subseafloor sedimentary microbes, which are typically of marine origin. This discovery suggests that the in situ communities are relicts of the original depositional communities that inhabited continental soils or swamps ~20 million years ago, rather than microbial migrants into the coal from the ocean or elsewhere in the subseafloor.

Geochemical and microbiological data indicate that this coal-associated deep subseafloor ecosystem contains heterotrophs that may be active in situ (Inagaki et al., 2015; Glombitza et al., 2016). Post-expedition cultivation experiments show that microbes from the 2 km deep sediment are capable of feeding on simple organic compounds, but are characterized by biomass generation times exceeding hundreds of years, even under laboratory incubation conditions (Trembath-Reichert et al., 2017; Figure 2). Position-specific analysis of stable carbon isotopes of lignite-derived methoxy groups (methyl groups bound with oxygen) suggests their transformation into methane by methanogenic communities over geologic time (Lloyd, 2018).

The Limit to Life in Subseafloor Sediment

IODP Expedition 329 (2010) showed that there is no limit to sedimentary life in the largest ocean desert (D'Hondt et al., 2015). More than 60 years ago, Morita and ZoBell (1955) studied shallow gravity cores to report "the lower limits of the biosphere" at 3.9–7.5 mbsf in abyssal clay of the oligotrophic North Pacific Gyre. Expedition 329 set out to test their claim in subseafloor clay of the most oligotrophic region in the world ocean—the South Pacific Gyre. Expedition 329 found that low concentrations of microbial cells and low rates of microbial respiration occur throughout the sediment column in this region, even in sediment deposited more than 100 million years ago (D'Hondt et al., 2015). The sediment is so thin and respiration rates are so low that dissolved oxygen penetrates the entire sediment column, from seafloor to the sediment/basement interface (Figure 3). As in anoxic sediment

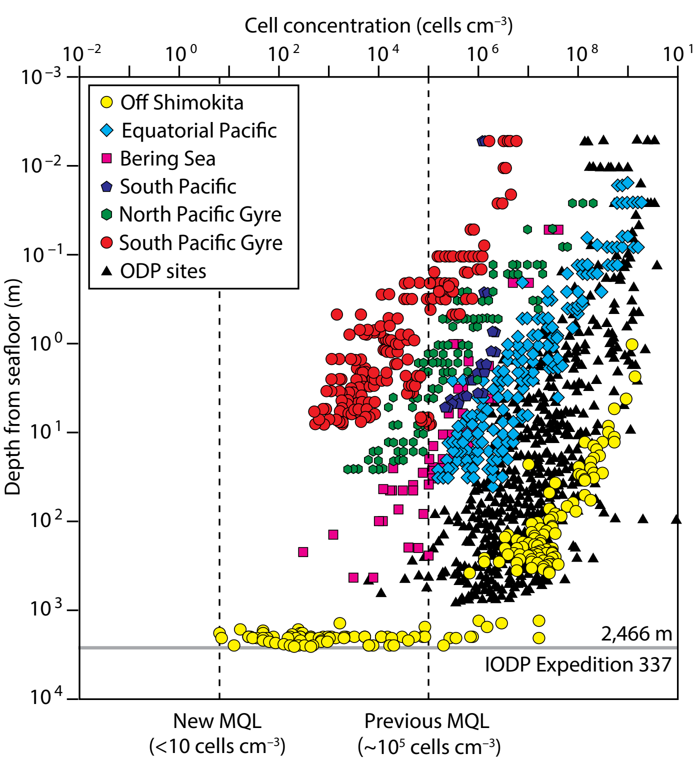


FIGURE 1. Cell concentrations in marine sediment. The yellow dots clustered around 2,466 meters below seafloor line identify cell concentrations in the deepest subseafloor sediment samples examined for life to date (IODP Expedition 337 Site C0020; Inagaki et al., 2015). MQL = minimum quantification limit for sedimentary microbial cells.

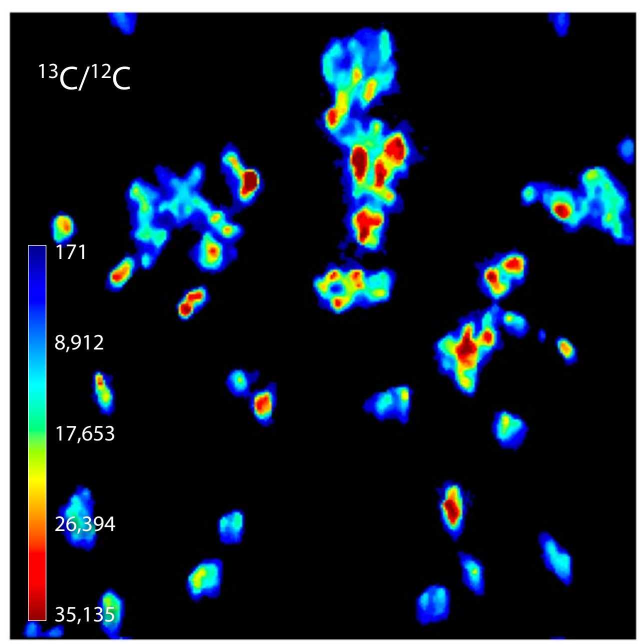


FIGURE 2. A NanoSIMS image of subseafloor sedimentary cells that incorporated ^{13}C from a mixture of stable isotope (^{13}C)-labeled amino acids, showing that microbial life in ~2 km deep coal formation is metabolically active (see Table T13 in Inagaki et al., 2013; Trembath-Reichert et al., 2017). The color gradient represents ^{13}C abundance expressed as $^{13}C/^{12}C$. *Figure courtesy of Yuki Morono and Motoo Ito, JAMSTEC*

and in the ocean, abundances of virus-like particles exceed microbial cell abundances by one to two orders of magnitude (Engelhardt et al., 2014).

As described above, Expedition 337 demonstrated that microbial life extends more than 2 km beneath the ocean floor in thick nearshore sediment (off Shimokita, Japan). To quantify microbial cells at extremely low concentrations so deep beneath the seafloor, novel techniques were established to improve cell enumeration by four to five orders of magnitude relative to the conventional manual counting techniques (Morono et al., 2013; Morono and Inagaki, 2016). The resulting concentrations were $\sim 10^2$ to 10^3 cells cm^{-3}, with local peaks in the brown coal horizons. These low concentrations suggest that this deeply buried sediment, with moderately elevated temperatures of 40°C to 60°C, may be situated close to the limit of habitability. Based on thermal data (Tanikawa et al., 2016), temperature-related increases in energetic costs of biomolecule repair may place an important constraint on the viability and size of subseafloor communities (Inagaki et al., 2015). It is also conceivable that physical factors such as low porosity, low permeability, and low free-water availability influence key fluxes of fluids, nutrients, and waste products in this semi-closed sedimentary basin (Tanikawa et al., 2018).

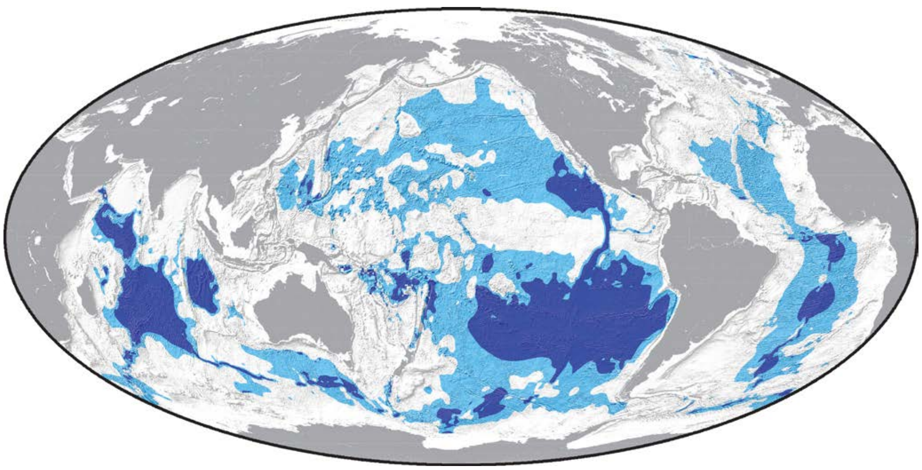


FIGURE 3. Geographic distributions of predominant net electron-accepting activities in subseafloor sediment. Sulfate reduction is the predominant net electron-accepting activity in the white regions. Oxygen reduction is the dominant net electron-accepting activity from seafloor to the sediment/basement interface in the dark blue regions and perhaps the light blue regions. *Figure modified from D'Hondt et al. (2015)*

Temperature is commonly hypothesized to estimate the lower boundary of the deep biosphere (LaRowe et al., 2017). The currently known high-temperature limit of life for microorganisms from energy-rich hydrothermal vents is 122°C (Takai et al., 2008). However, little is known about the temperature limit to subseafloor life. Two IODP expeditions have focused on this issue. IODP Expedition 331 (2010) tackled this challenge by drilling in the Iheya North hydrothermal field, which lies within the Okinawa Trough, an actively spreading back-arc basin. At Expedition 331 sites, evidence of subseafloor microbial communities was limited to the first 10–30 mbsf, which were characterized by relatively cool temperatures (less than a few tens of degrees Celsius). The absence of identifiable life at greater depths was interpreted as possibly due to recent sterilization by intense subseafloor hydrothermal activity (Brandt and House, 2016; Yanagawa et al., 2016).

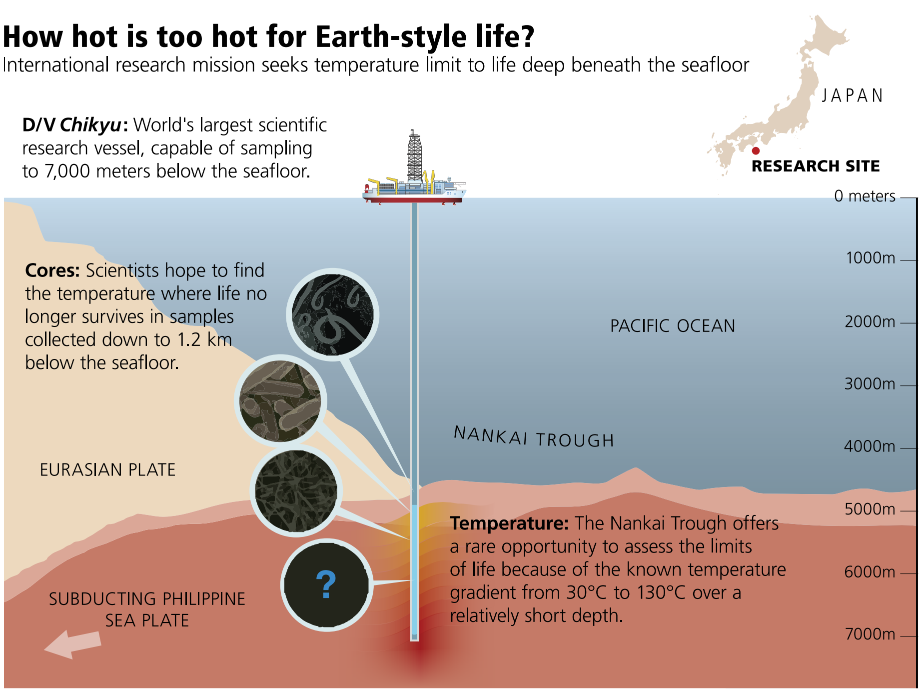


FIGURE 4. How deep is Earth's habitable zone? What are the factors that limit life's maximum depths? IODP Expedition 370 "Temperature-Limit of the Deep Biosphere off Muroto (T-Limit)" tackled these fundamental questions by drilling through the sediments at Site C0023 in the central Nankai Trough off Cape Muroto, Japan (Hinrichs et al., 2016; Heuer et al., 2017). Anomalously high heat flow regimes in this area result in temperature of 120°C at the sediment-basement interface and make the site an ideal target for in-depth examination of subseafloor microbial life close its upper temperature limit. *Figure courtesy of Deep Carbon Observatory and JAMSTEC*

To extensively study the influence of temperature in a more stable subseafloor environment, IODP Expedition 370 (2016) cored a 1.2 km thick sediment sequence where the thermal gradient is much less steep, but temperature reaches

~120°C at the sediment-basement interface (Hinrichs et al., 2016; Heuer et al., 2017; Figure 4). This sequence is in a well-characterized geological setting—along the Muroto Transect in the Nankai Trough off Japan. The coring site, IODP Site C0023, is located at the seaward end of the Nankai Trough accretionary prism, where the Shikoku Basin subducts beneath Japan. The 1.2 km of recovered subseafloor sediment thus spanned the range of suitable conditions for psychrophilic (optimal growth temperature range <20°C), mesophilic (20°C to 43°C), thermophilic (43°C to 80°C), and hyperthermophilic (>80°C) microorganisms. In order to effectively study very low-biomass communities at the limit of the biosphere, Expedition 370 researchers made an unprecedented effort to trace and minimize contamination of core samples, including in the processes of X-ray CT scans of cores before sampling and super-clean shore-based subsampling technologies (Heuer et al., 2017; Morono et al., 2018). Selected samples were transported daily by helicopter to the Kochi Core Center for microbiological analyses. In 2018, scientists used JAMSTEC's R/V *Kairei* and remotely operated vehicle (ROV) *Kaiko* to recover a 1.5 year record of in situ temperature data from an observatory installed in the drill hole. The data and samples from Expedition 370 and the post-drilling ROV expedition are now being analyzed to pinpoint the thermal limit to subseafloor sedimentary life.

The Composition and Global Significance of Life in Subseafloor Sediment

Several studies have used IODP data or samples from expeditions of opportunity to advance understanding of subseafloor sedimentary communities. For example, participants in IODP Expedition 317 (2010) found microbial communities present to nearly 2 km below seafloor in the Canterbury Basin (New Zealand) that contained members from all three domains of life (Ciobanu et al., 2014). Bering Sea IODP Expedition 323 (2009) scientists showed that taxonomic richness of marine sedimentary communities declines exponentially with sediment age and organic oxidation rate (Walsh et al., 2016). Other studies have used IODP data or samples from multiple expeditions to quantify global distributions of several key properties of subseafloor ecosystems, including microbial abundance and biomass in sediment (Kallmeyer et al., 2012), sedimentary microbial activities (Bowles et al., 2014; D'Hondt et al., 2015), potential thermal limits to sedimentary life (LaRowe et al., 2017), and relative abundances and diversities of Bacteria and Archaea (Hoshino and Inagaki, 2018). The last study found archaea to comprise 37% of the prokaryotic (bacterial and archaeal) cells in subseafloor sediment (similar to their relative abundance in the deep ocean).

Life in Subseafloor Crust

A rocky crust consisting mainly of basalt, but also including gabbro, peridotite, and serpentinite, exists beneath the sediment that blankets most of the seafloor. This rocky crust is a potentially expansive habitat for life (Edwards et al., 2011, 2012a; Orcutt et al., 2011b). However, before the current phase of the scientific ocean drilling program, there were few studies of microbial life and its consequences in this environment. Uncovering whether and how life exists in oceanic crust is important because (1) chemical reactions in the crust impact broader ocean systems, (2) it is a great analog for extraterrestrial life on other ocean worlds, and (3) it will greatly advance understanding of microbial mechanisms for survival between a "rock and a hard place" (IODP, 2011).

In the current phase of IODP, several major expeditions and observatory programs have focused on documenting the nature, extent, and function of microbial life in oceanic crust, augmented by additional studies on expeditions of opportunity. We briefly describe these scientific ocean drilling expeditions and their primary discoveries below.

The Composition and Origin of Subseafloor Crustal Communities

IODP expeditions have targeted the origin and composition of subseafloor life in diverse crustal environments, including warm anoxic aquifers (IODP Expeditions 301, 327) and cool oxic aquifers (IODP Expeditions 329, 336), basalt of the upper crust (Expeditions 327, 329, 330, 336) and gabbro of the lower crust (Expedition 360), young crust (less than 10 million years old; Expeditions 301, 327, 336) and old crust (up to 100 million years old; Expeditions 329, 330), normal seafloor (Expeditions 327, 329, 336, 360), ultramafic crust (Expedition 357), and seamounts (Expedition 330).

Three of these expeditions, 301 (2004), 327 (2010), and 336 (2011) set up observatories for long-term studies of microbial communities in crustal aquifers (Figures 5 and 6). Expeditions 301 (2004) and 327 (2010) built on the long history of research on the Juan de Fuca Ridge (following the earlier work of ODP Leg 168) to examine fluid-flow properties and the nature of life in oceanic crust. Expeditions 301 and 327 drilled multiple holes into basement and installed four

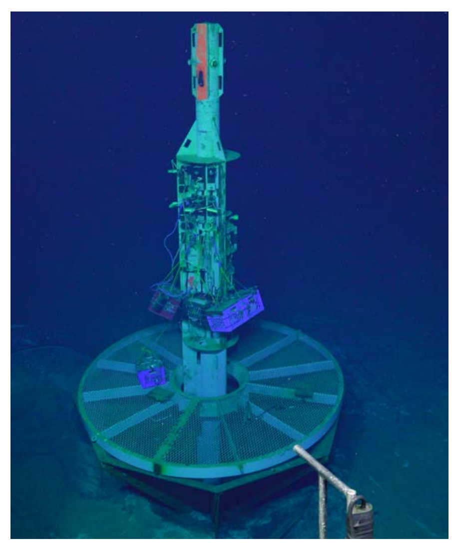


FIGURE 5. CORK borehole observatories, like this one installed by IODP Expedition 336 at the North Pond site on the Mid-Atlantic Ridge, allow access to the deep biosphere in oceanic crust. *Photo courtesy of AT39-01 cruise chief scientist C. Geoff Wheat, University of Alaska Fairbanks, US National Science Foundation, ROV* Jason, *2017, © Woods Hole Oceanographic Institution*

state-of-the-art borehole observatories to enable long-term microbiological studies. In addition, Expedition 327 cored several holes at a location where fluid was suspected to flow into the basement in order to study transitions of microbial communities from seawater, overlying sediment, and within basement (Fisher et al., 2011). Expedition 336 (2011) built on a decades-long history of ocean drilling and observatory science at Hole 395A (DSDP Leg 45) on the western flank of the Mid-Atlantic Ridge (Figure 6). This expedition focused on documenting the nature of life in cool basaltic ocean crust, which constitutes much of the global subseafloor (Edwards et al., 2014). It cored the entire sediment column and upper basaltic basement and installed three borehole observatories.

IODP Expeditions 301, 327, and 336 enabled unprecedented discoveries regarding the composition and structure of subseafloor crustal communities. Direct study of rock recovered by Expedition 301 provided evidence for microbial methane and sulfur cycling within the crust of the Juan de Fuca Ridge flank (Lever et al., 2013). Rock colonization experiments in the 301 and 327 observatories revealed the dynamic nature of microbial biofilms that form on rock surfaces in this warm anoxic habitat (Figure 7). Microbes readily colonize rock substrates incubated in the subseafloor crustal boreholes (Orcutt et al., 2011a; A. Smith et al., 2011). Temperature plays an important role in structuring the biofilm communities that colonize the incubated substrates (Baquiran et al., 2016). Comparison of the observatory results to sedimentary communities indicates that proximity to basement and/or seawater recharge locations does not impact sedimentary community structure (LaBonté et al., 2017), even though fluid diffuses from the permeable oceanic crust into sediment and stimulates microbial activity (Engelen et al., 2008). The first viral study of subseafloor crust found that, as in marine sediment and seawater, novel archaeon-infecting viruses are an order of magnitude more abundant than the archaeal cells that might possibly host them (Nigro et al., 2017). By measuring nanoscale changes in heat capacity during microbial growth, nanocalorimetry experiments with crustal fluid samples show that these microbial communities have potential for high metabolic rates (Robador et al., 2016).

Expedition 336 studies demonstrated that the subseafloor crustal habitat of the mid-Atlantic North Pond is fundamentally different than the warm anoxic habitat explored by Expeditions 301 and 327 on the Juan de Fuca Ridge flank. The North Pond system is relatively cool and oxic (Orcutt et al., 2013). Diffusion of oxygen from the basaltic crust into the overlying sediment stimulates a unique nitrogen cycling microbial community within the sediment (Reese et al., 2018). Unlike the Juan de Fuca ecosystem, the North Pond system exhibits significant overlap in microbial community structure between basal sediment and the basaltic rocks below, with both showing dominance of Proteobacteria groups that are also observed on exposed seafloor basalts (Jørgensen and Zhao, 2016). Fluid sampling from the North Pond observatories shows that the ecological structure of the planktonic microbial community in the aquifer is relatively stable, despite large shifts in dominant taxonomic groups over time and space (Tully et al., 2017). Although chemosynthetic carbon fixation could be linked in this ecosystem to oxidation of sulfide, elemental sulfur, thiosulfate, and hydrogen and ferrous iron (Meyer et al., 2016; Tully et al., 2017), biological imprints on the organic-carbon signature of fluid venting into the overlying ocean indicates that organic-fueled respiration exceeds organic production within the ecosystem (Shah Walter et al., 2018). Observatory studies continue at these sites, extending the legacy of deep-biosphere observatory research into a new era. Expedition 336 observatories were revisited in 2017, and

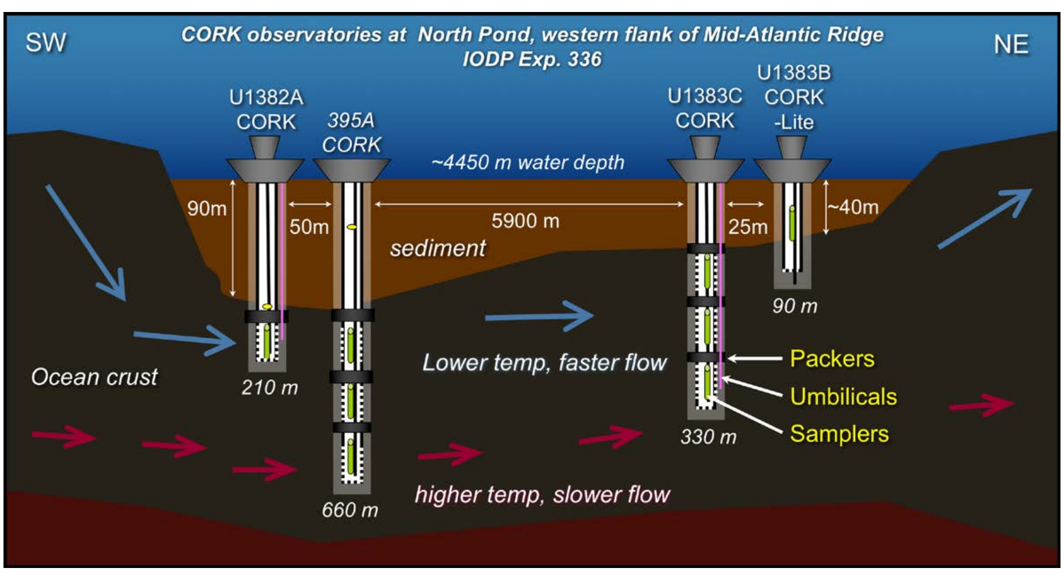


FIGURE 6. Schematic of borehole observatories installed by IODP Expedition 336 to study the deep biosphere in cool oxic oceanic crust. The CORK and CORK-Lite observatories enable microbial colonization experiments at depth within oceanic crust, as well as collection of pristine crustal fluids from depth. *Modified with permission of Edwards et al. (2012b)*

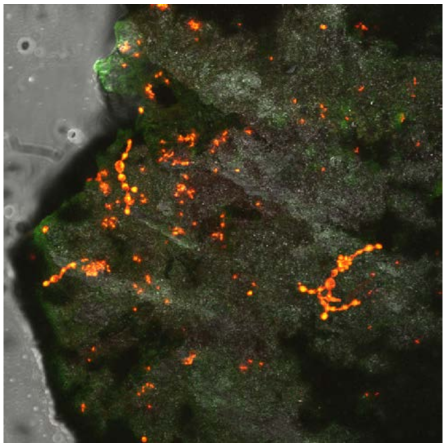


FIGURE 7. Confocal laser scanning micrograph of microbial colonization of mineral incubation experiments in subseafloor oceanic crust on the Juan de Fuca Ridge flank (Orcutt et al. 2011a). The orange dots are individual microbial cells. Image dimensions 175 µm x 175 µm.

Expedition 327 observatories will be visited again in 2019.

Several recent IODP expeditions have explored subseafloor life in crust environments other than the relatively young basaltic crust of Expeditions 301, 327, and 336. Expedition 329 scientists are testing the extent to which microbial communities persist in cool, oxic subseafloor crust of widely different ages, ranging from 13.5 to 104 million years old. Expedition 330 sampled older basaltic crust from submarine extinct volcanoes in the Louisville Seamounts from which a new species of a manganese oxidizing bacillus was isolated (Sylvan et al., 2015). Expedition 357 (2015) collected samples of ultramafic crust from an ocean core complex on the Mid-Atlantic Ridge to examine microbial life associated with serpentinization (Früh-Green et al., 2017). So far, results from this expedition have documented very low biomass in these shallow ultramafic samples from an actively serpentinizing system, in contrast to the elevated density of life in highly altered samples from the nearby Lost City hydrothermal vent field (Früh-Green et al., 2018). Expedition 360 (2016) collected gabbro from the lower oceanic crust at the Southwest Indian Ridge, where initial measurements indicated microbial life in many of the samples (MacLeod et al., 2017). Continued analyses of these samples will further expand our understanding of the nature, extent, and activity of life in the rocky subseafloor.

FUTURE RESEARCH

As described above, scientific ocean drilling is greatly advancing understanding of the quantity, diversity, and global significance of life in subseafloor sediment. It is also significantly enhancing knowledge of the composition and origin of communities in subseafloor igneous crust. These are major advances in the fundamental understanding of life on Earth as they extend the known biosphere to sediment depths as great as ~2.5 km below seafloor (Inagaki et al., 2015) and to sediment ages older than 100 million years (D'Hondt et al., 2015). These advances also radically challenge understanding of the low-energy limit to life (Hoehler and Jørgensen, 2013), because communities in subseafloor sediment appear to survive at per-cell metabolic rates that are orders of magnitude lower than rates in the surface world (D'Hondt et al., 2002, 2015). Knowledge of the microbial features and strategies that enable survival at these extraordinarily low metabolic rates will ultimately inform understanding of the limits to intraterrestrial life on Earth, the potential for life on other worlds, and the nature of persister cells in bacterial infections.

More complete understanding of subseafloor life and its effects on the world we live in requires a new generation of drilling expeditions and projects. For example, the limits to life remain unknown in both subseafloor sediment and igneous crust, because active microbial communities have been recovered from almost all subseafloor environments cored to date. More complete understanding will also require much closer focus on the diverse ways that organisms interact with each other in subseafloor communities. The global significance of subseafloor crustal communities remains unknown, because the extent to which those communities drive chemical alteration in their habitats is not yet clear. The processes by which subseafloor communities are established, and the ease by which they disperse and find new resources, are not yet well understood either. Finally, we do not yet fully understand the diverse mechanisms that they use to generate energy and fix carbon far from the influence of Earth's surface (photosynthetic) environments.

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The Limits of Life and the Biosphere in Earth's Interior

By Verena B. Heuer, Mark A. Lever, Yuki Morono, and Andreas Teske

Fifty years of scientific ocean drilling have shown that microorganisms are widespread deep inside the ocean floor. Microbial populations exist in both organic-matter-rich and nutrient-poor sediments (Kallmeyer et al., 2012; D'Hondt et al., 2015), in sediments that are millions of years old and are buried to over a kilometer depth (Roussel et al., 2008; Ciobanu et al., 2014; Inagaki et al., 2015), and deep inside the basaltic oceanic crust (Orcutt et al., 2011; Lever et al., 2013). In these varied environments, metabolic activity is extraordinarily low (D'Hondt et al., 2009; Hoehler and Jørgensen 2013; Lever et al. 2015a), but microbial cells remain physiologically active (Morono et al., 2011) or survive in their dormant phases (Lomstein et al., 2012). The total amount of subsurface biomass is still being debated (Hinrichs and Inagaki, 2012; Kallmeyer et al., 2012; Parkes et al., 2014), and the factors posing ultimate limits to deep life and the habitability of Earth remain to be resolved (Figure 1).

Within the ocean floor, geological, physical, chemical, and biological processes interact. Microorganisms can potentially exploit the energy released in these interactions, but they might also be substantially physiologically stressed in this environment. With depth below the seafloor, temperature increases and tectonic influences on heat and fluid flow result in vast temperature variations on local to global scales. Because temperature governs chemical reaction rates, its increase with depth becomes a major stress factor for microorganisms: rates of biomolecule-damaging reactions, such as DNA depurination, polymer hydrolysis, or amino acid racemization increase (Lindahl and Nyberg, 1972; Wolfenden et al., 1998; Steen et al., 2013), and so does the energy demand for biomolecule repair (Röling et al., 2003; Price and Sowers, 2004; Lever et al., 2015a). Conversely, heating of sedimentary organic matter may also provide microbes with energy through the release of low-molecular weight compounds (Wellsbury et al., 1997; Horsfield et al., 2006). These temperature effects deserve attention as an estimated ~52% of Earth's marine sediment volume resides at temperatures >40°C, including ~25% at >80°C (LaRowe et al., 2017).

In deep, energy-limited subseafloor sediments, the upper temperature limit of life is expected to be lower than in surface hydrothermal habitats (Inagaki et al., 2015; Lever et al., 2015a; Møller et al., 2018), where abundant geothermally produced electron donors and seawater-derived electron acceptors provide energy for hydrothermal vent organisms to thrive. Indeed, pure cultures of certain hydrothermal vent archaea can be maintained at ~120°C under elevated pressure in the laboratory (Kashefi and Lovly, 2003; Takai et al., 2008), and several groups of Archaea and Bacteria from shallow seafloor environments thrive at temperatures of 80°–105°C both in the laboratory and in the field (e.g., Burggraf et al. 1990; Jørgensen et al., 1990, 1992; Lloyd et al., 2005; Edgcomb et al., 2007; Teske et al., 2009). By contrast, so far all attempts to isolate high-temperature-adapted microorganisms from deep subsurface sediments have failed. While the absence of microbial activity and viable microbial populations in deep oil reservoirs at temperatures above ~80°C (Wilhelms et al., 2001; Head et al., 2003) is consistent with known thermal limits

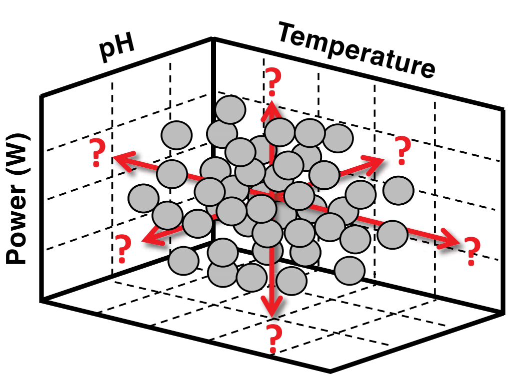

FIGURE 1. Concept sketch illustrating the niches of individual microbial strains (gray circles) with respect to power requirement (in Watts), pH range, and temperature range. The question marks indicate the currently unknown limits of microbial life in subsurface environments. For illustrational purposes, equal niche sizes among different microorganisms are assumed. In actuality, individual strains of subsurface microorganisms may differ greatly in cell-specific power, pH, and temperature ranges that allow them to thrive or survive. Furthermore, power requirements are likely to vary more systematically with pH and temperature than shown (i.e., subsurface microorganisms living at neutral pH and low temperature may generally have lower power requirements than counterparts living at extreme pH or temperature).

of microbial hydrocarbon degradation (Rueter et al., 1994; Holler et al., 2011; Kellermann et al., 2012; Laso-Perez et al., 2016; McKay et al., 2016), microbiological and geochemical investigations indicate even lower temperature maxima (~60°C) in deeply buried sediments (to ~2.5 km below seafloor; Inagaki et al., 2015).

Chemical disequilibria between seawater and crustal rocks (i.e., predominantly basalts) offer opportunities to exploit energy (e.g., Bach and Edwards, 2003), but the distribution and limits of life in subseafloor oceanic crust are even less understood than they are in sediments. Microbes in crustal rocks are difficult to sample with scientific ocean drilling because they are easily contaminated with microbes from drilling fluids. Sealed CORK borehole observatories, in which disturbances caused by drilling disappear and equilibrated fluid compositions similar to those in oceanic crust get re-established within a few years (Wheat et al., 2010), are an important alternative to acquiring microbial samples from cores. CORKs provide access to fluid samples and free-living cells, and they can be used for colonization experiments (Cowen et al., 2003; Orcutt et al., 2011; Jungbluth et al., 2013).

The still-limited data from rocks and CORKs show large location-specific microbiological diversity, with only minor phylogenetic overlaps between free-living and attached cells (Biddle et al., 2014), and between microbes in crustal rocks and those inhabiting overlying sediments or seawater (Meyer et al., 2016; Labonté et al., 2017; Nigro et al., 2012). Moreover, microbial communities near cold recharge zones (Jørgensen and Zhao, 2016; Tully et al., 2018) differ distinctly from warm locations tens of kilometers downstream from recharge areas (Orcutt et al., 2010; Lever et al., 2013; Robador et al., 2015). Yet, the factors controlling and limiting life in these hard rock environments are far from understood, and thus subseafloor oceanic crust remains a major frontier of deep biosphere research.

Ongoing analyses of samples collected by the International Ocean Discovery Program (IODP) promise to provide novel insights into some of these questions, because the challenges associated with accurate temperature measurement (Yanagawa et al., 2017), rigorous contamination control (e.g., Fisk et al., 2003; Lever et al., 2006, 2013; Santelli et al., 2010; Jørgensen and Zhao, 2016), and sensitive and reliable quantification of microbial populations and activity (Kallmeyer et al., 2008; Morono et al., 2013, 2014; Lever et al., 2015b; Glombitza et al., 2016; Ijiri et al., 2018) have been recognized and successfully addressed (Figure 2). Recent drilling into

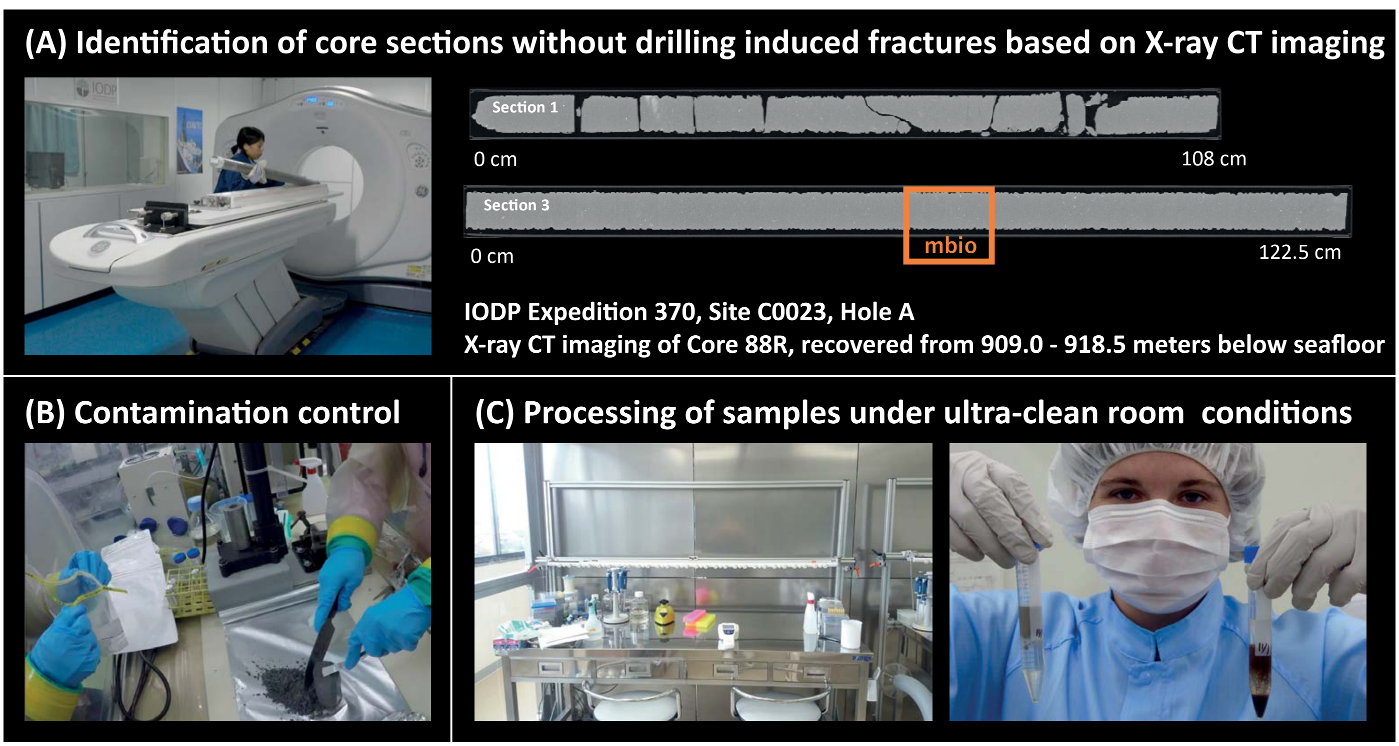

FIGURE 2. State-of-the-art contamination control for microbiological sampling from sediment cores during IODP Expedition 370. (A) On board the Japanese riser drilling vessel *Chikyu,* sediment cores were examined by X-ray computed tomography to identify lithological features and fractures induced in the course of drilling. Using the images, samples for microbiological investigations were selected from undisturbed core sections. The example shows the location of the "mbio" sample taken for cell counting. *Photo credit: Dan Brinkhuis, SCIENCEMEDIA.NL, X-ray images from http://sio7.jamstec.go.jp/xray-ct/370/C0023A/* (B) In order to avoid the intrusion of drilling fluid into the inner part of the "mbio" sample, the outer part was carefully removed with sterile tools inside an anaerobic chamber. (C) To avoid introduction of airborne contaminants into the sample, all further processing was conducted in an absolutely dust-free ultra-clean room laboratory at the Kochi Core Center/JAMSTEC. More detailed information is given in the Expedition Report (Heuer et al., 2016).

energy-poor subsurface sediment of the Nankai Trough subduction zone off Japan (IODP Expedition 370) and an upcoming expedition to energy-rich subsurface sediments of the Guaymas Basin in the Gulf of California (IODP Expedition 385, scheduled for 2019) will provide further constraints on the limits of life in subseafloor sedimentary environments as a function of energy supply and temperature-driven energy demand. Recent expeditions to the ultramafic Atlantis Massif on the Mid-Atlantic Ridge (IODP Expedition 357) and serpentinite mud volcanoes of the Mariana subduction zone (IODP Expedition 366) will offer new knowledge on the potential for deep water-rock reactions to fuel microbial life. Both of these locations also offer the opportunity to investigate the importance of variables other than temperature, for example, extreme pH, on the distribution of subseafloor microbial life.

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Future Opportunities in Scientific Ocean Drilling
ILLUMINATING PLANETARY HABITABILITY

By Fumio Inagaki and Asahiko Taira

ABSTRACT. Over the past several decades, scientific ocean drilling has significantly expanded our knowledge of life and Earth. The discovery of deep microbial life and its ecosystems beneath the ocean floor suggests that subseafloor microbial ecosystems may have uniquely co-evolved in association with Earth dynamics, and this inevitable interrelationship has shaped planetary habitability for more than 3 billion years. In the future, scientific ocean drilling—from the surface to drilling's accessible limit in the upper mantle—will permit a better understanding of what is life, why we are here, and what are the possible trajectories of our planet's habitability and its sustainability as well as that of other celestial bodies in the universe.

INTRODUCTION

Despite several catastrophic perturbations during its history, Earth has nevertheless remained habitable. There are many unknowns and mysteries about the origins and evolution of life and Earth. No less mysterious is how Planet Earth and its life will co-evolve and develop sustainably in the future. How will life (from microbes to humans) adapt and transform in response to future environmental changes? How will life continue to shape Earth? How can we decipher "planetary habitability" and illuminate the sustainability of life on our planet and beyond?

To date, we recognize through challenging missions to many frontiers of Earth's extreme environments that even in dark and energetically challenging conditions, intraterrestrial ecosystems have adapted and evolved and persisted over billions of years. One of the main tools for deciphering this past co-evolution is analysis of samples collected at deeply drilled sites. Expanding our knowledge of the ocean-Earth-life system through scientific ocean drilling inspires new insights into the essence of planetary habitability—down to Earth's upper mantle, which for today's drilling technology is the deepest accessible limit. Such explorations will lead to an understanding of how and why life emerged on our planet, as well as an estimate (prediction) of the possible trajectories of life on Earth. They will also provide hints as to whether life persists on other celestial bodies, and which ones are the most likely to be habitable and even inhabited.

DEEP BIOSPHERE FRONTIERS

Over recent decades, materials recovered through scientific ocean drilling have led to the discovery of microbial life in deep-sea sediment and in Earth's oceanic crust. The latest estimate of global subseafloor microbial abundance is ~10^{29} cells, accounting for 4 Gt of carbon biomass on Earth (Lipp et al., 2008; Hinrichs and Inagaki, 2012; Kallmeyer et al., 2012; Parkes et al., 2014; Figure 1). DNA-based molecular investigations have revealed that diverse, but previously unknown, microbial species (in three domains of life: Bacteria, Archaea, and Eukarya) are present in the deep subseafloor sedimentary biosphere, where they have evolved differently from microbes living in Earth's surface biosphere (e.g., Biddle et al., 2006, 2008; Inagaki et al., 2006; Fry et al., 2008; Orsi et al., 2013; Ciobanu et al., 2014). Using a microfluidic digital polymerase chain reaction (PCR) technique applied to 300 deep-frozen sediment core samples, Hoshino and Inagaki (2019) demonstrated that archaeal cells constitute 37.3% of total subseafloor sedimentary cells (i.e., 1.1 × 10^{29} archaeal cells). This comprises a biomass comparable to the estimated archaeal biomass in the global ocean of 41.9% (Karner et al., 2001).

The activity of subseafloor microbial communities is generally extraordinarily low (Hoehler and Jørgensen, 2013; D'Hondt et al., 2004, 2015). In fact, extensive research into deep life using culture-dependent as well as culture-independent molecular and isotopic analyses demonstrates that many sedimentary microbes are alive and can be revived after persisting in low-energy subseafloor habitats over geologic time (Morono et al., 2011; Trembath-Reichert et al., 2017). Their "ultra-slow life" processes and strategies for long-term survival beneath the ocean—and even below its thick ocean sediment blanket—may have affected global biogeochemical element cycles (D'Hondt et al., 2002; Lever et al., 2013; Bowles et al., 2014).

Biogeographical models and simulation studies show that up to 37% of the global subseafloor sedimentary environment is completely oxic, and thus that aerobic microbial life inhabits the entire sediment column from the seafloor down to the sediment-basement interface. These microbes have not fully consumed the available organic matter or the dissolved oxygen (D'Hondt et al., 2015; Estes et al., 2019; see also Orcutt et al., 2012), suggesting that there are no limits to subseafloor life in open-ocean sedimentary environments, and that the subseafloor sedimentary microbial ecosystems have developed an eco-physiological mode of persistence and survival over geologic time. In addition, ultra-slow metabolic activities (although we don't know the details yet), as well as their end products—dead biomass (i.e., necromass, detrital proteins), spores, and even viruses—may play significant ecological and evolutionary roles in Earth's deep biosphere (Lomstein et al., 2012; Lloyd et al., 2013; Engelhardt et al., 2014; Wörmer et al., 2019). Consequently, the deep subseafloor biosphere is possibly an important driver of element transformation and cycling between Earth's lithosphere, hydrosphere, and atmosphere.

THE LIMITS OF DEEP LIFE AND THE BIOSPHERE

To date, microbial life has been observed down to ~2.5 km below the seafloor on Pacific margins in organic-rich anaerobic sedimentary environments (Ciobanu et al., 2014; Inagaki et al., 2015). Multiple lines of analytical evidence from samples recovered in 2012 by the riser drilling vessel *Chikyu* during Integrated Ocean Drilling Program Expedition 337 "Deep Coalbed Biosphere off Shimokita" revealed that deeply buried microbial communities have played biogeochemical roles in carbon and other elemental cycling for millions of years, despite their extraordinarily slow metabolic activity. For example, using a stable isotope-probing nanometer-scale secondary ion mass spectrometry technique (SIP-NanoSIMS), it was demonstrated that indigenous bacteria slowly utilize methyl compounds in 20-million-year-old coal and shale beds at 2 km depth (Inagaki et al., 2015; Trembath-Reichert et al., 2017; Figure 2). Interestingly, the diversity of microbial communities in these deeply buried coal-associated habitats was found to be very different from commonly observed subseafloor sedimentary microbes. In fact, they resemble anaerobic terrestrial communities living in peat or forest soil and can be cultivated by using down-hanging sponge bioreactors (Inagaki et al., 2015; Imachi et al., 2019). Furthermore, diverse fungal species of both Ascomycota and Basidiomycota isolated from the lignite coal and shale samples resemble terrestrial wood-rotting fungal communities (Liu et al., 2017). These discoveries indicate that some of the active and revivable microorganisms are derived from the original depositional environments (referred to as "paleome"; Inagaki et al., 2006, 2012; Coolen et al., 2013; Kirkpatrick et al., 2016; Orsi et al., 2017) and persist in energy-limited sedimentary habitat over geologic time periods (Walsh et al., 2016; Jørgensen and Marshall, 2016; Starnawski et al., 2017). In addition, the deeply buried microbial cells could be transported back toward the surface through mud volcanism, which occurs globally along convergent margins, and dispersed as "deep-biosphere seeds" into the ocean (Hoshino et al., 2017; Ijiri et al., 2018). These natural seeding pipelines may be important for sustainability of deep subseafloor microbial ecosystems. But what factors limit the size, diversity, functionality, and extent of the deep subseafloor biosphere?

Recent advances in scientific ocean

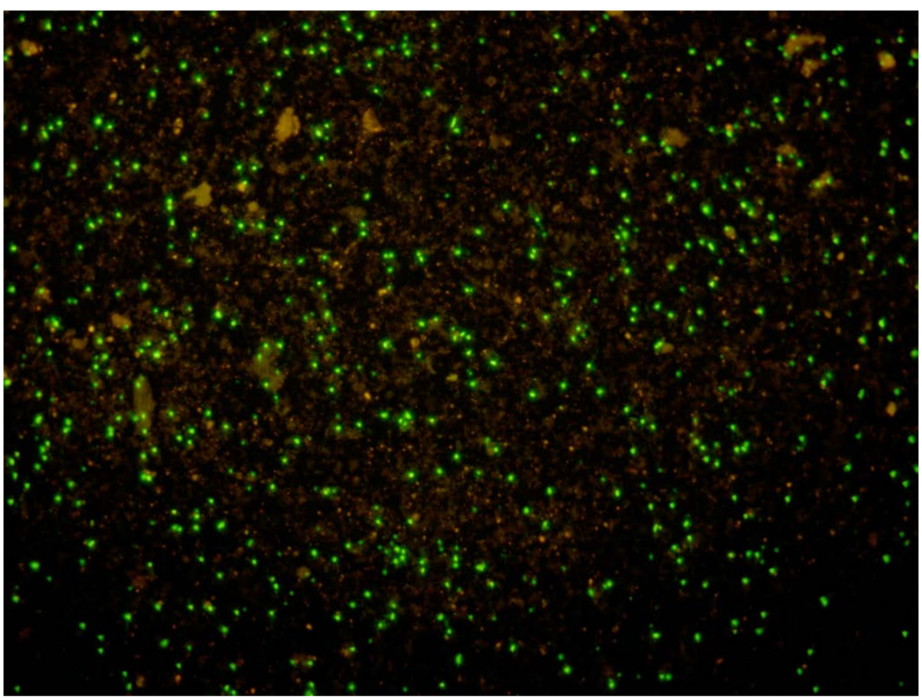

FIGURE 1. A microscopic view of microbial life in a subseafloor sediment core sample obtained during drilling vessel *Chikyu*'s shakedown expedition CK06-06 off Shimokita Peninsula, Japan. Green particles represent microbial cells, in which intracellular DNA is stained with a green fluorescent dye (Morono et al., 2009). The average cell is 200–500 nanometers in diameter. *Photo credit: JAMSTEC*

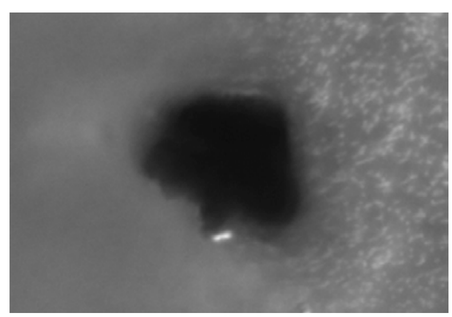

FIGURE 2. A microscopic image of a microbial cell (light blue) on a 2 km deep, 20-million-year-old lignite (coal) particle (black) obtained during *Chikyu*'s Integrated Ocean Drilling Program Expedition 337 (Site C0020; Inagaki et al., 2015; Trembath-Reichert et al., 2017). The microbial cell is approximately 500 nm in length. *Photo courtesy of Elizabeth Trembath-Reichert, Caltech*

drilling during the International Ocean Discovery Program (IODP), coupled with super-clean geomicrobiology facilities both at sea and on shore and with novel high-precision isotope geochemistry and microbiological techniques, will greatly enhance our knowledge of the limits and functionality of deep microbial life (e.g., IODP Expedition 370 "Temperature Limit of the Deep Biosphere off Muroto"; Heuer et al., 2017). To maintain essential life functions, not only geophysical constraints, such as temperature, but also the supply of water and bio-available nutrients and energy sources are crucial (Hoehler and Jørgensen, 2013; Lever et al., 2015; Jørgensen and Marshall, 2016; LaRowe et al., 2017; Ijiri et al., 2018; Tanikawa et al., 2018; Parkes et al., 2019). It may follow that this geosphere-biosphere interaction must be the essential driving force not only for Earth's deep biosphere but also for any possible ecosystems on Mars and other celestial bodies (Dzaugis et al., 2018: Yung et al., 2018; Stamenković et al., 2019).

PLANETARY HABITABILITY AND SUSTAINABILITY

Exploring biosphere frontiers through scientific ocean drilling will elucidate how the habitable world has been established and co-evolved with Earth's other subsystems and how the biosphere has responded to some drastic environmental changes during Earth history (see Challenge 7 in the IODP science plan for 2013–2024, available at https://www.iodp.org/about-iodp/iodp-science-plan-2013-2023). Traditionally, biological evolution and geological evolution have been studied separately, and as a consequence were considered to be different from each other. More recent views in geobiology and astrobiology make it clear that these two "spheres" (the biosphere and the geosphere) have systematically cooperated to evolve together for more than 3 billion years, with each adapting to and shaping the other. When rapid geological changes have occurred (e.g., asteroid impacts, oceanic anoxic events), life has responded with mass extinctions and (sometimes a quick) recovery, and over the course of Earth history, it is estimated that 99% (or more) of all species that ever existed have gone extinct (Barnosky et al., 2011; Lowery et al., 2018). Nevertheless, it remains uncertain whether environmental perturbations have historically occurred in the deep subseafloor biosphere and whether any life has ever gone extinct there.

In principle, life evolves with energy flow in Earth's many entropy-increasing systems. But, it remains a matter of debate as to whether such co-evolution of Earth's systems will be (more) resilient and sustainable in the future. For example, is plate tectonics absolutely required for the origin and long-term evolution of life on Earth (and other planets)? Sleep et al. (2011, 2012) suggest that CO_2 sequestration in the mantle during the Hadean was a necessary condition for making Earth's surface environment habitable by increasing O_2 in the atmosphere through photosynthesis. But, within this context, how did Earth generate unstable forms of prebiotic molecules that polymerized and that developed the ability to recognize surroundings (and even itself) in multiple dimensions and time?

It is worth noting here that such evolutionary multisphere interactions may have occurred and likely will occur repeatedly in the future. Since the Industrial Revolution in the eighteenth century—thus, within the Anthropocene—humanity and associated economic development have resulted in serious global issues, including global warming, ocean acidification, and the subsequent ecosystem changes that will be preserved in the geologic record (Steffen et al., 2015; Waters et al., 2016). Human influences are forcing the ocean and Earth's surface environment more than ever before, possibly with greater impacts than astronomical and geological factors like asteroids and super-volcano eruptions. What environmental factors constrained or forced co-evolution of life and Earth in the past and will do so in the present and the future? How is Earth's deep biosphere energetically connected to the dynamics of other subsystems? And how does humanity understand these (developing) threats to our planetary habitability and utilize this knowledge for developing a sustainable ocean-Earth-life system in the future?

EXPLORING EARTH'S MANTLE THROUGH SCIENTIFIC OCEAN DRILLING

Understanding and predicting the evolution of life (including humanity) and its effect on the ocean-Earth-life system has long been challenging. To tackle these issues important to science and human society, we need to strengthen both basic and applied sciences in a trans-disciplinary and global manner. Our core understanding of planetary habitability can be enhanced only by collecting multidisciplinary observations and by finding patterns through scientific exploration. Core-log-seismic-observatory-experimentation plays an integral part in this mission to help unravel anticipated natural behaviors as well as any possible global anthropogenic consequences in the future. For example, during Earth history, biosphere activity (including surface photosynthesis and subsurface microbial activity) has significantly modified the redox state of the crust and mantle (Sleep et al., 2012; Bell et al., 2015; D'Hondt et al., 2015). These geosphere-biosphere interactions may have created various redox-sensitive minerals in the surface and subsurface and at any major boundary, which may be necessary for the diversification of both life and minerals (Hazen et al., 2008). CO_2 in both the hydrosphere and the atmosphere has been continuously sequestered in (ultra) mafic rocks, and the carbonates trapped within the oceanic crust are expected to return to the deep mantle at subduction zones. Even though the modern Earth is much cooler than the ancient, such systematic natural reactions and recycling of elements still continuously occur and evolve along with humanity and the biosphere. Deep drilling into the ocean's thick accumulations of sediment and into other ocean regions provides an opportunity to study the vast history of and potential for the development of sustainable ocean-Earth-life systems.

Large gaps in our knowledge of the habitability of our own planet remain. Systematic understanding of "habitability dynamics" on Earth can only be addressed by scientific ocean drilling and through collecting long-term observations of the interactions of these multi-spheres. Scientific ocean drilling using *Chikyu* to drill down to the upper mantle—all the way through the Mohorovičić discontinuity (or Moho) as recognized in geophysical data—will deepen our knowledge of planetary habitability and its sustainability (Figure 3). Other example targets include geosphere-biosphere co-evolution along a transect from mid-ocean spreading ridge hydrothermal systems to the aerobic and stable open ocean lithosphere, as well as co-evolution in subduction zones where seawater penetrates the overriding plate and serpentinization occurs with increasing temperature and pressure. Continued international, transdisciplinary collaborations among the scientific ocean drilling community will help us to illuminate the trajectory of life and humanity with Earth's planetary system from deep geologic time to the present, and into the near future, and the deep future.

FIGURE 3. The deep-Earth drilling research vessel *Chikyu*. *Photo credit: JAMSTEC*

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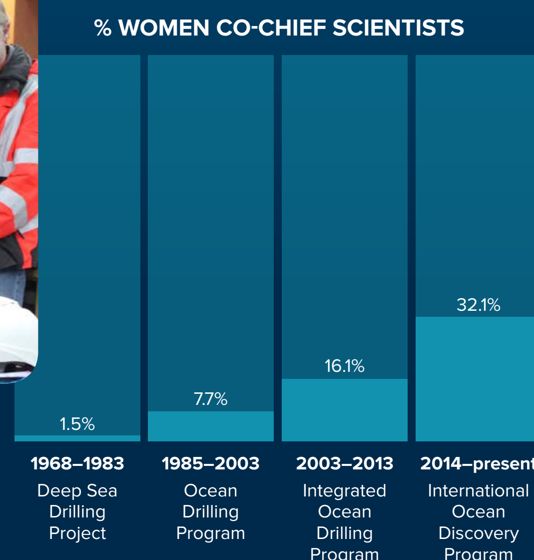
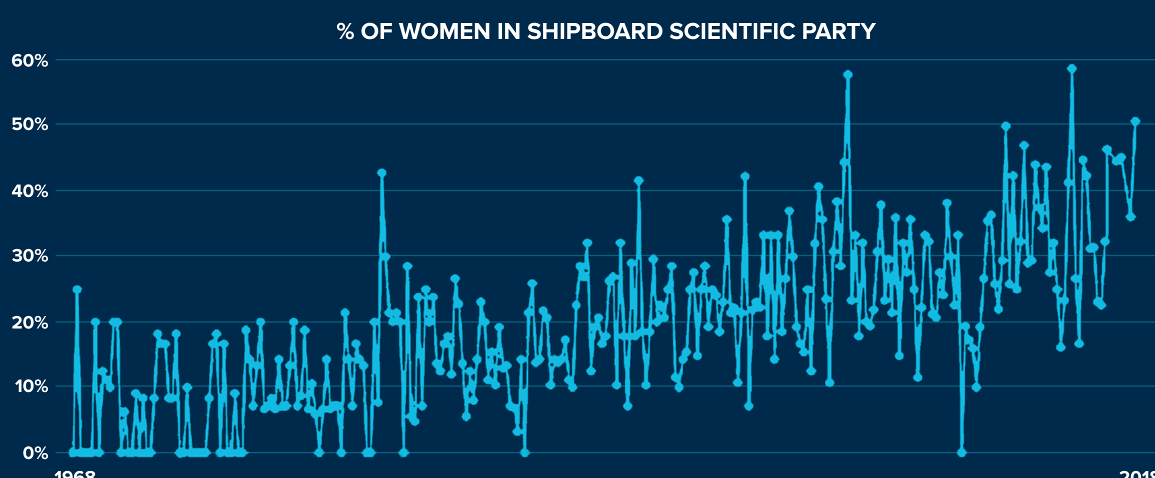
SPOTLIGHT 14. Gender Balance in Scientific Ocean Drilling

Over the first five decades of scientific ocean drilling, participation of women has increased significantly throughout the program. During the Deep Sea Drilling Project, expedition leadership included only three female co-chief scientists (1.5%; 1968–1983). The number increased to 17 during the Ocean Drilling Program (7.7%; 1985–2003), dipped to 10 during the Integrated Ocean Drilling Program (16.1%; 2003–2013), and again increased to 18 during the International Ocean Discovery Program (32.1%; 2014 to present). At the same time, gender and career level diversity within science parties changed. Today, on average, 34% of the science parties are women compared to 12% during DSDP. Graduate students comprise 22% of science parties, and 41% of that total are women. Finally, the current membership of the IODP Science Evaluation Panel is 24% women, and among the more than 1,000 active proponents of the current IODP drilling proposals, more than 20% are women. In the future, the program expects to continue to attract more women into its leadership ranks, many of whom are just now embarking on their first IODP voyages.

— Anthony A.P. Koppers, Adam Klaus, and Holly Given

In 2015, IODP Expedition 357 set out to study serpentinization and microbial life in the Atlantis Massif. This expedition had the first-ever majority female scientific party (67%), with all-female leadership, including Co-chief Scientists Gretchen Früh-Green and Beth Orcutt, Expedition Project Managers Carol Cotterill and Sophie Green, and Petrophysics Staff Scientist Sally Morgan. *Photo credit: Yuki Morono*





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Quo Vadis

Look to the *Future*

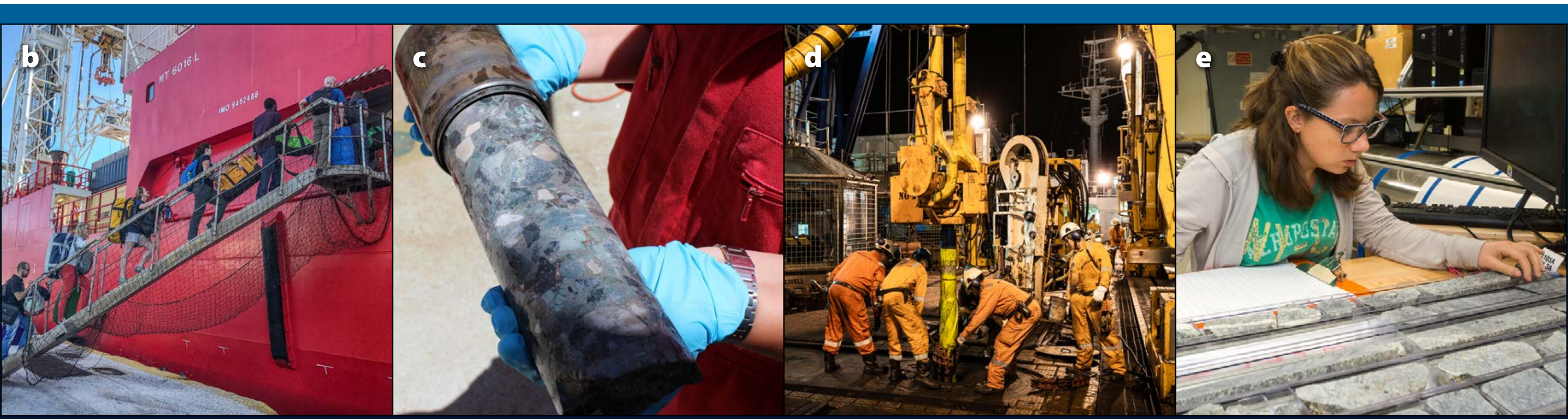
By Anthony A.P. Koppers, Carlota Escutia, Fumio Inagaki, Heiko Pälike, Demian M. Saffer, and Debbie Thomas

Over the last five decades, scientific ocean drilling has addressed a wide array of themes important to the Earth, ocean, and life sciences, adding valuable information to studies that required knowledge of the subseafloor environment to make progress. But it has also opened up new areas of research that would otherwise not be possible. This special issue of *Oceanography* can highlight only a few examples of such triumphs. Indeed, the repertoire and impact of scientific ocean drilling is far deeper than can be captured in these pages, transcending many disciplines, and enriching the work of thousands of researchers worldwide. Scientific ocean drilling has matured in parallel with emerging challenges in the Earth, ocean, and life sciences, remaining as relevant a scientific endeavor as it was in the early days of the Deep Sea Drilling Project in the late 1960s.

In the 2015 report by the US National Research Council, *Sea Change: 2015–2025 Decadal Survey of the Ocean Sciences* (https://doi.org/10.17226/21655), the importance of scientific ocean drilling to our community is powerfully highlighted. While understanding that scientific ocean drilling is a resource-intensive research enterprise, the report found its capabilities irreplaceable, fundamental, and—in some cases—critical to improving our understanding of sea level change, past ocean and climate variability, the processes that control formation of the ocean basins, geohazards, and the geophysical, chemical, and biological character of the subseafloor environment. These topics encompass five of the eight priority science questions identified in the *Sea Change* report. The four generations of scientific ocean drilling programs and their extensive research output continue to live up to their *transformative potential*, have accumulated findings that have had significant *societal impact*, have showcased *readiness* by mobilizing expeditions to investigate very recent geological events or hazards, and its 26-country membership has been a textbook example of true *partnership potential*.

The current 2013–2023 International Ocean Discovery Program (IODP) is adopting new scientific approaches, drilling strategic transects, and compiling regional scientific ocean drilling results while also scheduling multi-expedition missions to more comprehensively address major science questions. For example, the current program has emphasized work in three areas—mission monsoon, mission Antarctica, and mission earthquake—each potentially making use of all three currently available drilling facilities, *JOIDES Resolution*, *Chikyu*, and a mission-specific platform. Through these longer-term, multi-expedition efforts, IODP will dramatically advance our understanding of the on/off switching of the Asian monsoon and its influence on Earth's climate, the sensitivity of Antarctic ice sheets to changes in atmospheric carbon dioxide and the impact of this greenhouse gas on past and future sea level, and the mechanisms that cause large magnitude (M8+) earthquakes that can result in devastating tsunamis. While the new IODP mission approach aims to contribute significantly to our understanding of existing big science issues, as shown in the examples above, it is anticipated that results from the missions will also spawn new and exciting avenues of research to be addressed by a future scientific ocean drilling program.

The current IODP provides an excellent springboard for next-generation, post-2023 scientific ocean drilling. While the four IODP themes of *Climate and Ocean Change*, *Biosphere Frontiers*, *Earth Connections*, and *Earth in Motion* remain relevant across disciplines (the IODP science plan is available at https://www.iodp.org/about-iodp/iodp-science-plan-2013-2023), research



(a) Siem Offshore personnel on the *JOIDES Resolution* rig floor during coring operations, IODP Expedition 362, *credit: Tim Fulton, IODP JRSO*. (b) Scientists boarding the drillship *Fugro Synergy* in Corinth harbor, IODP Expedition 381, *credit: ECORD-IODP.* (c) A core sample in the core catcher, IODP Expedition 364, *credit: A. Rae, ECORD-IODP*. (d) Rig floor of *Chikyu*, NanTroSEIZE expedition, *credit: JAMSTEC*. (e) Structural geologist Carlotta Ferrando (University Montpellier II, France) examines the core and records her findings, IODP Expedition 360, *credit: Bill Crawford, IODP JRSO*

questions, expedition implementations, and techniques are changing rapidly. There is a need for deepening partnerships with, for example, the continental drilling, deep biosphere, astrobiology, and geodynamics communities. At the same time, focusing on multi-expedition missions that take advantage of efficient regional ship tracks and drilling along transects will allow the program to address science questions that cannot be answered within the timeframe of a typical single two-month expedition. New science challenges include the dynamics of climate variability at low latitudes and in the tropics, deep Earth geodynamics and its relation to surface processes, the fate of secure drinking water resources in coastal areas, how gas hydrates form, continental shelf stability and related landslide geohazards, the habitability of Earth and its environment in the past and projected into the future, and understanding the past M8+ seismology record in subduction zones.

On the heels of 50 years of extraordinarily successful scientific ocean drilling, there remains a need to continue the research endeavors that have produced a constant stream of high-impact knowledge of our Earth system. A refreshed IODP science plan will lay out the exciting new science challenges that can only be addressed through scientific ocean drilling, while a large community effort plans for replacement of the aging *JOIDES Resolution* with a modernized, more capable non-riser drilling vessel.

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Atlantic Warming Since the Little Ice Age

By Geoffrey Gebbie

"Winter Landscape with a Windmill" by Hendrick Avercamp, c. 1615. The Little Ice Age was a period of intense winters in Europe, as shown in this scene of a frozen river in The Netherlands that rarely freezes today. *Image from http://fiveminutehistory.com/20-amazing-winter-paintings-from-the-little-ice-age/*

ABSTRACT. Radiocarbon observations suggest that the deep Atlantic Ocean takes up to several centuries to fully respond to changes at the sea surface. Thus, the ocean's memory is longer than the modern instrumental period of oceanography, and the determination of modern warming of the subsurface Atlantic requires information from paleoceanographic data sets. In particular, paleoceanographic proxy data compiled by the Ocean2k project indicate that there was a global cooling from the Medieval Warm Period to the Little Ice Age over the years 900–1800, followed by modern warming that began around 1850. An ocean simulation that is forced by a combined instrumental-proxy reconstruction of surface temperatures over the last 2,000 years shows that the deep Atlantic continues to cool even after the surface starts warming. As a consequence of the multicentury surface climate history, the ocean simulation suggests that the deep Atlantic doesn't take up as much heat during the modern warming era as the case where the ocean was in equilibrium at 1750. Both historical hydrographic observations and proxy records of the subsurface Atlantic are needed to determine whether the effects of the Little Ice Age did indeed persist well after the surface climate had already shifted to warmer conditions.

INTRODUCTION

The Little Ice Age (LIA) was a period of cold surface temperatures over roughly the years 1400–1800 CE (e.g., Paasche and Bakke, 2010), the time of cold European winters immortalized in the works of European master painters. A period of modern warming has followed the Little Ice Age, but research is still being conducted to determine what fraction of modern warming is due to natural versus anthropogenic causes (e.g., Abram et al., 2016). To determine what physical processes are at play, key information includes the timing of the end of the Little Ice Age, the magnitude of modern warming, and whether these quantities are globally coherent or have regional variations (Bradley and Jones, 1993). Measurements of ocean temperature using modern instruments only go back as far as the 1870s HMS *Challenger* expedition (Murray, 1895), however, and probably do not capture the coldest sea surface conditions. Paleoceanographic records recovered from sediment cores provide information about sea surface temperature over the last millennium (e.g., Oppo et al., 2009), but their utility is sometimes limited by dating uncertainty and lack of temporal resolution.

Modern-day radiocarbon observations indicate that waters in the deep ocean were last in contact with the atmosphere several hundred years ago (Key et al., 2004). Atlantic deep waters are not as isolated from the surface as Pacific waters due to vigorous deep water formation, but their radiocarbon concentrations suggest radioactive decay over 200–500 years since they had atmospheric values. This timescale is long enough for some of the deep waters of the Atlantic to have last been in contact with the sea surface during the Little Ice Age. That the Atlantic could have such long timescales may be surprising, as the response of the Deep Western Boundary Current (DWBC) to surface perturbations is a few decades or less (e.g., Jackson et al., 2016), but this DWBC response is just the arrival of an initial signal, and the full equilibrium response takes much longer (Khatiwala et al., 2001; Gebbie and Huybers, 2012). In order to simulate the post-LIA deep ocean evolution accurately, a numerical model may require knowledge of the long-term surface history, or the initial conditions may need to contain the disequilibrium effects that result from this surface history.

The goal of this manuscript is to review what is known about centennial-timescale surface temperature changes and to use that information to set expectations about warming in the subsurface Atlantic since the end of the Little Ice Age. The relevant surface temperature history includes times that precede the instrumental record, and thus we reconstruct surface temperature by taking into account both instrumental and paleoceanographic proxy observations. We explore how well interior ocean variations on multidecadal and longer timescales can be inferred by the passive advection and diffusion of surface temperature anomalies. Due to the long memory of the deep ocean, the signal of the Little Ice Age occurs later in the subsurface Atlantic than at the surface. The remnant effect of the Little Ice Age has consequences for both the Atlantic heat uptake and air-sea fluxes in the modern warming period.

COMMON ERA SEA SURFACE TEMPERATURE EVOLUTION

Global-Mean Variations

Here, we reconstruct a plausible surface temperature history of the Common Era (i.e., the last 2,000 years) from the Ocean2k paleoceanographic proxy data compilation (McGregor et al., 2015) and the HadISST 1.1 product derived from modern thermometers (Rayner et al., 2003). For the years 1870–2015, the average sea surface temperature (SST) of the three coldest months in the HadISST product is selected because these waters are preferentially communicated to the ocean interior by the mixed-layer "demon" (Stommel, 1979; Williams et al., 1995). This quantity should be thought of as the "subduction temperature," or the temperature of subducted water, rather than a strict reconstruction of SST. Temperature reconstructions from late nineteenth century instrumental data are especially uncertain, as the

HadISST data set shows increased divergence from other instrumentally based products during this period (e.g., Huang et al., 2015).

The Ocean2k project reconstructed global-mean sea surface temperature for the years 100–1900 with 200-year resolution, and its statistical tests show a coherent global signal (McGregor et al., 2015). This proxy reconstruction must be interpreted carefully because the proxy data may best reflect spring and summer temperatures, the temperatures are anomalies that are not placed on an absolute temperature scale, and no estimate of twentieth century warming is provided. To produce a seamless simulation of the Common Era, these three issues must be addressed.

To address potential seasonal biases, we average the 57 individual marine paleoceanographic records in the Ocean2k SST network to produce a temperature anomaly time series up to 1950. By computing anomalies, any warm signal due to a spring or summer bias in the proxies is removed so long as there are no changes in seasonality. Furthermore, it is assumed that this time series well approximates the variations in winter temperature that subduct into the subsurface.

An improved estimate of modern warming can be produced by blending the instrumental and proxy data, but first the two data sets must be placed on the same absolute temperature scale. The missing quantity is the Common Era-average surface temperature that needs to be added to the proxy-data anomaly time series. We solve for the Common Era-average temperature that leads to a match with the global-mean surface temperature difference between HMS *Challenger* expedition measurements of the 1870s and the World Ocean Circulation Experiment (WOCE) data of the 1990s, where the instrumental and proxy data sets are blended with a linearly varying weight from 1870 and 1950. The weighting is such that the proxy record has 100% weight at 1870 and the instrumental product is given 100% weight at 1950. This process yields a single blended surface temperature history in which signals from the instrumental and proxy data sets are compared in a consistent manner.

The global-average subduction temperature is reconstructed to have cooled by ~0.5°C between the Medieval Warm Period (~900 CE) and the end of the Little Ice Age, followed by almost 0.9°C of modern warming since 1850 (Figure 1). The coldest subduction temperatures of the Common Era occurred in 1750 and again around 1850, suggesting that the Little Ice Age was not a stable cold climate, but instead was characterized by variability around a cold state. It is difficult to define the Medieval Warm Period because of decadal and centennial variability in the years 600–900. This variability arises in the average of 57 paleoceanographic proxy data sets but is not emphasized in the reconstruction provided by the Ocean2k project, which instead provides a smoother time series by averaging over 200-year intervals. Our reconstruction is probably best thought of as one possible realization of this climate interval, where the timing and magnitude of the multidecadal and centennial events are uncertain.

The global temperature reconstruction shows a number of strong warmings, such as those beginning in 1850, 1920, and 1970 (Figure 2). There is conflicting evidence about the physical mechanisms responsible for these events. The event that begins in the 1920s is detected in several surface meteorological measurements in Greenland as a rapid 4°C warming (Cappelen, 2014). A climate model study suggests that stochastic atmospheric forcing can cause Greenland climate transitions (Kleppin et al., 2015) along with other climate signals around the globe, including the tropical Pacific (Giese and Ray, 2011). This proposed mechanism does not require anthropogenic forcing. Furthermore, the magnitude of the earliest warming that starts around 1850 is uncertain. Paleoceanographic data have been interpreted such that this warming is a consequence of the early onset of human activities (Abram et al., 2016), but its magnitude is usually

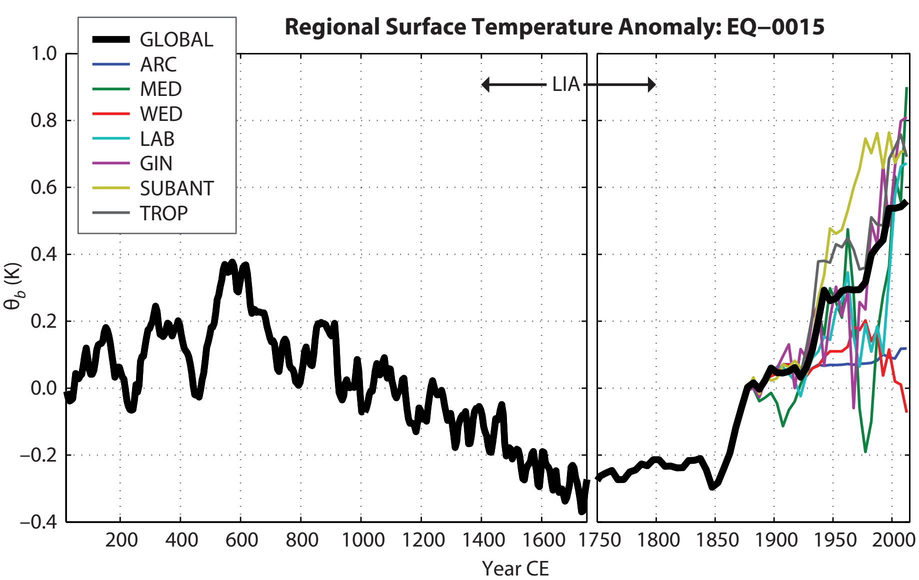

FIGURE 1. Reconstructed surface temperature, θ_b, from blended paleoceanographic and instrumental data products. Surface temperature time series are relative to a baseline value at the year 15 CE (i.e., EQ-0015), including the global area-weighted average (black line) and seven major surface regions of the Atlantic sector (colored lines). The surface regions are defined in the text. Prior to 1870, the regional anomalies collapse onto the global mean. A general definition of the Little Ice Age is included (LIA, horizontal bar; Paasche and Bakke, 2010). ARC = Arctic. MED = Mediterranean. WED = Weddell Sea. LAB = Labrador Sea. GIN = Greenland-Iceland-Norwegian Sea. SUBANT = The subantarctic region of the Atlantic. TROP = The remaining subtropical and tropical regions of the Atlantic.

reconstructed to be smaller than shown in Figures 1 and 2. Many of the Coupled Model Intercomparison Project version 5 (CMIP5) models are initialized around this time period and do not simulate any significant late nineteenth century warming (Gleckler et al., 2016). Here, the strong warming is corroborated by the surface HMS *Challenger* data, and additional historical hydrography from the Norwegian Sea could provide additional evidence (Helland-Hansen and Nansen, 1909).

Regional Temperature Variations

We reconstruct regional temperature variations after 1870 based upon the HadISST product. To mitigate the uncertainty of the small-scale structures in the HadISST product in the late nineteenth and early twentieth centuries, the surface temperature time series are regionally averaged in 14 oceanographically defined surface patches following Gebbie and Huybers (2010). Of the 14 regions, we consider seven to be the focus of this work: (1) Arctic (ARC), (2) Mediterranean (MED), (3) Weddell Sea (WED), (4) Labrador Sea (LAB), (5) Greenland-Iceland-Norwegian Sea (GIN), (6) the subantarctic region of the Atlantic (SUBANT), and (7) the remaining subtropical and tropical regions of the Atlantic (TROP). The Weddell Sea region is defined to be south of the southern extent of the Antarctic Circumpolar Current at a boundary given by the σ_o = 27.55 line (i.e., surface density of 1,027.55 kg m^{-3}; Sievers and Nowlin, 1984; Orsi et al., 1995), and bounded zonally by 70°W and 30°E. The subantarctic and the subtropics are divided by the 34.8 isohaline on the practical salinity scale that approximates the subtropical front (Deacon, 1937). The Labrador Sea region is defined to be north of the polar front marked by the 35.4 isohaline (Tomczak and Godfrey, 1994) and south of the Greenland-Scotland Ridge, and thus includes much of the North Atlantic subpolar gyre. The GIN Sea region extends northward from the LAB region as far as 82°N and 30°E, and any waters beyond those boundaries are considered Arctic. The Mediterranean is defined as all waters interior to the Strait of Gibraltar. Over 82% of the original variability in the HadISST product is retained after averaging, and we suggest that the remaining signals are more reliable due to averaging over large regions, although some regions such as the Arctic are severely data limited.

Temperature in the Labrador Sea region has not monotonically increased since the end of the Little Ice Age, but has been influenced by strong multidecadal variability ("LAB," Figure 2). This inference is consistent with the annual time series of temperature, salinity, and density of the central Labrador Sea that is available back to 1938 (Yashayaev and Clarke, 2008). The suggested cause of the multidecadal variability is intermittent deep convection that creates large quantities of Labrador Sea Water (e.g., Lazier, 1980; McCartney and Talley, 1982). Temperature change is often coincident with changes in salinity and other North Atlantic climatic variables (e.g., Dickson et al., 1975, 1988). When considering Labrador Sea surface temperature over the entire 1850–2015 interval, however, the warming has a similar magnitude as the global-mean signal. Our reconstruction suggests significant Labrador Sea warming prior to 1940, consistent with recent inferences from paleoceanographic data (Thornalley et al., 2018). An outstanding question is the extent to which the North Atlantic temperature variability is related to changes in the meridional overturning circulation, global warming, or both (e.g., Caesar et al., 2018).

Paleoceanographic proxies of the last 2,000 years show coherent global changes, but a recent analysis did not detect significant differences in sea surface temperature when compiled into regional bins (McGregor et al., 2015). For this reason, our reconstruction of surface temperature prior to 1870 makes the first guess that all surface regions covary with global-mean surface temperature (collapsed lines, Figure 1). Such an assumption does not imply that the sea surface was homogeneous prior to 1870, but instead that the spatial pattern is fixed. The reconstructed regional anomalies are small relative to the background temperature differences between regions, so the present-day

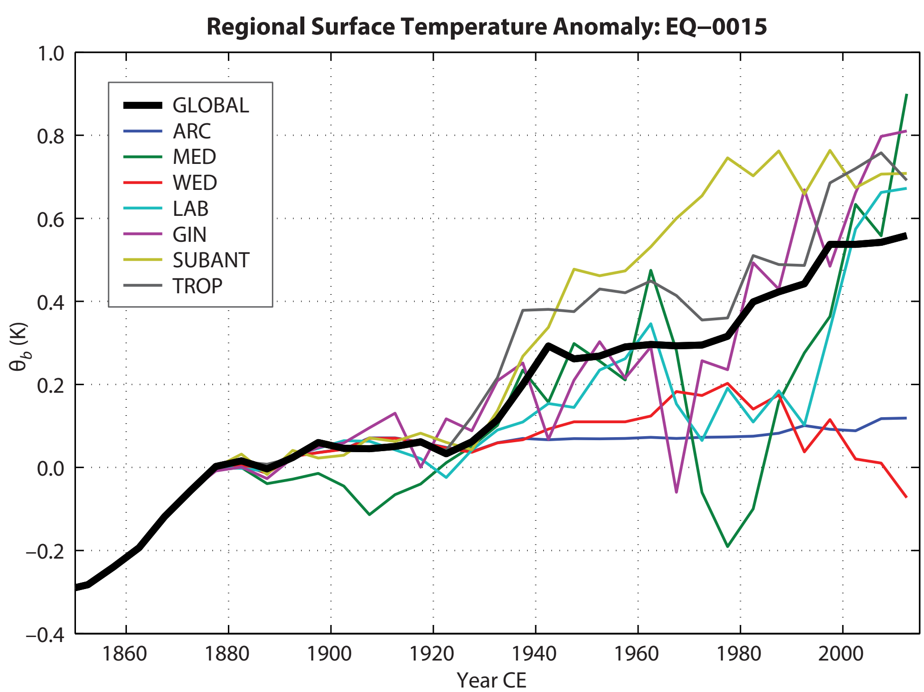

FIGURE 2. Reconstructed surface temperature after 1850. Identical to Figure 1, but restricted to the years 1850–2015.

spatial pattern is only slightly modified. Additional information is available in subsurface data from both paleoceanographic proxies (e.g., Mjell et al., 2016) and historical instrumental observations (e.g., Murray, 1895). There are thought to be shifts in the North Atlantic Oscillation, El Niño-Southern Oscillation, and the Pacific Decadal Oscillation that covary with the Medieval Warm Period and the Little Ice Age (e.g., IPCC, 2005). Efforts to fit a model to these types of observations have been successful over the time period 1815–2013 (Giese et al., 2016). It would be especially useful to produce an estimate that is also consistent with the pre-1815 surface history, and to make an estimate that conserves heat. To do so, an optimal control problem needs to be solved (e.g., Fukumori, 2002; Wunsch and Heimbach, 2007), but computational barriers to such a method would have to be overcome. Even in cases where surface temperature varies on monthly timescales, for example, the stable numerical integration of an ocean model typically requires a sub-hourly time step. At this level of time resolution, the equations for either the adjoint method or the Kalman smoother, two methods for solving the control problem, become computationally intractable.

SIMULATION OF THE COMMON ERA

Circulation Model

The interior ocean response to surface temperature variability includes the passive advection and diffusion of anomalies along the existing large-scale circulation, and a dynamic response that alters the circulation through the temperature effect on density (e.g., Banks and Gregory, 2006). Surface temperature variability may reflect a change in water mass formation rates, and this dynamical signal is communicated rapidly throughout the deep ocean (Kawase, 1987). In a realistic simulation with an ocean general circulation model, however, Marshall et al. (2015) find that anthropogenic warming is communicated to the interior on the centennial timescale primarily through the passive response to surface anomalies. The large-scale patterns of ocean heat uptake and storage are primarily controlled by the advection and diffusion of a background circulation, and changes in ocean circulation play a secondary role so long as warming is sufficiently small. Our reconstructed surface history indicates temperature perturbations smaller than 1°C and even smaller subsurface anomalies due to ocean mixing. In addition, comparison of hydrographic observations taken decades apart shows only minor changes in density perturbations (Roemmich and Wunsch, 1984). As the large-scale ocean circulation is in balance with the density structure through geostrophy, these observations suggest that the large-scale circulation did not undergo major reorganizations in the recent past (see also, Zanna et al., 2019). This assumption should be reassessed with additional data that are now available, and the potential effect of changes in circulation is later tested in the section on Penetration of Surface Anomalies.

Our goal here is to set expectations for the multidecadal to centennial temperature changes that characterize Atlantic warming after the Little Ice Age. Given the suggestion of stable circulation patterns, we represent interior ocean circulation by the advective and diffusive fluxes empirically derived from observations collected during the WOCE field campaign of the 1990s (Gebbie and Huybers, 2012). Distributions of temperature, salinity, nutrients, oxygen, and radiocarbon were inverted for the circulation and mixing rates while respecting conservation equations for mass and all other properties. Circulation is represented at 2° × 2° horizontal resolution across 33 vertical layers, leading to 291,556 grid cells. At this resolution, diffusive fluxes include the net effect of subgridscale processes such as mesoscale eddies.

The ocean circulation model was expressly derived from WOCE data to accurately represent connections between the surface and the deep. A demonstration of the model's skill is that it accurately reproduces independent carbon isotope values (Gebbie and Huybers, 2011) and deep-ocean radiocarbon concentrations while producing realistic estimates of the fraction of Antarctic Bottom Water and North Atlantic Deep Water in the deep ocean (Gebbie and Huybers, 2010; DeVries and Primeau, 2011). We suggest that issues inherent to models that parameterize small-scale processes are mitigated here by empirically training the model with data.

By using this simplified model of ocean physics, we can simulate back far enough into the past to capture the disequilibrium processes due to the Little Ice Age. While this manuscript focuses on the Atlantic Ocean, a global model domain is used because of the remote influences that can affect the Atlantic on these long timescales. We refer to the simulation as EQ-0015 because it is a 2,000-year simulation that assumes equilibrium in year 15 of the Common Era. Even starting at the year 15 CE does not completely remove sensitivity to initial conditions. In the Atlantic, there is little memory from earlier than 15 CE, as the percentage of water with age greater than 2,000 years is nowhere greater than 6%. Due to uncertainties in small-scale temperature patterns during the Common Era, we force the simulation with the average temperature in 14 surface regions described earlier. The surface boundary conditions are also averaged with a five-year timescale. In order to accurately resolve tracer transport, we use an adaptive time step that is much shorter than the five-year timescale of the surface boundary conditions and is adjusted depending upon spatial gradients.

The evolution of subsurface temperature is also affected by potential changes in the winds, tides, and freshwater forcing that are not considered in the model. Variations in wind forcing, in particular, are known to be transmitted to the deep ocean more rapidly than the advective-diffusive processes in the model. Unfortunately, the magnitude of centennial-scale variability in winds is not known, nor is the sensitivity of internal redistributions of heat to these potential wind shifts. As a major effect of winds is to set off planetary waves that lead to isopycnal heave and a redistribution of ocean waters, large-scale averages can be taken to mitigate the net effect of wind forcing (Roemmich et al., 2015). Here we emphasize that the dynamics of our simulation are expected to be most accurate on the largest spatial and temporal scales.

Penetration of Surface Anomalies

Our 2,000-year simulation permits centennial-scale deep Atlantic temperature anomalies to be coherently tracked back to surface climate variability (Figure 3). The signals of the warm anomaly of the Medieval Warm Period, the cold anomaly of the Little Ice Age, and modern warming all propagate from the surface to the seafloor, as can be seen when an Atlantic-wide average temperature profile is diagnosed. On the scale of the Common Era, the penetration of these anomalies appears rapid, but the deep Atlantic generally lags the surface by a century or more. The range of deep Atlantic temperature over the last 2,000 years is expected to be greater than 0.2°C, consistent with the relatively rapid propagation to depth being only slightly damped by ocean mixing processes.

The three-dimensional, global temperature distribution at the beginning of the Common Era is not known, but this field is not needed to initialize the simulation under the assumptions given above. To initialize the simulation in the year 15, the temperature anomaly vanishes under the assumption of equilibrium. Then, the surface boundary conditions are translated to anomalies relative to the year 15. The evolution of the full temperature field can be backed out after the anomaly simulation is completed by calibrating with the WOCE-era (1990s) temperature distribution (Gouretski and Koltermann, 2004).

According to the simulation, the amount of Atlantic-average warming since the Little Ice Age varies strongly as a function of depth. The coldest conditions of the Common Era occur later as depth increases, and the deep Atlantic doesn't begin warming until about 1950. Thus, the simulation suggests that there has been a long-term warming trend at all depths in the Atlantic since at least the mid-twentieth century. The amount of warming is larger than 0.5°C at the surface, and diminishes to less than 0.05°C at the seafloor.

The simulation indicates that cold anomalies persist in the deep Atlantic below 2,200 m depth until the end of the simulation. In this case, cold anomalies do not indicate a present-day cooling trend, but rather that the Atlantic is cooler today than in the year 15 at those depths. If the advective-diffusive processes of the model are representative, the cumulative effect of surface cooling from the Medieval Warm Period to the end of the Little Ice Age is expected to have some signal today. The signal of warm anomalies, however, is penetrating rapidly into the deep Atlantic, especially after 1980.

The meridional overturning circulation may have changed by up to ±25% during the Common Era (Lund et al., 2006; Rahmstorf et al., 2015), and the potential influence of these changes is not captured in the previous simulation of this work. To address this issue, we note that the simulation of temperature anomalies is accomplished through a set of linear equations. Under this assumption, the potential temperature at an interior point is a linear function of the boundary temperatures at previous times. Only the surface-to-interior lag and water-mass decomposition are important for determining the response. These linear functions are often called the multiple-source boundary propagator (Haine and Hall,

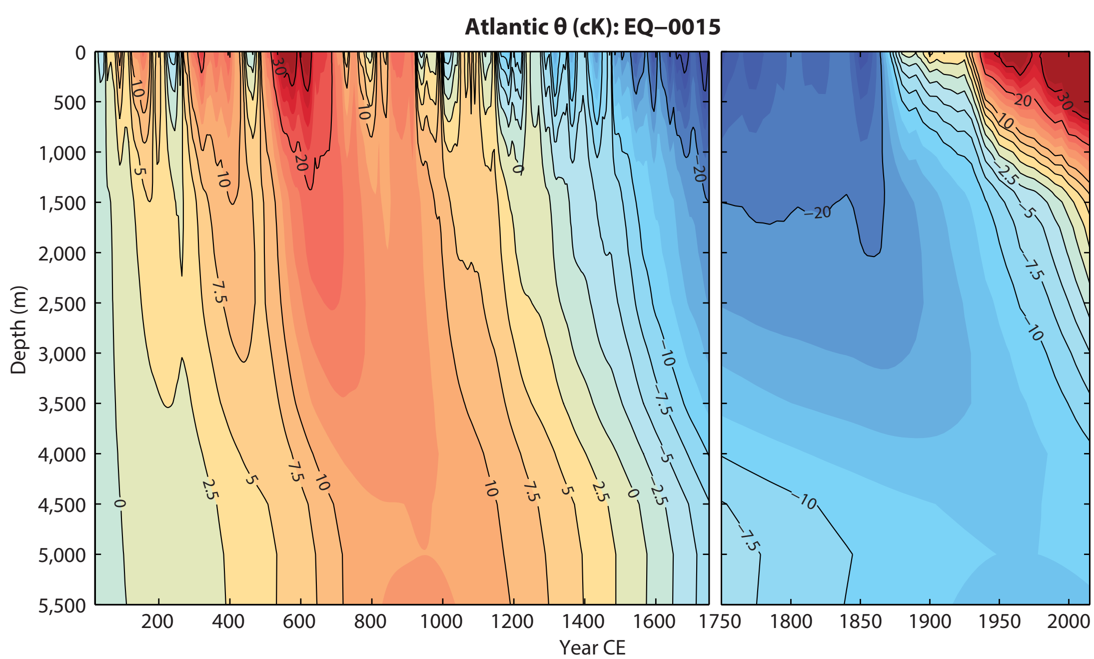

FIGURE 3. Simulation of Atlantic Ocean subsurface temperature anomaly. Time evolution of the vertical profile of Atlantic-average potential temperature anomaly relative to a baseline value at the year 15 CE. The units of the contour labels are hundredths of a degree Celsius.

2002) or the boundary Green's function (Wunsch, 2002). A uniform speedup of the circulation acts to contract the time-axis of the boundary Green's functions, leading primarily to decreased lag times in the interior Atlantic.

We explore the effect of a time-varying circulation by performing simulations of the Common Era where the global-mean surface temperature is assumed to linearly covary with ocean circulation strength (not shown). To approximate how this forcing might affect ocean circulation, we performed one simulation in which the Little Ice Age circulation was 25% slower than found for the 1990s, and another that was 25% faster. Despite the large opposing effects of the time-varying circulation in these two additional simulations, Common Era temperature evolution at 3,500 m depth shows the telltale signs of the Medieval Warm Period, the Little Ice Age, and modern warming, in both cases much like Figure 3. The time-varying circulation modifies the timing of the coldest conditions from the Little Ice Age and the rate of vertical propagation. In all simulations presented here, the present-day Atlantic is warming at all depths, although there are some slight differences in the rate of warming in the deep Atlantic.

Spatial Pattern of Deep Atlantic Warming

The expected spatial pattern of deep Atlantic warming is highlighted by diagnosing the simulated temperature difference between two decades. The 1870s are chosen due to the maximum depth-integrated effect of the Little Ice Age at that time, and the 1990s are chosen because they represent the most recent top-to-bottom global assessment of ocean temperatures (Gouretski and Koltermann, 2004). Greater warming is indicated in the North Atlantic relative to the South Atlantic, as well as the western basin relative to the eastern basin (Figure 4). Although the model is only forced by surface data, the simulation suggests a warming of North Atlantic Deep Water and an enhanced propagation of the signal along the Atlantic deep western boundary current. Ocean reanalyses show a similar pattern of warming over the last few decades (Palmer et al., 2017), indicating that this ocean response is similar in more complex general circulation models. In this study, the model produces a deep western boundary current with a realistic boundary tracer plume (Figure 4). The core of strong currents in the deep western boundary is smaller than the 2° × 2° horizontal resolution of our model, but the net effect of tracer transport along the boundary is enforced through fitting several million modern-day ocean observations in the derivation of the empirical circulation.

While the simulation shows Atlantic warming nearly everywhere after 1870, sediment core data from an intermediate depth on the West African margin shows cooling and strong interdecadal variability (Morley et al., 2011). This cooling trend may be a continuation of the cooling after the Holocene climatic optimum as observed in both Atlantic (Morley et al., 2014) and Pacific (Rosenthal et al., 2013) cores. This cooling could be explained by an intermediate water mass with source waters that do not warm in step with the rest of the ocean, and suggests that the model assumption of globally coherent surface temperature anomalies should be relaxed as in the study of Gebbie and Huybers (2019).

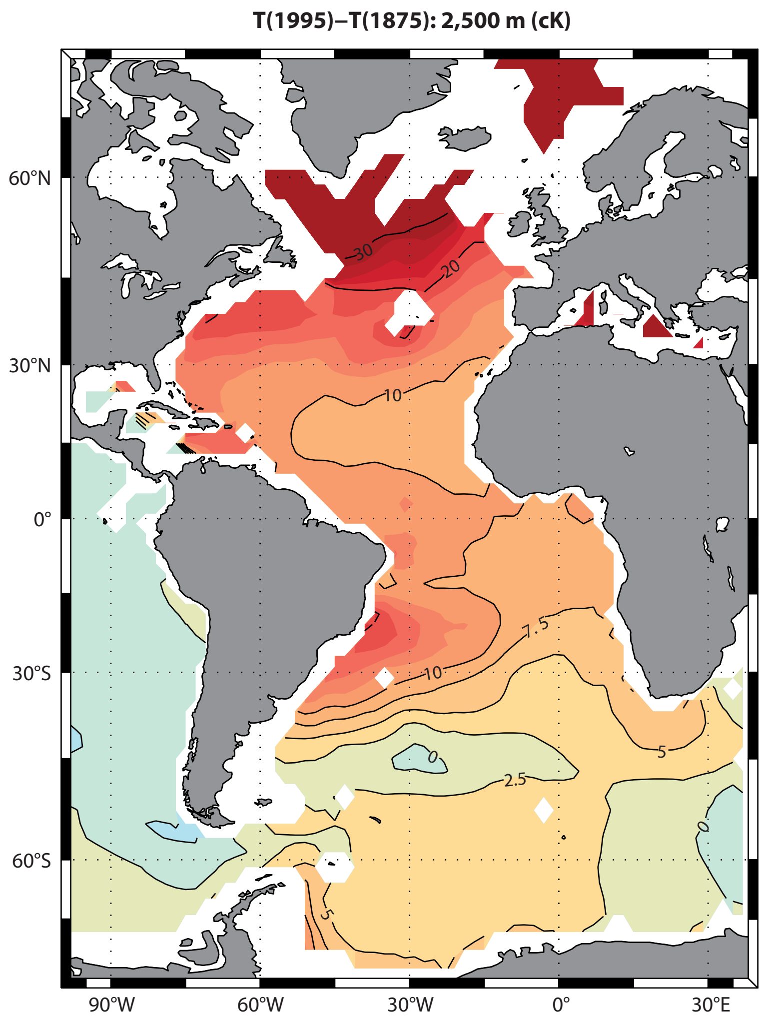

FIGURE 4. Simulated Atlantic temperature change from the 1870s to 1990s at 2,500 m depth. Temperature differences are expressed in hundredths of a degree Celsius.

ATLANTIC ENERGY BALANCE

Atlantic Heat Uptake

Ocean heat uptake is diagnosed by taking the change in ocean heat content over time. Ocean heat content is most accurately computed as a function of the thermodynamic property of potential enthalpy (McDougall, 2003). Here, we calculate ocean heat content by taking into account the density, specific heat capacity, potential temperature, and volume of the 291,556 grid cells of the model. Our diagnostic is likely to have errors that approach 1% due to the assumption of a fixed density field through time, and the replacement of Conservative Temperature with the model variable, potential temperature. Other assumptions made in deriving the passive temperature anomaly model likely cause greater errors. Globally, about 160 ZJ (1 ZJ $\equiv 10^{21}$ J) of heat are taken up in the upper 700 m of the model between 1970 and 2005, consistent with observational estimates (Levitus et al., 2012) and the CMIP5 simulations (Durack et al., 2014). As our model is not as complex as those of the CMIP5 project, reconstructing the exact amount of heat uptake is not the focus here.

After the Little Ice Age, most of the Atlantic heat uptake occurred above 700 m depth, followed in importance by mid-depth (700–2,000 m) and deep (2,000–4,000 m) layers (Figure 5). The order of importance is related to the response time of each layer, as the upper layer was the first to increase heat content. The deep layer did not uptake heat until 1870. Despite the late start and the relatively small size of the Atlantic basin, the deep Atlantic layer uptakes a significant 70 ZJ of heat after 1870. When integrating below 700 m depth, the model simulates 180 ZJ of heat uptake over 130 years in the Atlantic. This corresponds to a nearly 0.1 W m^{-2} energy flux over the entire surface of the planet and is a significant term in the global energy budget.

Changes in heat content in the deep Atlantic were larger than in the surface ocean prior to 1750. This importance of the deep layer is due to the long timescale of the Little Ice Age cooling trend, where the deep Atlantic had enough time to fully respond to the surface. Our findings highlight how the memory of the ocean preserves the signal of temperature variability in intermediate and deep waters, as previously inferred from paleoceanographic observations over the Holocene (Rosenthal et al., 2017).

The EQ-1750 simulation describes a counterfactual case where the ocean is prescribed to be in equilibrium in the year 1750. After 1750, the surface conditions follow those in the EQ-0015 simulation. To accomplish this, the 1750 initial conditions are set to zero anomaly everywhere, and the post-1750 surface conditions are input to the model as anomalies relative to 1750. Differences in EQ-1750 and EQ-0015 heat content evolution reflect the memory of surface conditions before 1750 (dashed lines, Figure 5). In the upper layer, only small differences exist because the ocean memory is relatively short and the surface history before 1750 is quickly forgotten. In the mid-depth and deep layers, however, the heat uptake in EQ-1750 is greater than in EQ-0015. We hypothesize that such a bias in heat uptake may exist in any model that is initialized at the end of the Little Ice Age, including the state-of-the-art CMIP5 models (Gleckler et al., 2016). The decrease in heat uptake due to the pre-1750 surface history can be understood in the context of Figure 3. In 1750, the EQ-0015 simulation shows cold anomalies penetrating into the deep Atlantic. The EQ-1750 simulation instead starts with a period lacking any deep ocean changes due to being initialized at equilibrium and the slow response to surface conditions. Consequently, the EQ-1750 heat content doesn't change much for almost a century. During this period, the EQ-0015 and EQ-1750 simulations diverge due to the subsurface response to the LIA-related surface cooling.

This analysis focuses on heat uptake since 1750 by independently setting the temperature anomalies in each simulation to a 1750 baseline, but it doesn't provide any information about the temperature difference between EQ-0015 and EQ-1750. The year 1750 has nearly the coldest surface temperature of the Common Era, and thus the initial conditions of EQ-1750 reflect these cold conditions throughout the globally equilibrated ocean. Consequently, EQ-1750 is colder than EQ-0015 at all times (1750–2015).

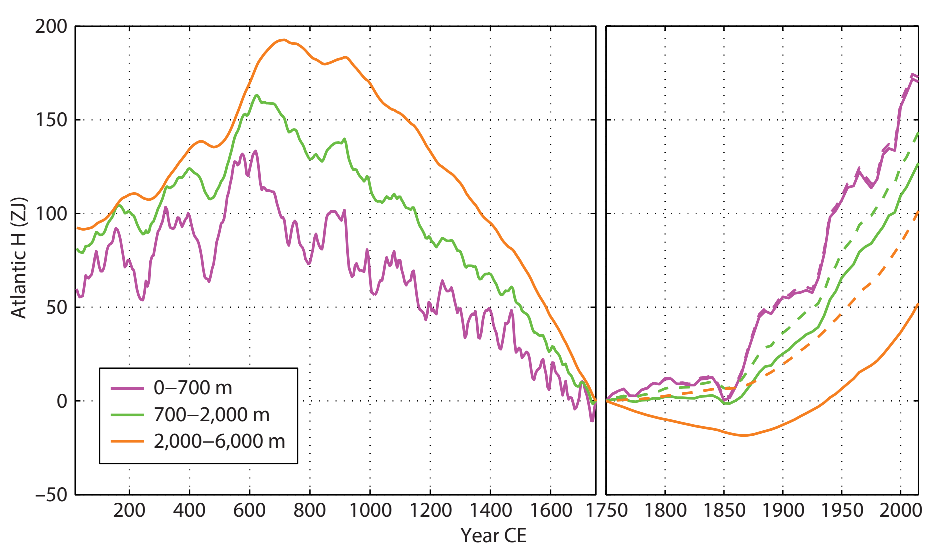

FIGURE 5. Simulated Atlantic heat content changes, 15–2015 CE. Time series of the Atlantic heat content anomaly relative to 1750 CE as decomposed into the upper (magenta, 0–700 m), mid-depth (green, 700–2,000 m) and deep (orange, 2,000–6,000 m) ocean from simulation EQ-0015. Atlantic heat content from an equilibrium simulation initialized at 1750 CE (EQ-1750, dashed lines) diverges from the EQ-0015 simulation. Heat content anomaly is in units of zettajoules (1 ZJ $\equiv 10^{21}$ J).

As these cold, deep waters upwell to the surface in EQ-1750, a larger heat flux is required to produce the observed surface temperature warming, in accordance with the heat content evolution.

Inferred Heat Fluxes

The anomalous global heat flux is calculated by distributing the rate of change in ocean heat content over Earth's surface area. We take the entire planetary area, rather than the oceanic area, in order to facilitate comparison with other contributions to the planetary energy balance. The modern warming period is marked by significant decadal variability, although there is clearly a consistent net heat flux into the ocean. The implied heat flux is between 0.2 W m^{-2} and 0.8 W m^{-2}, with an average of 0.47 W m^{-2} between 1965 and 2015 (top panel, Figure 6). The simulated global heat flux is variable but generally consistent with recent estimates (e.g., Lyman and Johnson, 2014).

The global heat flux evolution makes clear that there was no time before the modern warming period when the ocean could be considered in equilibrium. The cooling period of the Little Ice Age is described as a time when the number of years with heat flux out of the ocean exceeded those years when the ocean absorbed heat. Whether the decadal variability of global heat flux during these years reflects actual climatic variation or noise in paleoceanographic records deserves further study.

To what extent does the North Atlantic Ocean contribute to the global energy imbalance? To compute the impact of the North Atlantic, we first diagnose the heat content in all subsurface waters that originated from either the LAB or GIN surface regions, here denoted the NATL region. The source of water is pre-computed using the assumption of an equilibrium circulation (Gebbie and Huybers, 2011), with the result being a water-mass distribution for the world ocean. Heat content can increase due to air-sea fluxes through the surface of the NATL region, or through advective-diffusive fluxes through the subsurface water-mass boundaries. This calculation is similar to a water-mass transformation budget (Walin, 1982), but we use a water-mass distribution rather than an isopycnal layer to define the control volume. Like the global calculation above, the rate of heat content change is translated to heat flux by dividing by an appropriate area. Here, we use the area of the NATL surface region as we suggest that air-sea fluxes will dominate the water-mass transformation.

During Atlantic warming after the Little Ice Age, 1–5 W m^{-2} of anomalous heat flux must enter the North Atlantic to explain the simulated increase in heat content (bottom panel, Figure 6). The implied heat flux reverses from almost 1 W m^{-2} out of the ocean in 1825 to 5 W m^{-2} into the ocean in 1995. These values are much greater than those found in the global calculation because these fluxes must replace and counteract the heat transported to depth by deep water formation. While the decadal-average North Atlantic fluxes are large relative

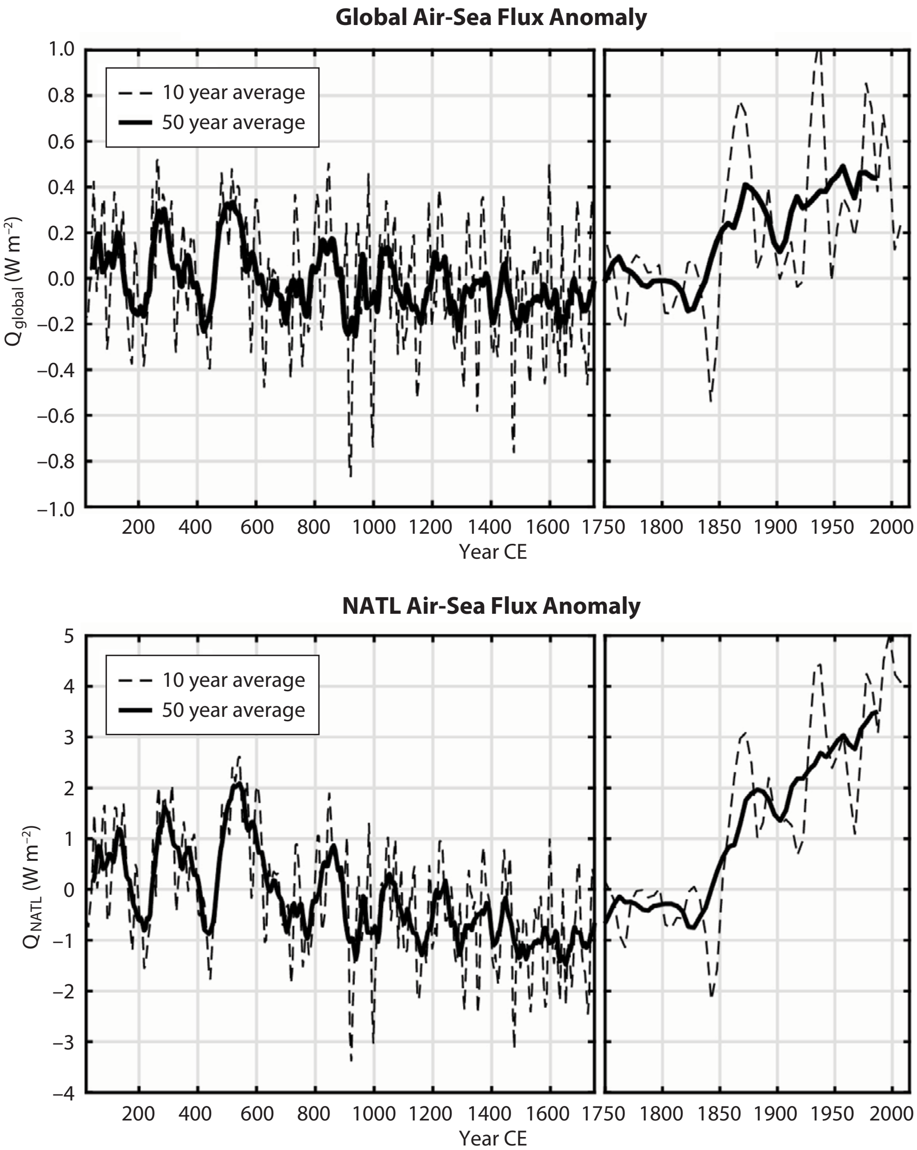

FIGURE 6. Heat fluxes from the EQ-0015 simulation. (top) Global air-sea fluxes with a 10-year (dashed) and 50-year (solid) averaging timescale, where the reference area is the global surface area in order to facilitate comparison with planetary energy balance calculations. (bottom) Similar, but the heat flux into all waters originating from the NATL (LAB + GIN) region of the subpolar North Atlantic, where a regional value of the reference area is used. The NATL region includes both the Labrador Sea and GIN Sea subregions.

to other oceanic regions, these fluxes are small compared to those that are extracted from the ocean during deep water formation (e.g., Våge et al., 2008). Therein lies one major challenge in this problem: deep ocean variations result from the small residual of episodic high-intensity surface events.

CONCLUSION

The modern warming period is occurring at the end of a long cooling period extending from the Medieval Warm Period through the Little Ice Age. The long memory of the ocean dictates that the modern warming is influenced to some degree by the preceding surface history. Thus, some error is incurred if it is assumed that the ocean was in equilibrium prior to modern warming. The size of the error depends upon the response time of the ocean. Even though the deep Atlantic communicates with the atmosphere more rapidly than does the deep Pacific, as it hosts deep water formation in both its northern and southern extremes, the full response of the deep Atlantic can take several hundred years. Influences on temperature from the ocean's long memory are small, but the expected temperature trends are long-lasting and thus can potentially be detected from data that are far enough apart in time (Gebbie and Huybers, 2019). In addition, these small temperature trends represent large amounts of energy when integrated over the Atlantic basin for these long periods of time.

To quantify modern Atlantic warming, several important issues must be addressed. For example, we must account for the surface temperature of the ocean during times that pre-date our instrumental record as well as potential ocean circulation change during times in which the wind field was uncertain. Here, we proceed by using paleoceanographic observations to fill in gaps in the surface temperature history and to make the plausible assumption that the large-scale circulation was not dramatically altered given the relatively small temperature perturbations over the Common Era. A simulation of the last 2,000 years has basic features that are expected to be robust: (1) the cumulative effect of the Little Ice Age occurring in the deep Atlantic well after the surface climate forcing occurred, and (2) the reduction of heat uptake in the deep Atlantic due to the effect of ocean disequilibrium at the onset of modern warming.

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FORCES IN AN ESTUARY

Tides, Freshwater, and Friction

By David Fugate and Felix Jose

PURPOSE OF ACTIVITY

The goal of this activity is to help environmental science students understand and compare hydrodynamic forces in an actual estuary. The interplay of physical forces in an estuary determines the currents and the amounts of mixing and stratification within the water column. The currents, in turn, are an important control on the distribution of phytoplankton, which form the base of the food web, and suspended sediments, which contain nutrients and pollutants. During this activity, students estimate the relative strengths of the key forces in an estuary, the barotropic and baroclinic pressure gradients, and friction. In addition, students estimate how these values change during flood and ebb and spring and neap tidal phases.

Another purpose of this activity is to provide students with experience in analyzing data using spreadsheets, in organizing and collaborating within a fieldwork team, and in producing a scientific report.

AUDIENCE

This field experiment was designed for an intermediate- to upper-level Introduction to Physical Oceanography class and is also appropriate for upper-level undergraduates or graduate students in marine or environmental studies.

TIME REQUIRED

In this activity, the class is split into four groups, each of which participates in a separate two- to three-hour field trip. In addition, the entire class meets for two two-hour class periods that involve analyses and syntheses, though this portion may be assigned as homework.

BACKGROUND

Estuaries are crucial environments for many aquatic species. Over 70% of commercial fish and shellfish utilize estuaries as spawning grounds and nurseries (US EPA, 1992), and these organisms depend directly and indirectly on estuarine currents and water-column mixing. Variations in currents and mixing in an estuary are critical to determining the transport of phytoplankton, sediment, pollutants, and nutrients, as well as the flux of O_2, CO_2, and other materials vertically and horizontally, through the estuary. Currents and mixing also help determine the location and strength of the estuarine turbidity maximum (ETM), which in many estuaries is an important habitat for phytoplankton and juvenile and larval fish (e.g., North and Houde, 2003).

Currents and mixing in an estuary are determined by the interaction of tides and freshwater discharge, as well as the estuary's geometry. A variety of mechanisms form subtidal currents, but for this activity we investigate the forces causing density-driven residual currents, which are often associated with salt wedge, partially mixed, and well-mixed estuarine types (Figure 1a–c). Other estuary types, such as fjord and inverse, are also recognized.

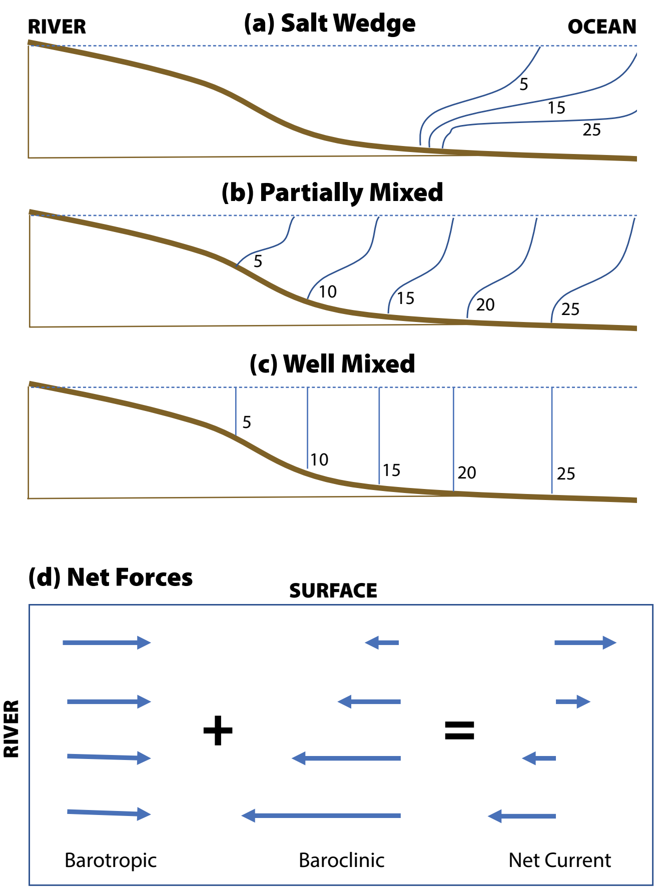


FIGURE 1. Diagrams of estuarine types and combinations of barotropic and baroclinic pressure gradients. Blue contours show isohalines. (a) Salt wedge. (b) Partially mixed (c) Well mixed. (d) Net forces in a partially mixed estuary.

The physical forces that dominate tidal and subtidal currents in most small estuaries are barotropic and baroclinic pressure gradients and bottom friction (e.g., Friedrichs and Aubrey, 1988; Geyer et al., 2000). Wind can also be an important factor (e.g., Scully et al., 2005; Wong and Moses-Hall, 1998), but is not addressed in this activity other than to make simple observations of wind strength and direction and to speculate about how they may affect our conclusions. Depending on the time and length scales of the physical properties, the Coriolis force may be relevant in some sections of larger estuaries such as Chesapeake Bay, but can be neglected in smaller estuaries. Advanced students may want to test whether the Coriolis force can be neglected in their estuary by researching and evaluating the Rossby number. The main analysis for this exercise is a very basic approach that treats the problem as a vertically averaged balance between acceleration, friction, and the pressure gradients. Nevertheless, it is a good starting point for students interested in learning about the play of forces in an estuary and is relatively easy to measure. The terms used to calculate these quantities are from the depth-averaged shallow water equations of momentum.

Friction Force

As water moves in an estuary, resistance from the bottom opposes the flow in the form of friction. Though the dynamics of friction in the bottom boundary layer can be complicated, we can get a reasonably good estimate of the degree of friction by using a simple quadratic drag formulation and vertically averaging over the water column:

$$\textit{Friction from the bottom} = -\frac{C_D u|u|}{H}, \qquad (1)$$

where u is the along channel current, C_D is the drag coefficient (set to a typical value for muddy estuaries of 0.003; e.g., Dyer, 1986; Trowbridge et al., 1999; Winterwerp and Wang, 2013), and H is the water depth. The value for u is conventionally the current speed one meter above the bottom, but in practice in shallow estuaries, the vertically averaged currents are often used (e.g., Li et al., 2004; Traynum and Styles, 2007).

Baroclinic Pressure Gradient Force

Horizontal differences in water density create a baroclinic pressure gradient that increases with depth in the water column (Figure 1d). Along a partially mixed estuary, the water is denser near the ocean at the saltier mouth of the estuary and least dense at the fresher head of the estuary. Combined with the barotropic pressure gradient (see below), this creates a two layered subtidal (i.e., tidally averaged) current in which saltier water moves up the estuary from the ocean at the bottom, and fresher water moves toward the ocean at the surface (Figure 1d). This residual current is not observable from shore or a boat. Instead, only the much stronger instantaneous flood and ebb currents can be observed.

Imagine a parcel of water near the bottom that moves upstream with the flood current for 10 km. During the subsequent ebb, the parcel of water may move downstream only 9.9 km. After many tidal cycles of moving up 10 km and moving back only 9.9 km, the net movement of the water parcel is upstream. This subtidal, or residual, current can be measured by tidally averaging time series of flow measurements. While the measurement of these currents is beyond the scope of this exercise, we will measure the force that causes them. It is also this current that is responsible for the classically formed ETM. At the upper extent of the salinity intrusion, the horizontal density gradient and its associated subtidal currents stop. This results in a near-bottom convergence of the landward-directed, density-driven current and the seaward-directed freshwater discharge. At this location, suspended sediments and weakly swimming organisms can be trapped and focused, creating a region of high turbidity. The force due to the vertically averaged baroclinic pressure gradient is

$$\textit{Force due to baroclinic pressure gradient} = -H\frac{g}{\rho_0}\frac{\partial \rho_x}{\partial x}, \qquad (2)$$

where H is the mean water depth, g is the force of gravity (9.8 m s^{-2}), ρ_0 is the mean density of the water, $\partial \rho_x$ is the horizontal difference in vertically averaged density, and ∂x is the distance along the estuary. Because of the relatively shallow depth of estuarine systems, pressure has a negligible effect on density. Students can then calculate the density of the water by measuring only the temperature and salinity. Instead of using the complex equation of state, students use a linear approximation that utilizes the thermohaline coefficients of expansion and contraction and ignores the effect of pressure. Densities can then be calculated using the equation

$$\rho = 1{,}000 - 0.15 * (T - 10) + 0.78 * (S - 35), \qquad (3)$$

where ρ is the density in kg m^{-3}, T is temperature in degrees centigrade, and S is salinity, and −0.15 and 0.78 are the thermohaline coefficients of expansion and contraction around 10°C and salinity of 35, respectively.

Barotropic Pressure Gradient Force

A slope in the sea surface creates barotropic pressure gradients. In estuaries, the slope is usually dominated by the differences in water height between the estuary and the open ocean caused by tides, but also includes a slope associated with the freshwater flow out of the estuary. The water is forced from higher pressure under the top of the slope to lower pressure regions where the water elevation is lower. The magnitude of this barotropic pressure gradient is the same at all depths in the water column (Figure 1d) and can be described as:

$$\textit{Force due to barotropic pressure gradient} = -g\frac{\partial \eta}{\partial x}, \qquad (4)$$

where $\partial\eta$ is the difference in height of the water column along the length, ∂x, of the estuary being measured. Surface slopes are particularly difficult to measure because of the very slight changes in elevation with distance and difficulties in establishing an equal geopotential reference level. Instead, we assume that the Coriolis effect is negligible in a small estuary and estimate the force due to surface slope using the force balance:

Total Acceleration = Surface Slope force + Density Gradient force + Friction force.

After calculating acceleration (described below), the density gradient force, and the friction force, the barotropic force can be calculated by subtraction, and the difference in water elevation along the measured transect can also be calculated.

Total Acceleration

An estimate of total acceleration is made by comparing the velocity measured at the beginning of each field trip with the last velocity measurement of that trip at a stationary site. The acceleration is the difference between the two velocities divided by the time interval between the measurements.

ACTIVITY

This activity allows students to measure and compare the relative size of estuarine forces described above through gathering the appropriate data in the field. Like a game of tug-of-war, in which the opposing forces may be strong but the net movement of the knot in the middle may be small, subtidal currents may also be small. The measurement of the density differences along the estuary and the resulting baroclinic force provides evidence for this force, which is not easily observed by our senses. Students may be surprised at the small change in water elevation that can cause substantial tidal currents.

A secondary aspect of this activity is the experience and learning acquired through coordinating and organizing results in a team-based approach. Students find that a relatively simple field experiment requires much effort to coordinate data, provide quality checks, and check units, among other activities, with their team. This is the reality of much of scientific research, but students get little taste of it in traditional lecture-based science classes.

Materials

- Small power boat such as skiff with depth meter and GPS
- Hand-held CTD (we use YSI Pro Plus) along with a weight to help the instrument sink to the bottom, if it is not provided
- Current meter (we use OTT MF Pro), or grapefruit drifters and stopwatch
- Spreadsheet software (MS Excel, or similar)
- High-frequency depth profiling CTD (we use a SBE 19plus; optional)
- Handheld anemometer (we use a Kestrel 1000; optional)
- Lead line or depth sounder if not available on boat

Setup

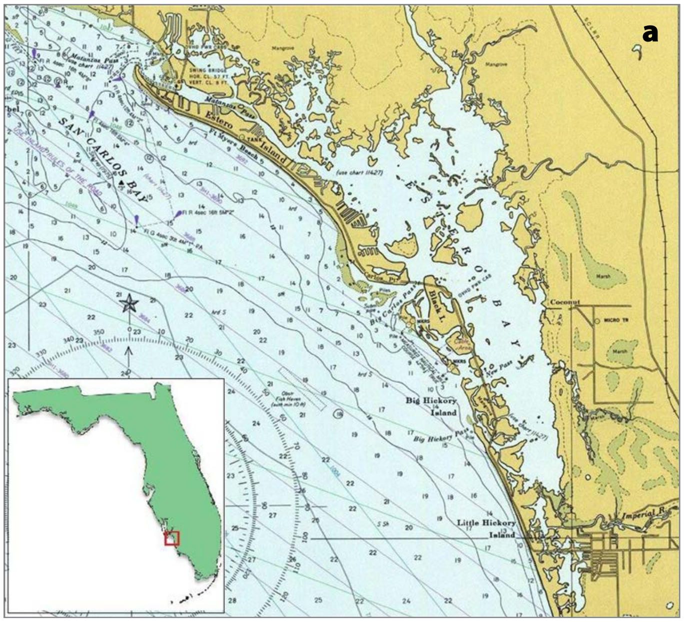
Instructors should first use the classroom to teach the concept of pressure and the relevant forces in an estuary from a qualitative and intuitive perspective. For example, most students have been in a swimming pool where, when diving to the bottom, their ears popped from the increased pressure due to the weight of the water above them. Barotropic pressure gradients are easily observed in a river moving down a mountain slope. Baroclinic pressure gradients can be observed in a tank that is separated into two sections, with freshwater and saltwater sides each dyed a different color. When the barrier is removed, the saltwater will be seen to move toward and under the freshwater region.

At the end of the topic lecture, students are introduced to the relevant terms of the momentum equations, which are shown to only be "shorthand" notation for what they have already learned qualitatively. In addition to expressing the relationships precisely, the terms allow us to quantify the pressure and forces (per unit mass). Students are given a few practice calculations and questions from some realistic examples, for example, contrasting the barotropic pressure gradient in an oceanic gyre with that from a tidal height gradient along an estuary.

Students are divided into four groups for their work both in the field and during the analysis and report writing. Our classes typically have about 36 students, so four groups provide enough students to accomplish the primary tasks should a few not be able to make the field trip. Each group attends only one of four field excursions (completed in two different days about a week apart) that are planned to provide for sampling during flood and ebb of both a neap and a spring tidal cycle. This sampling schedule then requires that the instructor be present for two days, and that each student attends only one two- to three-hour field trip. Students have pre-prepared log sheets that they bring with them. For more advanced classes, the students may be given the preparation of log sheets ahead of time as an exercise.

Fieldwork

In the field, we establish one or two subgroups to be responsible for collecting current data (usually two students in a canoe for each subgroup), depending upon the number of students available, at one or two stationary sites. The sites are best positioned along relatively straight lengths of the estuary. The rest of the students perform a longitudinal transect with the skiff. At the stationary sites, the students measure the current velocity at regular intervals; about every 15 minutes usually works well. If a flow meter is available, they measure a vertical profile of velocity at near bottom (about 0.2 m above bottom), mid-level, and surface (about 0.2 m below surface) depths. This profile is taken in the center channel and in the shoal areas on both sides of the channel. If only a drifter (usually a grapefruit) is



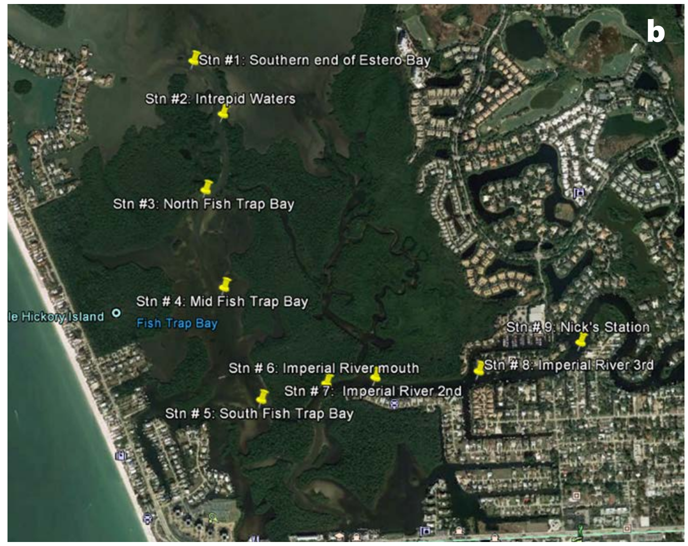


FIGURE 2. Site maps. (a) Location of Estero Bay (adapted from Florida Center for Instructional Technology), and (b) student example showing their sampling stations.

available, they measure surface currents using a stopwatch and GPS. The students usually measure out and mark a known distance and then time how long it takes the drifter to transit. The times and distances are adjusted for the relative speed of the current to get an accurate estimate of the velocity and to obtain multiple measurements over about one and a half hours for a semidiurnal tide.

The rest of the students on the motorized skiff measure temperature and salinity at the surface and near bottom at five to nine evenly spaced stations along the transect. The upstream location of the first transect station is where the water is nearly fresh. The downstream location is determined by the closest logistically available site near the ocean. Our downstream transects are located at the end of Fishtrap Bay, which opens into the southern portion of Estero Bay, Florida, about 3–4 km from the upstream transect (Figure 2). During the dry season, salinity reaches farther up the estuary and requires more stations than during the wet season. At each station, the students record latitude and longitude, depth, surface and bottom temperature, and salinity (Figure 3). The students log the data onto their prepared data sheets.

FIGURE 3. Students near the bow are measuring temperature and salinity with a YSI Pro Plus hand-held CTD. Near the stern, students are measuring the current speed with an OTT MF Pro. A student in the middle is measuring wind speed with a Kestrel 1000. The other students are logging data from the instruments, or GPS coordinates and depth measurements from the boat console. *Photo credit: FGCU photographer James Greco*

Analysis and Report

Each of the four groups writes a collaborative report that includes the measurements and analyses of the data that they collected. The analysis and plot generation are usually done with Microsoft Excel software, although we allow them to use whatever software they prefer. The students are also provided with the results from the other groups so that they can make comparisons over tidal phases. Within the groups, students choose roles for themselves according to the instructions:

"Each student will take on one or more of the following roles: raw data preparation, data analysis and interpretation, background information writer, liaison to collaborate with other groups and to coordinate efforts within their own group, first draft writers (more than one), proofers and editors (more than one), and figure editors (legends, captions). Remember, ultimately you will be working together. If you are finished with one of your tasks, or waiting, volunteer to help with something else. At the end of the project, you will fill out peer assessment forms."

Learning to work together is an important aspect of this activity, and a skill that students will need if they pursue careers in science. The peer assessment helps provide incentive for the members to participate and allows the instructor some flexibility in assessment should one of the members prove to be especially weak or strong in their participation. The peer assessments are ratings from 5 (superior) to 1 (weak) on each of the following attributes:

- Participated in group discussions
- Helped keep the group on task
- Contributed useful ideas
- Amount of work done
- Quality of completed work

Basic Report Instructions and Overreaching Questions

Your written field report should include:

1. Short background of estuarine circulation and a description of the study site
2. Site map with transect location indicated
3. Materials and methods section
4. Results section which should include:
   - Plots of along-transect salinity, temperature, and density for your transect; for each parameter, there should be two lines on the graph, one showing surface values and the other showing bottom values
   - Time series plots of current speeds, both surface and bottom, from the stationary site
   - Any other relevant results or observations that were made
   - The calculations of the acceleration; the baroclinic, barotropic, and friction forces; and differences in water elevation along the transect.
   - The values for the above forces calculated by the other groups (but it is not necessary to show all the calculations from the other groups)
   - Your data in a table form in an appendix.
5. Discussion and conclusions
   - Your report should be written in a cohesive manner and should at a minimum address the following questions:
   - Which force(s) were the most important to determining the current in the estuary? Typically, we are comparing the order of magnitude of the forces in question, so small errors in measurement should not make much difference to your conclusions.
   - Do you see changes in stratification (the difference between surface and bottom density) between ebb and flood phases?
   - Is density variability caused mostly by salinity or temperature? How do you know?
   - Describe any spring neap variations in any of the above processes that you observed.

EXAMPLE RESULTS

Students calculate the distance between stations using the GPS coordinates that they recorded and the Ruler tool in Google Earth. In the baroclinic pressure gradient calculation, *H* is the mean depth of the first and last stations. For friction calculations, the mean of the surface and bottom currents from all the stations is used. Some example results from a recent class and their captions are shown in Figure 4 and in Table 1. During this transect, the water was well mixed and the students unnecessarily went well past the extent of the salinity intrusion. For this reason, their calculations of the forces (Table 1) are based upon the first five stations. Though the Imperial River is relatively shallow,

LONGITUDINAL PLOTS OF SALINITY, TEMPERATURE, AND DENSITY

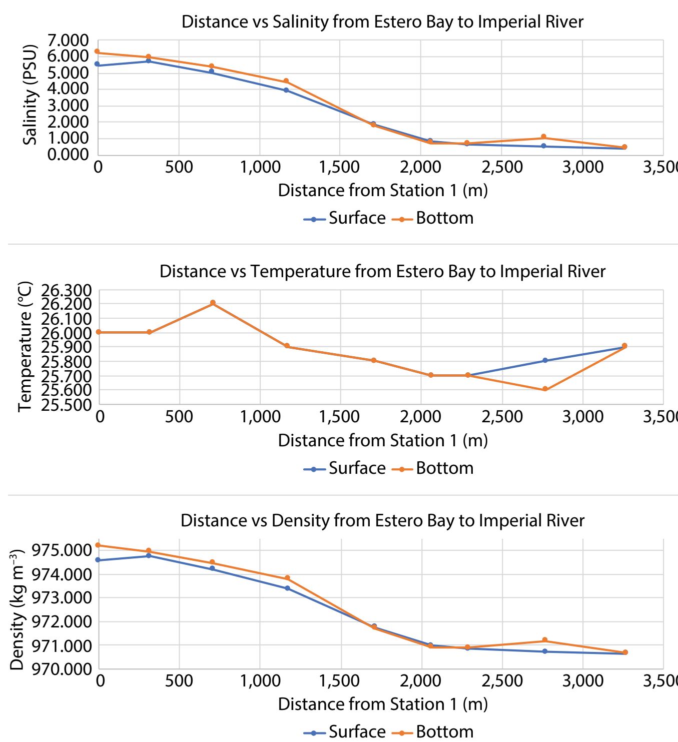


FIGURE 4. Example results and captions from student report. (a) Salinity decreases from Estero Bay into the Imperial River. Bottom water is slightly saltier than surface water. (b) Temperature remained the same for top and bottom water at each location for sites 1–7 as well as site 9. Site 8 has a slight variation in temperature as the surface water is slightly higher in temperature. (c) The density decreases gradually from Estero Bay into the Imperial River. Surface water (blue curve) is slightly lighter than the bottom water.

TABLE 1. Example of student estimates of the hydrodynamic forces in the Imperial River, Florida.

TERM	VALUE
Friction	2.06×10^{-4} N kg^{-1}
Baroclinic Pressure Gradient	-6.89×10^{-6} N kg^{-1}
Barotropic Pressure Gradient	-2.1×10^{-4} N kg^{-1}
Change in Elevation along Estuary	0.036 m

with depths usually 2 m or less, the water column often becomes much more stratified. Despite the many assumptions and simplifications of this approach, their estimates of the forces and the elevation of the water column are realistic. Future implementations of this activity will include a discussion of the assumptions and simplifications, such as the assumptions of relatively similar width and depth of the channel, and the effects of nonsimultaneous measurements.

ALTERNATE APPROACHES AND EXTENSIONS

- Use grapefruit drifters if flow meters are not available.
- Use a nautical map and choose sites at channel markers if depth meter and/or GPS are not available.
- If no powerboat is available for transects, the force measurements can be made from canoes positioned at each end of the estuary. Before deployment, each canoe group can establish a sampling routine, then take measurements at the same time at each site, for example, every half hour.
- Deployment of a fixed current meter, or current data from the one or two stationary sites, allows discussion of flood and ebb asymmetry and likely directions of net sediment transport.
- If a turbidity meter is available, students can also examine variations in turbidity and whether there is a classical ETM. If a classical ETM is not observed, what other processes can create turbidity maxima?
- How sensitive are the force calculations to the estimate used for the drag coefficient?
- A further preparation exercise is to have each group prepare their own log sheets ahead of time. This activity helps them focus on exactly what information they need to complete the analysis and how to organize it.
- Further analysis for more advanced students can include log layer estimations of friction from higher spatial resolution profiles of currents at the stationary sites. Cross-sectional variations can also be examined, and the effect of friction along the sides of the estuary can be discussed.
- Further discussion for more advanced students could include the effects of asymmetries in mixing and how they can also drive subtidal currents (e.g., see Geyer et al. 2000).
- Depending upon availability, we also take vertical profiles of temperature, salinity, and turbidity with an SBE 19plus CTD. Data from this instrument are processed by the instructor and provided to the undergraduates to compare their results with the higher vertical resolution obtained from the instrument. Graduate students may be assigned the task of processing the Sea-Bird CTD data as well.
- A quantitative approach to evaluating the stratification can easily be accomplished with this data by researching and calculating the Brunt–Väisälä frequency at one or more sites and times.

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Dr. No (or Yes?)

By Simon Boxall

It is that time of year when final year students are coming to see me to discuss what should be the next step in their oceanographic careers. Some have plans for, and even jobs lined up in, the marine industry. Some always wanted to become accountants—they will be back in a couple of years, once boredom sets in. Many will be asking, "Should I do a PhD?" Of my five MOcean[1] tutees, four are planning this as their next stage. One could argue that if they have to ask the question, then it is probably not the best pathway for them—but it is actually a very valid query. When I started year one in my bachelor's at university, I genuinely had no idea that postgraduate degrees were a natural progression—I naively assumed that my degree was the pinnacle of the education system. I quickly learned otherwise and had always wanted to do oceanographic research (blame Cousteau), so I went on to earn a PhD.

We tend to subconsciously stream our students and could be accused of focusing on the research potential of our charges rather than what might best suit them. It has certainly been the case for a number of years now that if you want to progress in research or in the academic environment, then a PhD is the baseline to start from—it shows an ability to develop independent learning and ideas. This has not always been the case. Professor Henry Charnock, FRS, CBE, was head of my department at Southampton when I joined. In his lifetime, he had been Deputy Vice-Chancellor of the university, President of the Royal Meteorological Society, and Director of the UK's National Institute of Oceanography; he had published over 70 papers; and he was arguably among the best-known oceanographers worldwide. In Henry's day, very few people did doctorate degrees. Today—the lack of a doctorate could set a relatively low ceiling for a young scientist wanting to progress at a university or a government research lab in most parts of the world. Indeed, many of my international PhD students have been mature students who studied with me in order to progress back in their own countries.

So—is the answer to that question that my students are asking, "only if you want to go into research?" No, not at all. Many of the big science consultancies around the world like some of their senior partners to have PhDs. I picked this up from working with them on many projects over the years. The prescript "Dr." scattered sparingly among the author list can give reports a perceived gravitas. There is, rightly or wrongly, a notion that if someone has achieved doctoral status, they must know something about the subject. The fact that their thesis was on the fine-scale deep ocean mixing in the Tyrrhenian Sea has absolutely nothing to do with, let us say, the efficacies of a new tidal barrier in the Hudson. It is not seen as an issue. While it is no substitute for experience, obtaining a PhD is an experience in its own right. It requires dedication to the task at hand, substantial amounts of work, sometimes in difficult circumstances, and an ability to undertake independent and novel assessment of a particular problem. In the field of oceanography, it usually requires an ability to work constructively as part of a team—particularly when field studies are involved. Unlike the life of a postgraduate student a few decades ago, there are regular interim reports, presentations, and panel meetings, all of which are critical to the student's progression. With ever decreasing funding, PhD candidates needs to budget their research and determine the best ways of getting their findings into both the scientific and the wider public domain. An increasing number of PhD posts in the UK are in partnership with industry, and so have a direct commercial application or relevance as well as the experience of working directly in industry. The notion that PhDs have their heads in the clouds is very far from the truth, and the average modern-day postgraduate is very workplace ready.

Of the many doctoral oceanographers we produce each year from my own faculty, more go into government departments and commerce than into the university system. This is not actually that new. Of the three PhD oceanographers in my year (small numbers in those days), I was the only one who opted for

[1] At the University of Southampton, we run a standard three-year bachelor of science (BSc) degree or a four-year MOcean, which is effectively a bundled BSc and master's. As with many universities around the globe, we would normally expect a PhD candidate to have the equivalent of a master's level qualification.

the academic route. One of my contemporaries went onto a government track after a brief postdoctoral position and reached the top of his field, while the other went into industry and similarly went to the top.

One concern of students thinking about studying for a PhD is the fear of three or four more years of paying student fees and having to find their own living costs. Many do not realize that, unlike a master's course, a PhD is relatively well funded in most countries. In the UK, the Natural Environment Council funds a significant number of PhD studentships for UK citizens, and these cover fees as well as a living stipend. While the grant is not as high as someone might earn going straight to a first full job, it is tax-free and carries various benefits, which means that the real gap between starting work as a new graduate or continuing onto a PhD is not that big.

> "...if you want to progress in research or in the academic environment, then a PhD is the baseline to start from."

What are the motivations that the student should think about before starting a doctoral pathway? Never choose it to put off deciding what you want to do when you graduate! Life as a postgrad is different from life as an undergraduate. The prospective student needs to appreciate that a PhD is the same as a full-time job—there are no long vacations and a supervisor will be leaning on them to ensure they deliver high-quality work and on time. The days of the seven-year PhD are faint memories. I have seen a number of students do this, and they have often ended up hating their subjects. The sensible ones admit it was a bad choice, based on indecision, discuss the issues with their supervisor or another academic, and either change topic or stop. The more a disenchanted postgraduate tries to push forward, the worse it gets—an unloved PhD topic has a very high viscosity coefficient.

The topic must excite you—you are going to be working on it in fine detail longer than any other piece of work previously or in the future. You don't have to be aiming for an academic career; you can do it to satisfy your scientific curiosity—indulgence of this type has the advantage that it is non-fattening. I know of a PhD student in my own family who started off with a dream of an academic career but had a change of mind and went into industry, and another who was intending a commercial postdoctoral career at the outset but got drawn into university research and teaching.

There is also a third candidature for PhD positions—scientists coming to the end of their full-time working lives who want to do the one thing they never got around to doing—a doctorate. Before you write in saying that is not fair—that surely they are taking away opportunities from young budding scientists—be assured that most of these are self-funding. I have supervised a few mature students in this situation, two of whom were very much at the tops of their careers, but like Henry Charnock, they had not really had the chance to study for a PhD. One of them already had a portfolio of over 40 first-authored papers, and as a university our biggest problem was finding an external examiner qualified enough to examine the thesis. My father is another case in point. As a medical laboratory pathologist, he had taken a direct route and at the outset of his career, no one in his field studied for a first degree in the subject, let alone a postgraduate degree. Toward the end of his career, he was responsible for routine work for a university hospital, a number of research projects, and about 30 staff—all of whom had degrees, including half with PhDs. I remember when he sat the family down (by this stage, both my brother and I had completed our doctoral theses) to announce he was going to start a part-time PhD. Four years later, the Drs. Boxall went out on a celebration dinner after his graduation and his final retirement. He didn't need it to advance his career—he needed it for his own satisfaction and to show to himself that he could.

We need well-trained and motivated scientists working in all aspects of our subject, from blue skies research to contemporary and applied issues. Today, a PhD is an important qualification for progression in the modern university and government laboratory environment, and is not by any means out of place in the commercial world. But never start one as a stop-gap, and choose the subject and supervisor with care—both will influence how successful and enjoyable the experience will be. It is not the panacea for a successful science career, and many do very well both in terms of job satisfaction and even higher salaries without one.

Finally, to the title of this column. Of course, we also need PhDs to create a requisite number of evil scientists. Would Dr. No (James Bond), Dr. Frankenstein (Mary Shelley), and Dr. Evil (Austin Powers) have the same impact as Mr. No, Mr. Frankenstein, and Mr. Evil? I suspect not.

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CAREER PROFILES Options and Insights

COURTNEY SCHMIDT | Staff Scientist, Narragansett Bay Estuary Program (courtney.schmidt@nbep.org)

Degree: When, where, what, and what in?

After receiving a Bachelor of Science in Marine Science and Biology from the University of Tampa and working for a few years, I returned to graduate school. I earned both a Master of Science and a PhD at the University of Rhode Island (URI) Graduate School of Oceanography (GSO). I studied biogeochemical cycling of nutrients for both degrees—carbon during the master's study and nitrogen during the PhD study. My PhD research developed from the need to understand how reductions in nitrogen loading from wastewater treatment facilities would impact the food webs of Narragansett Bay. Both degrees enabled me to understand the complexities of nutrient cycling, and with the PhD, how altering sources can have dramatic impacts. I received my PhD in 2014, and am still working with colleagues (both researchers and environmental managers) to understand the ecosystem impacts of the nitrogen load reductions.

Did you stay in academia at all, and if so, for how long?

When it was time for my job search, I was geographically limited. Therefore, I had to be open to all opportunities that came my way. I applied for my current position as I was finishing up my PhD. I interviewed for the position shortly before I officially graduated, and started working for the Narragansett Bay Estuary Program shortly thereafter.

How did you go about searching for a job outside of the university setting?

I tapped into the university's career office to help me tailor my CV to a resume for non-academic positions. I used their expertise to translate my lab and field experience into skills that are easily recognized by multiple industries. I applied for jobs that interested me and seemed to present a challenge, and where I felt my expertise could be of use. I also relied on my professional network for tips on job hunts, interviews, and negotiation.

Is this the only job (post-academia) that you've had? If not, what else did you do?

This is the first job I've had since earning my PhD. I am a mother to two young boys and balance two other activities, as well. In 2014, I was elected treasurer of the New England Estuarine Research Society (NEERS). I manage the finances for this small professional society, which is a 501(c)(3). I work with the executive board to plan regional meetings (twice per year), and network with estuarine research professionals from Maine to New York. I will join the Omicron II class of Leadership Rhode Island in 2019. This group is dedicated to connecting and encouraging a diverse leadership for the state of Rhode Island in all aspects of Rhode Island life through professional development and personal growth.

What is your current job? What path did you take to get there?

I am the staff scientist of the Narragansett Bay Estuary Program, one of the 28 designated National Estuary Programs supported by the US Environmental Protection Agency's Clean Water Act. I manage the scientific projects and programs of the Estuary Program, coordinating with partners to expand research ideas and strategically use limited research funds. I routinely synthesize data for the Narragansett Bay watershed, and work with partners to disseminate our findings. My graduate career provided an easy transition to this position, where I tap into my professional network daily and use what I learned in graduate school to protect, preserve, and restore Narragansett Bay and its watershed.

What did your oceanographic education (or academic career) give you that is useful in your current job?

I find that my coursework at GSO was invaluable. These courses challenged me to see the larger picture and to understand the many links between humans and their environment. Both my dissertation and master's thesis work introduced me to a large network of researchers, citizens, and future partners around the bay and watershed who are passionate about the region. These are the people I rely on today to help me do my job. I took opportunities to present my work at local, regional, and national conferences, and to learn science communication methods to bridge gaps and learn from others. I took on two very different projects during my graduate career. Going through the scientific process, making mistakes, and learning from them gave me the confidence to tackle the challenges I encounter in this job.

Working with various graduate student associations at URI has probably given me some of the most valuable skills to tackle my job. Through those organizations, I learned how to gain consensus with diverse groups, look for common interests, and identify the most important concerns. These skills allow me to work with diverse partners and pursue a common agenda to protect and restore the water quality and habitats throughout the watershed.

Is there any course or other training you would like to have had as part of your graduate education to meet the demands of the job market?

When I started graduate school, I wanted to take as many different types of classes as I could. I found that I couldn't fit everything in and I wish I had further training in Geographic Information Systems (GIS), computer coding languages (R, Python, or MATLAB), and science communication. In my current position, I complete professional development training classes in computer coding and science communication. These skills help me analyze/understand data and disseminate information to our partners and the public. GIS is very demanding, and I collaborate with specialists in that field (including two staffers at NBEP) to maximize my organization's abilities to disseminate results and generate research. Grant writing is very important, and while graduate students often do get that experience, formal classes or workshops would have been useful. Finally, negotiation is a topic that does not get much attention in graduate school. Negotiating is an important process during job interviews, and being comfortable doing that takes time and training.

Is the job satisfying? What aspects of the job do you like best/least?

Yes, my job is satisfying because it can be very challenging. I am no longer a classic field or lab researcher (and I do miss that at times), but rather someone who spends her time communicating with partners, synthesizing data, and disseminating those results. I meet with people from both Massachusetts and Rhode Island regularly to identify ways to partner and write proposals. Until recently, my main objective has been to establish and synthesize data for 24 environmental indicators. Now, my position has shifted focus to link those indicators together to better understand our watershed and how those data and conclusions advance science and policy. The main challenge of this job is telling the "watershed's" story. It is very easy to tell the story of where data were collected, but it is sometimes difficult to find the same or complementary data in another location. What we observe at Site A does not necessarily apply to Site B. How, then, do we tell a complete story? At the same time, our watershed spans two states—Massachusetts and Rhode Island—that have very different wants/needs and data collection/interpretation capacities. The NBEP staff spend a significant portion of our time with partners overcoming these challenges. We recently published *State of Narragansett Bay and Its Watershed*, which focuses on the watershed's story, and places many environmental indicators in context with location, climate change, and history. Overcoming these challenges is very satisfying.

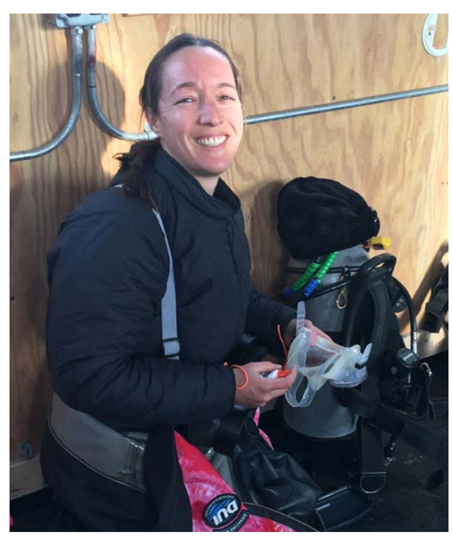
Do you have any recommendations for new grads looking for jobs?

Job hunting is an exhausting experience. Be open and honest with yourself and your network. Opportunities are found in the oddest of places, and many times through word-of-mouth. Use all resources you can to tailor your CV/resume and letters to the job application. Don't get discouraged if you don't get interviews right away—something will click eventually.

LISA MUNGER | Independent Contractor and Research Affiliate/Lecturer at University of Oregon (lmunger4@uoregon.edu)

Degree: When, where, what, and what in?

I completed a PhD in oceanography at the Scripps Institution of Oceanography (SIO) in 2007. My dissertation was on passive acoustic monitoring of endangered North Pacific right whales (*Eubalaena japonica*) in the Bering Sea. I analyzed several years of acoustic data from seafloor-moored recorders to characterize the whales' seasonal occurrence and daily calling behavior. I also spent many months at sea on research vessels in Alaskan waters to conduct cetacean surveys, collect real-time acoustic data, and assist in deploying and recovering moorings, and I traveled to several remote native Alaskan villages to spend time in their communities and schools. Prior to my graduate studies, I completed a BA in ecology and evolutionary biology in 1999 at the University of Colorado, Boulder.



Did you stay in academia at all, and if so, for how long?

Yes, for a little over four years. I continued as a postdoctoral scholar at SIO for a couple years in my graduate advisor's lab, then moved to Hawaii for another two-year postdoctoral appointment, which was a joint position with the University of Hawaii and NOAA Pacific Islands Fisheries Science Center (PIFSC) in the Coral Reef Ecosystem Program.

How did you go about searching for a job outside of the university setting?

My postdoc in Hawaii allowed me to bridge the marine research communities at University of Hawaii and NOAA, and the connections I made led to some opportunities to remain there and continue working in my field. I worked for one year as a contractor within the Cetacean Research Program at NOAA PIFSC, and then as a senior researcher for several years for Oceanwide Science Institute (OSI), a nonprofit that focuses on marine bioacoustics research and outreach. In each case, I was more or less tapped for the position by the respective program leaders, who are friends and colleagues from grad school or a work situation. It was a combination of whom I knew and being in the right place at the right time with the right skills.

Is this the only job (post-academia) that you've had? If not, what else did you do?

In addition to working for NOAA and OSI, I also began teaching an undergraduate course at the University of Hawaii in 2012. I have taught this course nearly every year since then.

What is your current job? What path did you take to get there?

I'd say I'm now the oceanographic equivalent of a freelancer in the "gig economy." I keep a foot in the door of academia by teaching undergraduate courses at the University of Hawaii and the University of Oregon; these are part-time, temporary lecturer positions for which I am rehired each year. I recently returned from a three-month deployment as a research technician and scientific diver at McMurdo Station, Antarctica—another opportunity that arose sort of organically by getting to know researchers at the University of Oregon and discovering that my skills and training were a good (and timely) match for a project need. I held the title of Science Director for Oceanwide Science Institute for a year but am now transitioning to more of an independent contractor role, where I continue to pitch in on projects for OSI as needed, and I'm beginning to offer my services in acoustic data analysis and reporting more widely.

What did your oceanographic education (or academic career) give you that is useful in your current job?

The ability to evaluate information and synthesize ideas from multiple sources and perspectives, whether reading scientific papers, browsing websites, or attending a meeting. Experience working in a wide variety of settings, often with limited resources, and often in tight quarters with the same people for extended periods—requiring lots of flexibility, creativity, and diplomacy to make things work. Being meticulous in all things—setting up equipment, troubleshooting, taking notes, organizing and backing up data, budgeting my time. Perhaps most importantly, a network of friends and colleagues that continues to grow. These people are so important for so many reasons—not just for finding jobs and opportunities, but also friendship, geeking out together, and providing support and encouragement!

Is there any course or other training you would have liked to have as part of your graduate education to meet the demands of the job market?

- Computer programming
- Electrical and/or mechanical engineering
- Business—management, communications
- Geographic Information Systems

Is the job satisfying? What aspects of the job do you like best/least?

I have always had many interests throughout my life and no single overriding passion, so on the one hand it is very satisfying to work on a variety of projects, either in parallel or by switching it up every few months. And I do find teaching to be immensely rewarding, and a challenge that I enjoy. The aspect of the job(s) I enjoy least is the "feast or famine" of working from one project to the next and not being assured of a steady income or benefits.

Do you have any recommendations for new grads looking for jobs?

As others have said, build up skills in a variety of disciplines. In my opinion, quantitative and engineering skills seem to be especially beneficial—there will always be a demand for tech-savvy folks who are good at making and troubleshooting things. Also, keep trying! It's tough out there, and most of your applications will be ignored or rejected. Stay positive, keep an open mind, and talk to everyone, whether they are in your field or not—you never know where a conversation might lead.

INTERNATIONAL OCEAN DISCOVERY PROGRAM
Member Offices

Program Member Offices (PMOs) manage and fund the participation of researchers working in a member country or consortium in International Ocean Discovery Program (IODP) activities. PMOs nominate scientists for IODP expeditions and to serve on IODP boards and panels. They are generally responsible for broadening national interest and participation in IODP research opportunities within their countries.

Note: An individual scientist's PMO is determined by the location of his or her employer or primary academic affiliation, not by citizenship or adjunct status.

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1 Physical Properties Specialist Nana Kamiya (Nihon University, now at Kyoto University), IODP Expedition 370, Temperature Limit of the Deep Biosphere off Muroto. *Photo credit: Yusuke Kubo, JAMSTEC/CDEX EPM*

2 Logging and Physical Properties specialist Elizabeth Griffith (University of Texas at Arlington, USA) collects discrete samples from the working halves of each core for moisture and density analysis, IODP Expedition 355, Arabian Sea Monsoon. *Photo credit: William Crawford, IODP JRSO*

3 Paleontologist Oliver Friedrich (Institute of Geosciences, University of Frankfurt, Germany) cleaning a sieve in the paleontology prep lab, IODP Expedition 342, Newfoundland Sediment Drifts. *Photo credit: John Beck, IODP/TAMU*

4 Outi Hyttinen (Geological Survey of Finland) describes cores during the IODP Expedition 347, Baltic Sea Paleoenvironment, onshore science party at the IODP Bremen Core Repository. *Photo credit: A. Gerdes, ECORD-IODP*

5 Petrophysics/Downhole Measurements Specialist Srisharan Shreedharan (Pennsylvania State University, USA) takes a penetrometer measurement, IODP Expedition 375, Hikurangi Subduction Margin. *Photo credit: Tim Fulton, IODP JRSO*

6 Sedimentologist Francesca Meneghini (Università degli Studi di Pisa, Italy) and Structural Geologist Ake Fagereng (Cardiff University, UK) at the core description table, IODP Expedition 375, Hikurangi Subduction Margin. *Photo credit: Patrick Fulton & IODP*

7 Sedimentologist Shunli Li (China University of Geosciences, Beijing) examines a core during the IODP Expedition 381, Corinth Active Rift Development, onshore science party at the IODP Bremen Core Repository. *Photo credit: V. Diekamp, ECORD/IODP*

8 Sedimentologist Karen Strehlow (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) makes core description notes, IODP Expedition 376, Brothers Arc Flux. *Photo credit: William Crawford, IODP JRSO*

9 Paleontologist Thiago Pereira dos Santos (Universidade Federal Fluminense, Brazil) works at the sample table, IODP Expedition 361, South African Climates. *Photo credit: Tim Fulton, IODP JRSO*

10 Physical Properties Specialist/Petrophysics Iona McIntosh (JAMSTEC, Japan), IODP Expedition 376, Brothers Arc Flux. *Photo credit: Kannikha Kolandaivelu & IODP*

11 Inorganic Geochemist Kelly Gibson (University of South Carolina, USA) works with a whole round core section in the chemistry lab, IODP Expedition 363, Western Pacific Warm Pool. *Photo credit: William Crawford, IODP JRSO*

12 Structural Geologist Oliver Pluemper (Utrecht University, Netherlands) at the core description table, IODP Expedition 360, SW Indian Ridge Lower Crust and Moho. *Photo credit: William Crawford, IODP JRSO*

13 Sedimentologist Hannah Rabinowitz (Lamont-Doherty Earth Observatory, Columbia University, USA) at the sampling table, IODP Expedition 375, Hikurangi Subduction Margin. *Photo credit: Tim Fulton, IODP JRSO*

14 Sedimentologist Satoshi Tonai (Kochi University, Japan) watching a CT-scan image, IODP Expedition 370, Temperature Limit of the Deep Biosphere off Muroto. *Photo credit: Yusuke Kubo, JAMSTEC/CDEX EPM*

15 Organic Geochemist Lauren O'Connor (Oxford University, UK) prepares a fresh sample to be tested in the chemistry laboratory, IODP Expedition 369, Australia Cretaceous Climate and Tectonics. *Photo credit: William Crawford, IODP JRSO*

16 Calcareous Nannofossil Paleontologist Claire Routledge (Florida State University, USA) prepares a microscope slide from the latest core, IODP Expedition 355, Arabian Sea Monsoon. *Photo credit: William Crawford, IODP JRSO*

17 Inorganic Geochemist Mark Kendrick (The Australian National University, Australia) examines a thin section under the microscope, IODP Expedition 360, SW Indian Ridge Lower Crust and Moho. *Photo credit: Alejandra Martinez & IODP*

18 Petrophysicist Mai-Linh Doan (University Grenoble Alpes, France) takes physical properties measurements on a core during the IODP Expedition 381, Corinth Active Rift Development, onshore science party at the IODP Bremen Core Repository. *Photo credit: V. Diekamp, ECORD/IODP*

19 Sedimentologist Junichiro Kuroda (University of Tokyo, Japan) investigates a thin section using a petrographic microscope, IODP Expedition 369, Australia Cretaceious Climate and Tectonics. *Photo credit: William Crawford, IODP JRSO*

20 Paleontologist Xuan Ding (China University of Geosciences) splits samples for foraminifer counts, IODP Expedition 353, Indian Monsoon Rainfall. *Photo credit: William Crawford, IODP JRSO*

21 Sedimentologist Gerald Auer (University of Graz, Austria) preparing to take a smear slide sample from the working half of a core section, IODP Expedition 356, Indonesian Throughflow. *Photo credit: William Crawford, IODP JRSO*

22 Core Description Scientist Jianghong Deng (University of Science and Technology of China) and organic geochemist Olivier Sissmann (IFP Energies Nouvelles, France) sample a core, IODP Expedition 366, Mariana Convergent Margin. *Photo credit: Tim Fulton, IODP JRSO*

23 Inorganic Geochemist Hideko Takayanagi (Tōhoku University, Japan) performing an ammonium analysis in the chemistry laboratory, IODP Expedition 356, Indonesian Throughflow. *Photo credit: William Crawford, IODP JRSO*

24 Sedimentologist Kaoru Kubota (University of Tokyo, Japan) works with a core in the Core Lab, IODP Expedition 361, South African Climates. *Photo credit: Tim Fulton, IODP JRSO*

25 Sedimentologist Joyeeta Bhattacharya (Rice University, USA) at the core description table, IODP Expedition 371, Tasman Frontier Subduction and Climate. *Photo credit: Michelle Drake & IODP*

26 Inorganic Geochemist John Kirkpatrick (University of Rhode Island, USA) prepares a dilution for pore water sample analysis, IODP Expedition 353, Indian Monsoon Rainfall. *Photo credit: William Crawford, IODP JRSO*

27 Physical Properties Specialist Nambiyathodi Lathika (National Centre for Antarctic and Ocean Research, India) samples the working half core, IODP Expedition 361, South African Climates. *Photo credit: Tim Fulton, IODP JRSO*

28 Core Description Scientist Baptiste Debret (University of Cambridge, UK) works at the Section Half Image Logger, IODP Expedition 366, Mariana Convergent Margin. *Photo credit: Katsuyoshi Michibayashi & IODP*

29 Microbiologist Tatsuhiko Hoshino is scraping contaminated core surface under the anaerobic condition, IODP Expedition 337, Deep Coalbed Biosphere off Shimokita. *Photo credit: Fumio Inagaki, JAMSTEC*

30 Organic Geochemist Hannah Liddy (University of Southern California, USA) injects a headspace gas sample into a gas chromatograph to measure the amount of methane in the core, IODP Expedition 355, Arabian Sea Monsoon. *Photo credit: William Crawford, IODP JRSO*

31 Sedimentologist Romain Hemelsdaël (University of Montpellier, France) describes the archive half of the core during the IODP Expedition 381, Corinth Active Rift Development, onshore science party at the IODP Bremen Core Repository. *Photo credit: V. Diekamp, ECORD/IODP*

32 Igneous Petrologist Natsue Abe (JAMSTEC, Japan) works at the microscope, IODP Expedition 345, Hess Deep. *Photo credit: William Crawford, IODP JRSO*

33 Physical Properties Specialist Rajeev Saraswat (National Institute of Oceanography, India) runs whole-round core sections through the Whole-Round Multisensor Logger, IODP Expedition 355, Arabian Sea Monsoon. *Photo credit: William Crawford, IODP JRSO*

34 Sedimentologist Alejandra Cartagena-Sierra (University of Notre Dame, USA) collects rhizon samples from the core in the downhole lab. IODP Expedition 361, South African Climates. *Photo credit: Tim Fulton, IODP JRSO*

35 Organic Geochemist Thorsten Bauersachs (Christian-Albrechts-University, Germany) takes samples at the sampling table, IODP Expedition 379, Amundsen Sea. *Photo credit: Tim Fulton, IODP JRSO*

36 Stratigraphic Correlator Sietske Batenburg (University of Oxford, UK), IODP Expedition 369, Australia Cretaceious Climate and Tectonics. *Photo credit: William Crawford, IODP JRSO*

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