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SCIENTIFIC DRILLING ACROSS THE SHORELINE

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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.

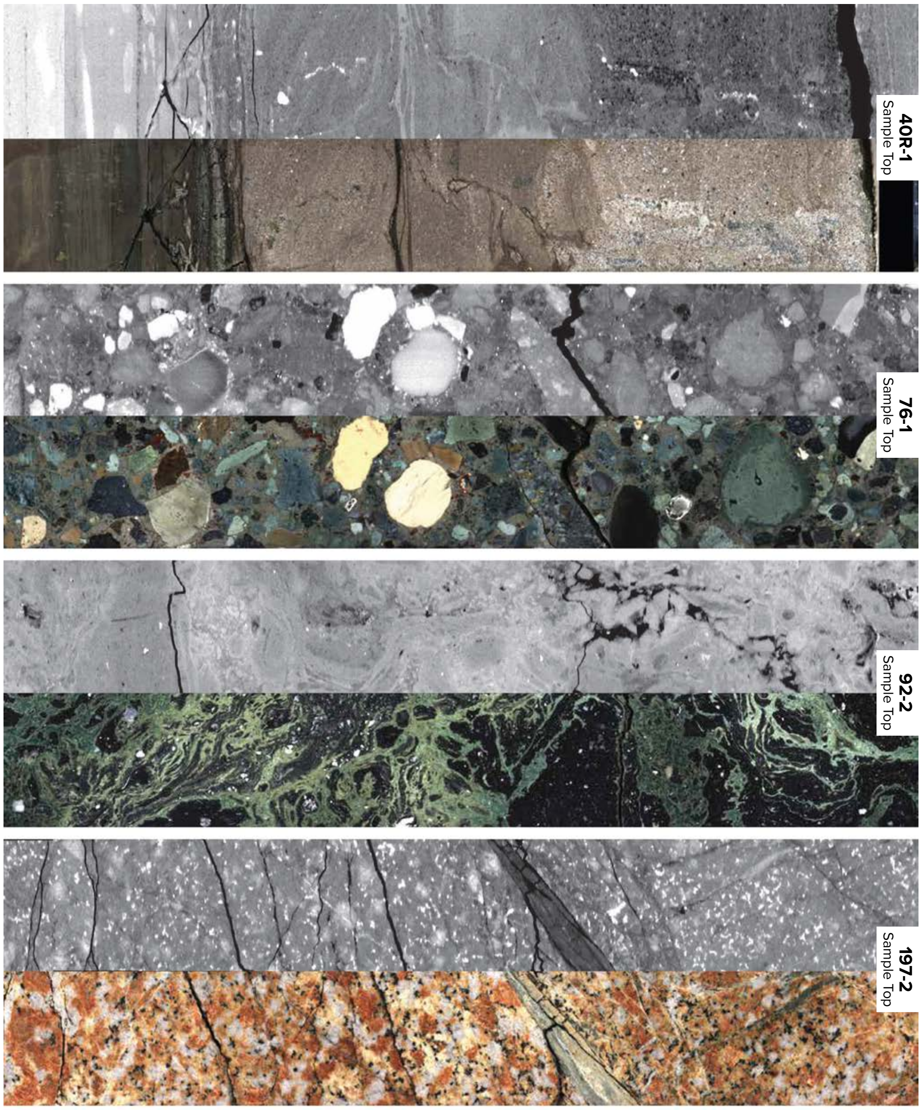

FIGURE 1. Paired images of 1 m long sections of the IODP-ICDP Expedition 364 core. For each pair, a CT scan and photographic line scan image of the same plane through the core is shown. Top to bottom: 40R-1 (618–619 meters below seafloor [mbsf]) shows the top impact breccia (suevite) layer, with evidence 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

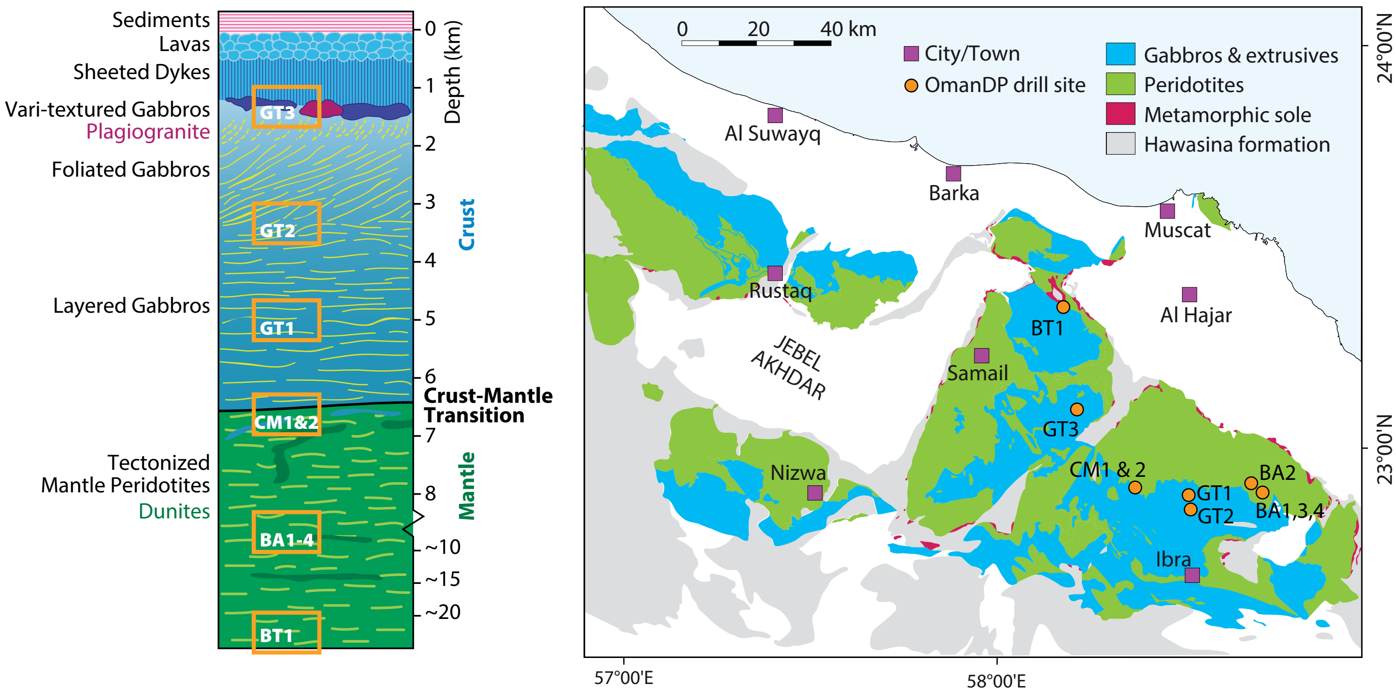

FIGURE 2. Geological map of the southeastern massifs of the Samail ophiolite showing the OmanDP drill site locations and their relative stratigraphic positions. *After Nicolas et al. (2000)*

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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