Ultraslow-Spreading Ridges
Rapid Paradigm Changes

BY JONATHAN E. SNOW AND HENRIETTA N. EDMONDS

Ultraslow-spreading ridges (< 20 mm yr^{-1} full rate) represent a major departure from the style of crustal accretion seen in the rest of the ocean basins. Since the 1960s, observations of fast- and slow-spreading mid-ocean ridges of the Pacific and Atlantic Oceans, combined with those of ophiolites (pieces of oceanic crust that have been thrust onto land through plate-tectonic processes), were used to define the conceptual structural, tectonic, and hydrothermal architecture of oceanic crust. Over the last 15 years, studies of ultraslow-spreading ridges have identified several anomalies that cannot be explained by the standard model of oceanic crustal formation. Thus, in recent years, ultraslow-spreading ridges have become recognized as a class unto themselves. Their "anomalous" characteristics in fact provide key information about many of the underlying processes that govern crustal accretion at all spreading rates. Ultraslow ridges include the Southwest Indian Ridge (between Africa and Antarctica), the Gakkel Ridge (which bisects the Arctic Ocean), and several smaller ridges (Figure 1).

Since the advent of plate-tectonic theory, mid-ocean ridges have been classified based on their structural, morphological, and volcanologic characteristics into two major types based largely on their spreading rate: "fast" (> 60 mm yr^{-1} full rate) and "slow" (< 60 mm yr^{-1} full rate). An "intermediate" type is often placed between them. Both types of ridges share certain characteristics: (1) they have roughly the same crustal thickness (6–7 km—see Figure 2), (2) in plan view they have a characteristic stair-step geometry of volcanic rifts separated by perpendicular transform offsets, and (3) they generate a characteristic outcrop pattern of elongate, fault-bounded abyssal hills trending normal to the spreading direction. Their differences lie primarily in their across-axis morphology: fast-spreading ridges have an axial rise with a very narrow summit graben that is the locus for most volcanic and tectonic activity, whereas slow-spreading ridges have rugged rift mountains enclosing a broad axial valley. Fast-spreading ridges tend to be dominated by volcanism, while the morphology of slow-spreading ridges is dominated more by tectonics. This distinction was widely accepted for many years as a basic principle by the worldwide geologic community. It was taught to undergraduates as a fundamental characteristic of seafloor geology, and its causes were debated as one of the not-completely understood corners of plate-tectonic theory.

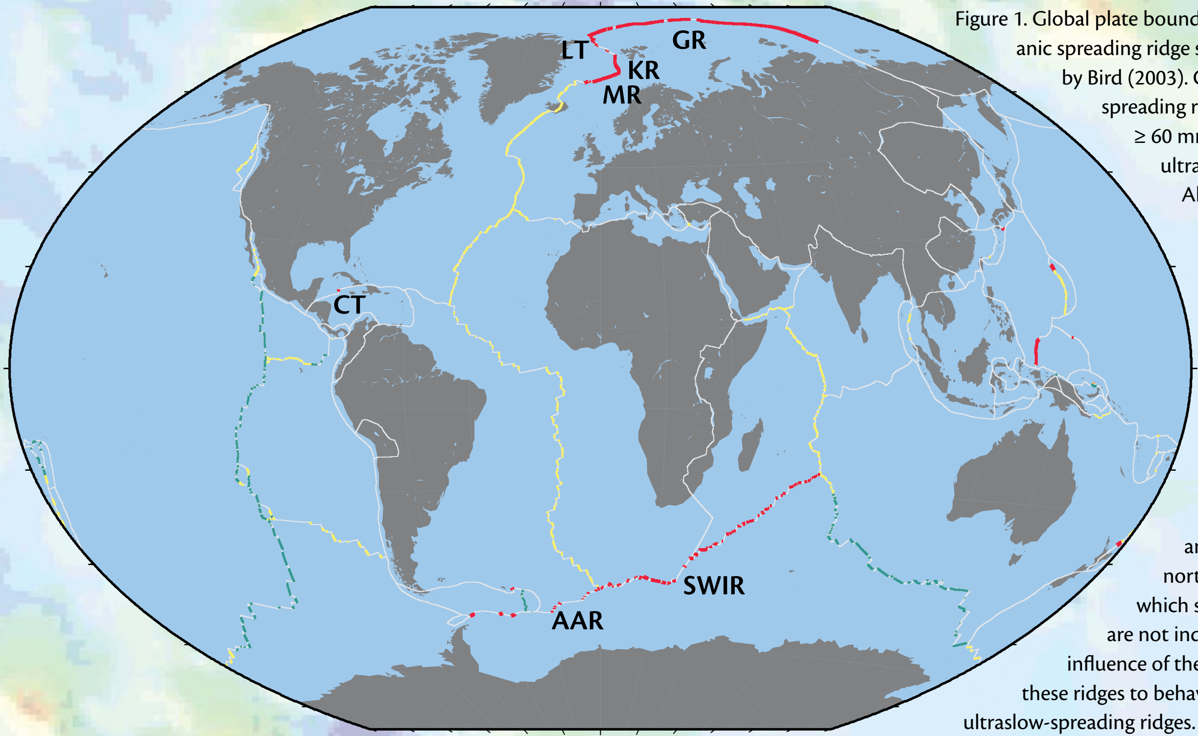

Figure 1. Global plate boundaries (gray) and oceanic spreading ridge segments as defined by Bird (2003). Green indicates fast-spreading ridges (full spreading rate ≥ 60 mm yr^{-1}). Red indicates ultraslow-spreading ridges. All other ridge segments are indicated in yellow. GR = Gakkel Ridge, LT = Lena Trough, KR = Knipovich Ridge, MR = Mohns Ridge, CT = Cayman Trough, AAR = America-Antarctic Ridge, and SWIR = Southwest Indian Ridge. Note that sections of the Kolbeinsey and Reykjanes Ridges north and south of Iceland, which spread at < 20 mm yr^{-1}, are not indicated in red because the influence of the Iceland hotspot causes these ridges to behave differently than other ultraslow-spreading ridges.

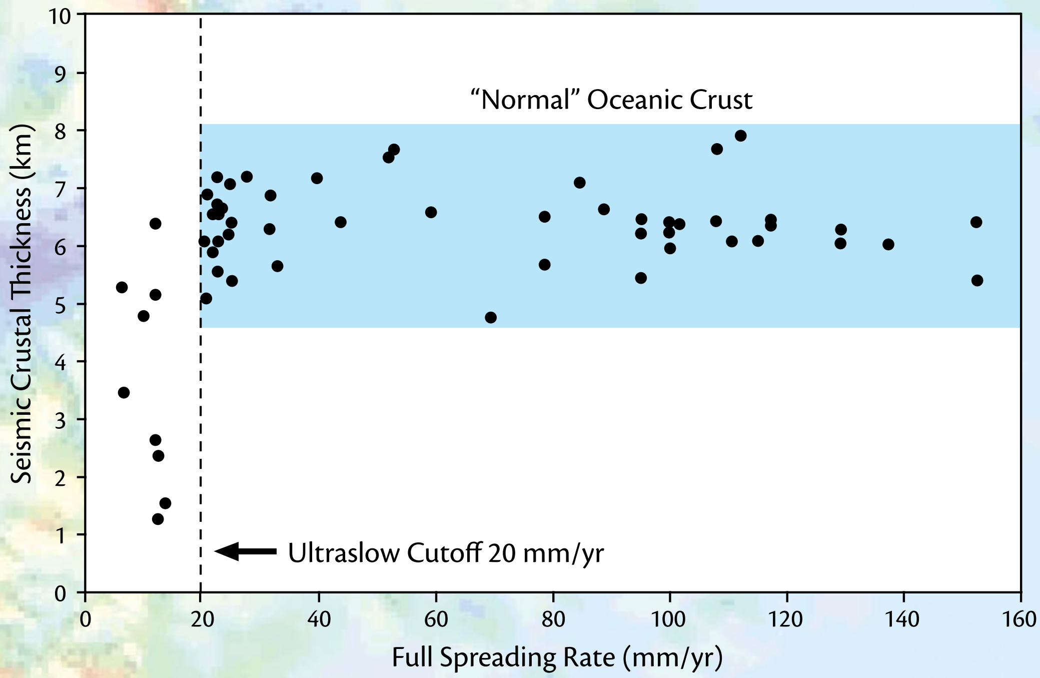

Figure 2. Crustal thickness, determined by seismic refraction, as a function of spreading rate. Normal oceanic crust has a mean thickness of 6 km at all spreading rates above 20 mm yr^{-1}. *Modified after Bown and White (1994)*

The characteristics of both slow- and fast-spreading ridges fit well with the ophiolite model for the formation of oceanic crust, which entered the geological canon at the 1972 Penrose Conference on Ophiolites and Ocean Crust (Conference Participants, 1972). This model, based on geologic mapping on land in ophiolites, calls for a layered structure of pillow basalts, sheeted dikes, gabbro, and mantle (see Figure 3) in a thickness and proportion consistent with the seismic structure of both fast- and slow-spreading crust. These characteristics have been an important cornerstone of plate-tectonic theory for the past 35 years and have continuously proven useful in helping to understand the most inaccessible parts of Earth's crust (Nicolas, 1995).

PROBLEMS WITH THE PENROSE MODELS

Outcrop of mantle ultramafic rocks on the ocean floor was first described at the slow-spreading Mid-Atlantic Ridge (Aumento and Loubat, 1970). In the Penrose model, a 6-km layer of basaltic rock covers the mantle; thus, ultramafic rocks at the seafloor should be rare. Their emplacement to the ocean floor requires

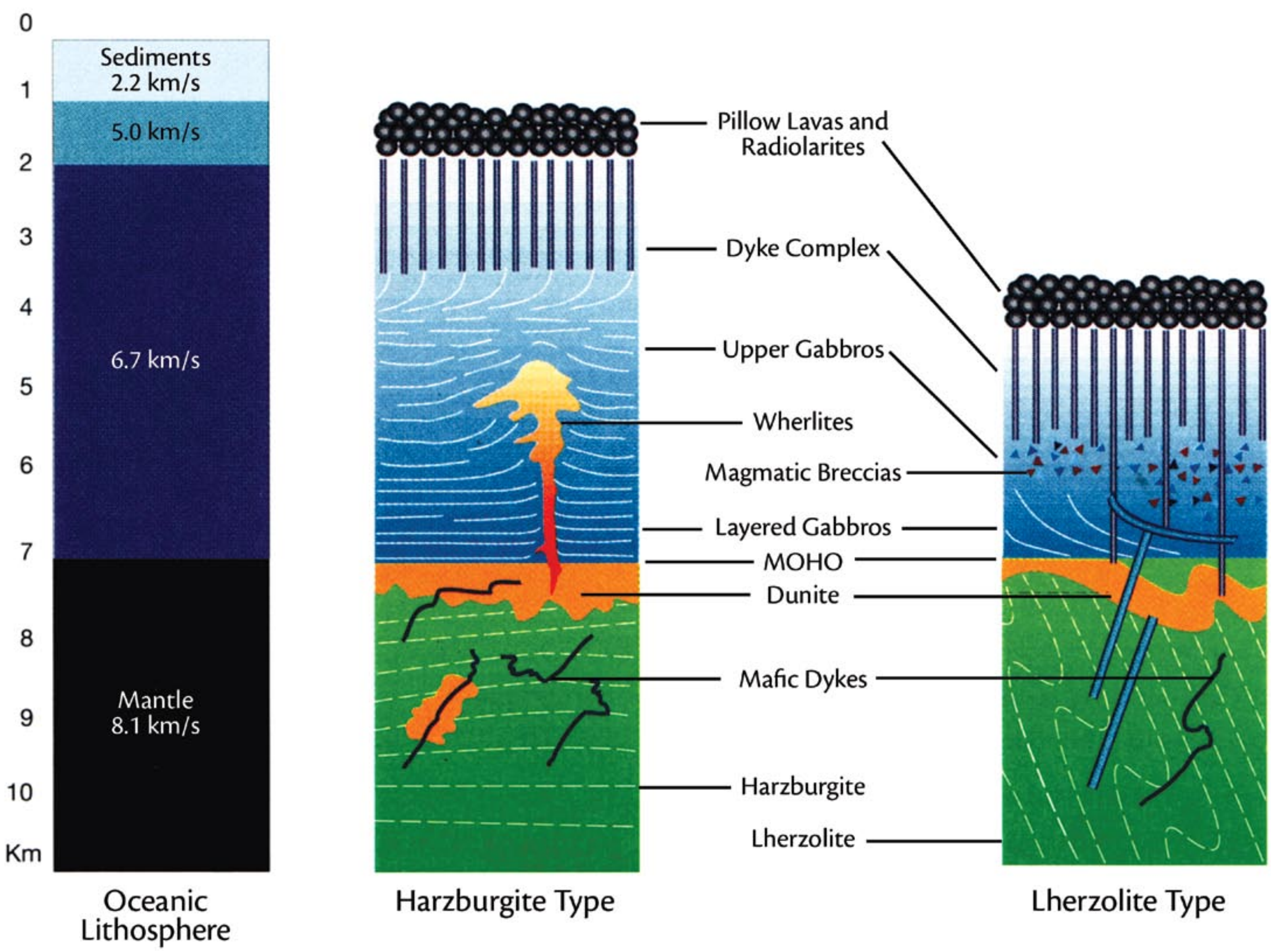

Figure 3. Models of oceanic crustal structure (Nicolas, 1995). The harzburgite-type model describes crust similar to "normal" Penrose-style mid-ocean ridge crust. The origin of lherzolite-type crust was debated for many years, but is now correlated with nonvolcanic rifted margins and to ultraslow-spreading ridges.

mechanisms that would seem implausible, such as faults with a minimum of 6-km displacement (though such faults were in fact later found), or serpentinite diapirism when the serpentinites themselves have densities hardly less than the basaltic rocks through which they must rise. Also, there is no indication how water might penetrate through many kilometers of oceanic crust to create serpentinites in the mantle. Early on, these problems were explained by the idea that great transform faults (Morgan, 1968), which offset ridge segments, provided a pathway for water to enter the mantle and for serpentine diapirs to rise to the surface. Most abyssal peridotites were recovered from the walls of large-offset transform faults, or near them. On the Southwest Indian Ridge (SWIR), peridotites were even more common (Dick, 1989; Engel and Fisher, 1975).

By the mid-1990s, unusual ridge segments were also found on the SWIR that were anomalously deep and not perpendicular to the spreading direction, as Penrose-style volcanic rifts are supposed to be. Neither were they transform faults, which are geometrically required to be parallel to the spreading direction. The walls of these rifts instead trend at a highly oblique angle to the prevailing spreading direction. These oblique rift segments frequently contain mantle peridotites as well as basalts of unusual composition. Although these types of basalt were already known from ocean islands and ridges near major hotspots, their presence in these anomalous rifts, often called "leaky transforms," could not easily be reconciled with prevailing ideas about crustal accretion or the generation of oceanic basaltic magmas (Cannat et al., 1999; le Roex et al., 1992; Patriat et al., 1997)

Another major change to ideas of crustal accretion came through discoveries at ridge-transform intersections. Dredging results showed that the elevated inside-corner-high sections of transform faults contained abundant rocks from the lower crust and upper mantle. While the faults bounding the inside corner high were large, with as much as 500 m of obvious vertical displacement, this was nowhere near enough to bring up mantle rocks from beneath a full section of oceanic crust (Dick, 1989; Karson and Dick, 1983). Subsequently, improved bathymetric imaging showed obvious signs that this faulting was along many tens of kilometers of displacement (Cann et al., 1997; Tucholke et al., 1998). Nearby dredging of anomalously deep regions of the ridge (so-called zero-offset fracture zones, or nontransform discontinuities) also recovered lower crustal and upper mantle rocks, far from the effects of transforms (Cannat et al., 1995). At this point, one was forced to wonder, even on slow-spreading ridges, just how much of the crust could be considered "normal."

Almost from the beginning, the observation of a constant crustal thickness across the entire range of spreading rates (see Figure 2) began to unravel as well. While it remained true at most spreading ridges that the seismically determined crustal thickness was nearly constant, at the slowest spreading rates, notably in a seismic study done through the ice of the Arctic Ocean, the oceanic crust seemed to be dramatically thinner than along the rest of the global mid-ocean ridge system (Figure 2). The crust was so thin, in fact, that the very concept of a "crust" had to be called into question, as the seismic structures found could easily be satisfied by a thin layer of serpentinite overlying bare mantle (Bown and White, 1994; Jackson et al., 1982; Reid and Jackson, 1981).

Ultraslow-spreading ridges have recently emerged as a unique, new class of mid-ocean ridge spreading centers.

EVIDENCE FROM THE FROZEN NORTH: AMORE 2001

A consensus thus evolved during the 1990s that while the Penrose model still held for most mid-ocean ridge systems,

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the very slowest spreading ridges were quite different, and thus might illustrate extreme forms of the fundamental geodynamic forcing functions driving mid-ocean ridge construction everywhere. A major effort then evolved to investigate the world's slowest-spreading mid-ocean ridge—the Gakkel Ridge in the Arctic Ocean (InterRidge Arctic Working Group, 1998). Gakkel Ridge is the northern continuation of the Mid-Atlantic Ridge, and extends over 2000 km from the northeast tip of Greenland to the Laptev Sea continental shelf in Siberia. The full spreading rate varies from about 14 mm yr^{-1} at the Greenland end to less than 8 mm yr^{-1} at its Laptev Sea termination (Reid and Jackson, 1981; Vogt et al., 1979). Thus, at its fastest end, the Gakkel Ridge spreads more slowly than any other mid-ocean ridge. Pack-ice cover had prevented Arctic hard-rock dredge operations until 1999 when the icebreaker PFS *Polarstern* (Alfred Wegener Institute, Bremerhaven, Germany) recovered the first peridotite, basalt, and hydrothermal rocks from the Lena Trough, just to the south (Snow et al., 2001). At the same time, a US Navy-civilian science cooperation used civilian instruments on a US nuclear submarine to produce the first bathymetric and sidescan sonar images of Gakkel Ridge (Coakley and Cochran, 1998; Cochran et al., 2003; Edwards et al., 2001).

AMORE 2001, the international mapping and sampling program that left Tromsø, Norway, in July 2001, was an unprecedented success (Edmonds et al., 2003; Jokat et al., 2003; Michael et al., 2003). Encountering good ice conditions, scientists aboard PFS *Polarstern* and the new US Coast Guard Cutter *Healy* were able to create a detailed bathymetric map of much of the rift valley of Gakkel Ridge (Figure 4), carry out over 200 rock sampling stations, record a dozen seismic crustal thickness measurements, and conduct continuous seismic-reflection transects across both the Nansen and Amundsen basins. The two ships reached the North Pole together on September 6, 2001 (Jokat et al., 2003; Michael et al., 2003). In 2004, PFS *Polarstern* mapped and sampled the Lena Trough and returned to Gakkel Ridge for additional mapping and sampling (Snow and Petrology Group ARK-XX-2, in press).

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A "NEW" CLASS OF MID-OCEAN RIDGE

The new observations made along Gakkel Ridge were confusing. There was significantly more volcanism than had been expected. The western part of Gakkel Ridge was magmatically robust, despite its relatively thin crust, with no outcrops of mantle peridotite. On either side of this western volcanic zone, however, were long rift segments where apparently no magmatic crustal construction occurred at all (Michael et al., 2003; Snow and Petrology Group ARK-XX-2, in press), and to the east, volcanism *increased* in discrete volcanic centers separated by amagmatic basins.

The SWIR and Gakkel Ridge together thus required a new entry in the table of mid-ocean ridge types (Dick et al., 2003). At ultraslow-spreading ridges, the seismic crust is thinner (~ 1–4 km) than at other ridges (see Figure 2) (Bown and White, 1994; Jokat et al., 2003; Reid and Jackson, 1981). The changeover from slow- to ultraslow-spreading characteristics is not strictly a function of spreading rate. Rather, a number of factors can influence the style of crustal accretion: plate-boundary geometry, mantle magmatic productivity, and mantle potential temperature (Dick et al., 2003).

Ultraslow-spreading ridges uniquely possess amagmatic rifts that expose mantle peridotite directly on the seafloor, with only scattered basalt and gabbro (Dick et al., 2003). Along with magmatic rifts, transforms, and subduction zones, amagmatic rifts form a new, fourth class of plate-boundary structure. Figure 5 shows an amagmatic segment on the SWIR (Dick et al., 2003); similar segments also occur on the Gakkel Ridge (Michael et al., 2003) and Lena Trough (Snow and Petrology Group ARK-XX-2, in press). Unlike magmatic segments, they have mantle peridotite walls formed by long sloping scarps or irregular uplifts rather than the basaltic-block, normal faulting of Penrose crust (Dick et al.,

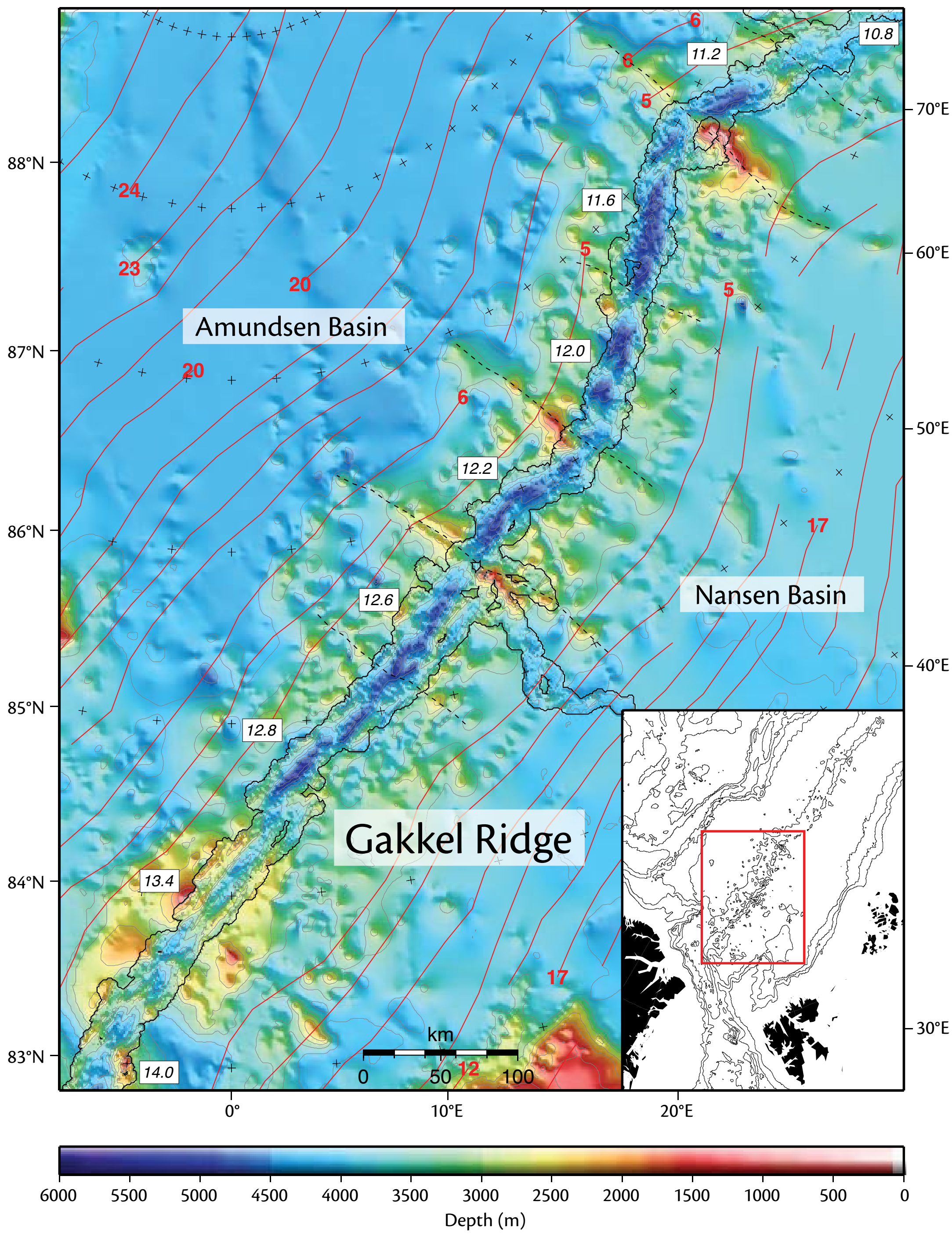

Figure 4. Gakkel Ridge bathymetry based on AMORE 2001 and International Bathymetric Chart of the Ocean data sets. Full spreading rates in each identified section are given in mm yr^{-1}. Red lines show magnetic lineation picks. *Modified from Figure 1, Jokat et al. (2003)*

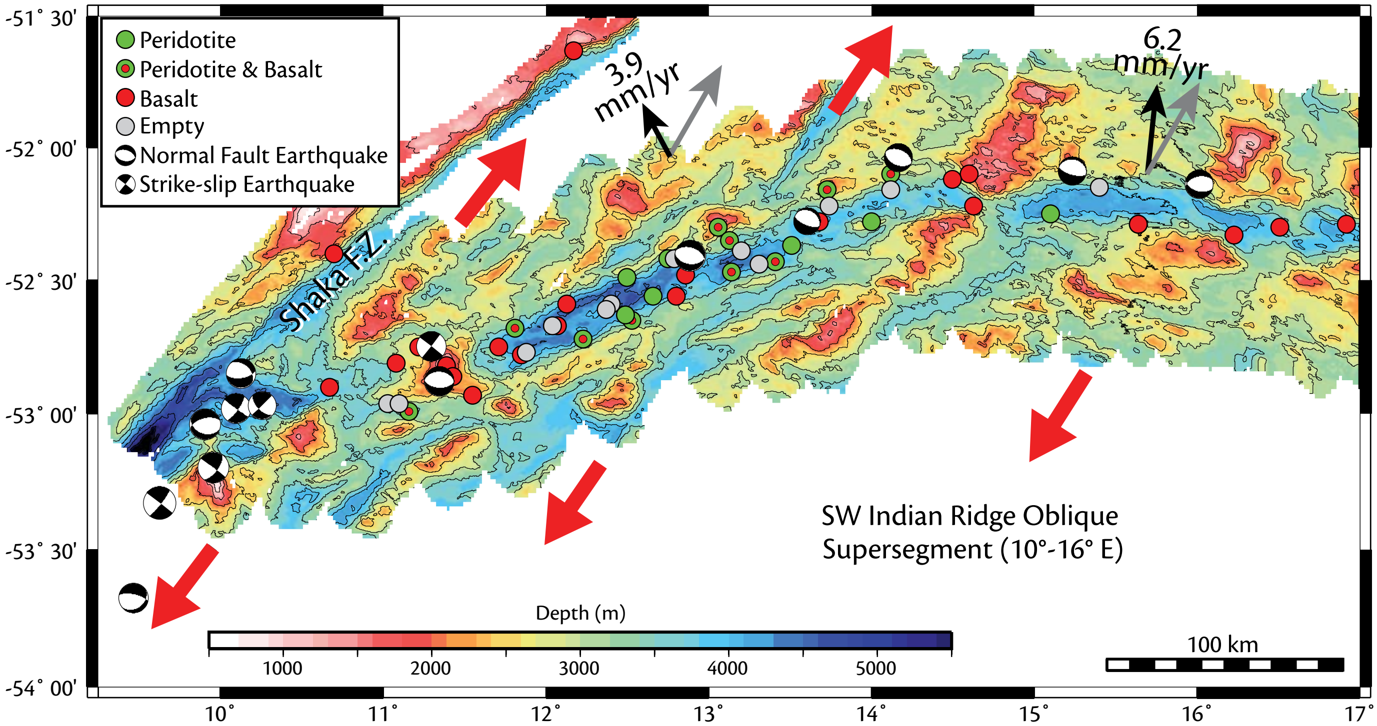

Figure 5. Oblique amagmatic accretion on the Southwest Indian Ridge (Dick et al., 2003). Filled circles show sampling points, giving rock type coded by color as shown in key. Note that the spreading direction (red arrows) is not at a right angle to the strike of the rift. This type of spreading, far from being anomalous, is characteristic of ultraslow-spreading ridges.

2003; Michael et al., 2003; Okino et al., 2002). Amagmatic segments can also assume any orientation to the spreading direction, sometimes forming oblique rifts (Dick et al., 2003; Snow et al., 2001), and they can produce a unique "smooth" seafloor (Cannat et al., 2006). Magmatic accretion at ultraslow-spreading rates can either be robustly magmatic, as at the orthogonal supersegment of the SWIR (Dick et al., 2003) or the western Gakkel Ridge (Michael et al., 2003), or it may be confined to highly focused, short magmatic segments (producing crust with orthogonal structures) linked by amagmatic segments. Where the plate boundary runs oblique to the direction of spreading, the amagmatic style of spreading is enhanced such that oblique amagmatic segments can form at higher spreading rates than would otherwise be possible (Dick et al., 2003).

The more variable and alkalic nature of basalts from ultraslow-spreading ridges (le Roex et al., 1992; Meyzen et al., 2003; Snow et al., 2001) can be explained by an overall lower degree of partial melting in the mantle (which produces magma rich in alkali elements relative to silica), and the presence of mantle geochemical components not observed at slow- and fast-spreading ridges (Hart, 1984). Mantle peridotites from ultraslow-spreading ridges afford unique, nearly direct access to Earth's mantle. Analyses of these rocks have led to the conclusion that there is primary mineralogic variability in the upper mantle that affects partial melting (Dick et al., 1984), that mid-ocean ridge melting occurs by a process of near-fractional melting (Johnson et al., 1990), and that deep melts formed in the presence of garnet are a component of mid-ocean ridge basalt (Hellebrand and Snow, 2003).

INSIGHTS ON CONTINENTAL RIFTING AND OPHIOLITES

Ultraslow-spreading ridges have increasingly become a model for understanding some of the more puzzling aspects of ophiolites and continental rifts. The Penrose model had always met with difficulty in explaining some aspects of the tectonic setting and structure of ophiolites. Far too many ophiolites (the "lherzolite-type" in Figure 3 and Nicolas, 1995) did not conform to the 6-km-thick crust observed nearly everywhere in the oceans. Proponents of the ophiolite paradigm concluded that the incomplete ophiolites had been dismembered during the process of obduction onto the continent. Among the incomplete lherzolite-type ophiolites are the original ones, those where the association of volcanic rocks, serpentinite, and deep-sea sediment was first recognized and called "ophiolite" in 1905 (Steinmann, 1905). These ophiolites contained little middle crust, consisting largely of a thin layer of pillow basalt erupted directly on peridotite and covered by deep-sea sediments. Harry Hess, a Princeton mineralogist and early mentor to the founders of plate-tectonic theory, first recognized their significance as the trace of ancient plate boundaries (Hess, 1962). His idea, however, that the ocean floor consisted entirely of serpentinite was ultimately displaced by the Penrose ophiolite model shown in Figure 3.

Then, in the 1990s, the Ocean Drilling Program completed a series of deep-sea drill holes off the coast of Portugal that showed the existence of serpentinite-floored oceanic crust on the European continental margin (Whitmarsh et al., 1996; Whitmarsh et al., 2001; Whitmarsh et al., 1993). At the same time, sedimentary sequences in the western Alps were recognized as the margin of a rifted continent (Froitzheim and Manatschal, 1996; Manatschal, 2004). The basement of this fossil continental rifted margin changes, just as on the present-day Iberia margin, from continental basement to mantle rocks, sometimes with a thin cover of basalt, and covered by deep-sea sediments. The rock types, structures, and ultimately the mechanisms of exhumation of deep crustal and mantle rocks in both of these locations bear striking similarity to that occurring today at ultraslow-spreading ridges. Thus, on some continental margins, the rifting that creates new ocean basins occurs in an amagmatic "Hess-type" manner analogous to ultraslow mid-ocean ridges. This combination of Alpine rock types was exactly the one whose tectonic significance Harry Hess noticed 50 years ago. In fact, the western Alpine outcrops involved were the same ones where Steinmann originally described his unique rock association 100 years ago (Steinmann, 1905).

> Observations made on these ridges have brought tremendous advances in understanding the tectonics, magmatic architecture, and hydrothermal evolution of oceanic crust at all spreading rates, and are continuing to do so.

HYDROTHERMAL ACTIVITY ON ULTRASLOW-SPREADING RIDGES

Ultraslow-spreading ridges have also provided surprises and new insights in hydrothermal vent research. Before the first high-temperature venting was observed on the Mid-Atlantic Ridge (Rona et al., 1986), many scientists had been skeptical about whether even slow-spreading ridges were capable of supporting such venting due to their colder thermal structure. By the 1990s, a linear relationship was proposed between hydrothermal venting and spreading rate, largely based on results from the faster-spreading ridges (Baker, 1996; Baker et al., 1994). German and Parson (1998), in extending this work to the slow-spreading Mid-Atlantic Ridge, pointed out that the length scale over which survey results are considered may lead to substantial variability, particularly on slower-spreading ridges, where tectonic fabric plays a stronger role in controlling hydrothermal circulation and can also limit the dispersal of hydrothermal plumes. All of these studies predicted that hydrothermal activity would be very low at ultraslow-spreading rates, and the perception persisted that the occurrence of high-temperature venting might drop to near zero. At the Gakkel Ridge, for example, vent-site frequency was predicted to be on the order of one site per 200–300 km.

It is thus perhaps ironic that ultra-slow-spreading ridges have now been surveyed more thoroughly for hydrothermal activity than ridges in most other spreading-rate classes (Baker and German, 2004). This discrepancy is the result of the coincidence between the beginning of the international ridge community's focus on ultraslow-spreading ridges and the development of strategies for systematic large-scale mapping of hydrothermal plumes (e.g., Baker and Milburn, 1997). Such mapping relies on the plumes' optical backscatter, a measure of suspended particles in the water column that result from the mixture of metal-rich, high-temperature hydrothermal fluid and seawater. The deployment of optical sensors during rock sampling and deep-towed geophysical operations enables much more efficient detection of plumes than earlier exploration strategies that relied on "spot" sampling by conductivity-temperature-depth (CTD) instruments. Three sections of ultraslow-spreading ridges, totaling ~ 2250 km, have now been thoroughly surveyed (Figure 6), including the SWIR from 58° to 60°E and 63° to 66°E (German et al., 1998), the SWIR from 10° to 23°E (Bach et al., 2002; Baker et al., 2004), and the Gakkel Ridge from 8°W to 85°E (Edmonds et al., 2003).

The results of these surveys, along with isolated discoveries on the Mohns and Knipovich Ridges (Connelly and German, 2002; Pedersen et al., 2005) and in the Lena Trough (Snow et al., 2001), demonstrate that high-temperature hydrothermal venting is ubiquitous on ultraslow-spreading ridges. The three densely surveyed sections yield a site frequency of about one site per 100 km. Recent normalization of site frequencies to the ridge magma-production rate suggests that ultraslow-spreading ridges may be two to four times as efficient as fast-spreading ridges at converting the available magmatic heat into vent fields (Baker et al., 2004; Baker and German, 2004). With the exception of the Mohns Ridge sites (Pedersen et al., 2005), which are located in about 500-m water depth, all of the sites are in deep water and none have yet been surveyed or sampled with deep submergence technology.

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Ultraslow-spreading ridges may have even more hydrothermal activity than outlined above. Optical plume mapping does not detect some forms of hydrothermal activity likely to be more common on slow- and ultraslow-spreading ridges. Hydrothermal circulation in peridotite-hosted systems can be driven by the exothermic serpentinization reactions, rather than by magmatic heat. These reactions result in colder and less metal-rich vent fluids than "traditional" basalt-hosted systems and do not lead to formation of a particle-rich plume. A case in point is the 40–75°C fluid temperatures at the Lost City ultramafic hydrothermal field in the Atlantic Ocean (Kelley et al., 2001). The only water-column signal that ultramafic-hosted systems might consistently generate is elevated methane, but as yet there is no reliable, robust sensor for in situ detection of methane at the expected levels. Such "non-traditional" hydrothermal systems may be especially important because of their unique contributions to global geochemical cycles. High-temperature systems that involve magmatic heat as well as ultramafic rocks (such as Rainbow and Logatchev on the northern Mid-Atlantic Ridge) also exhibit elevated precious-metal concentrations and the abiogenic production of complex (multi-carbon) organic molecules. Furthermore, hydrothermal systems on slow- and ultraslow- spreading ridges may be active for longer time periods and lead to the deposition of larger ore bodies due to their localization on long-lived fault structures.

Ultraslow-spreading ridges also occupy regions of particular interest for vent biogeographic studies (Tyler and Young, 2003; Van Dover et al., 2002). The deep Arctic ridges are isolated from the rest of the mid-ocean ridge system due to the presence of Iceland astride the Mid-Atlantic Ridge, and to the shallow connections between the Arctic and

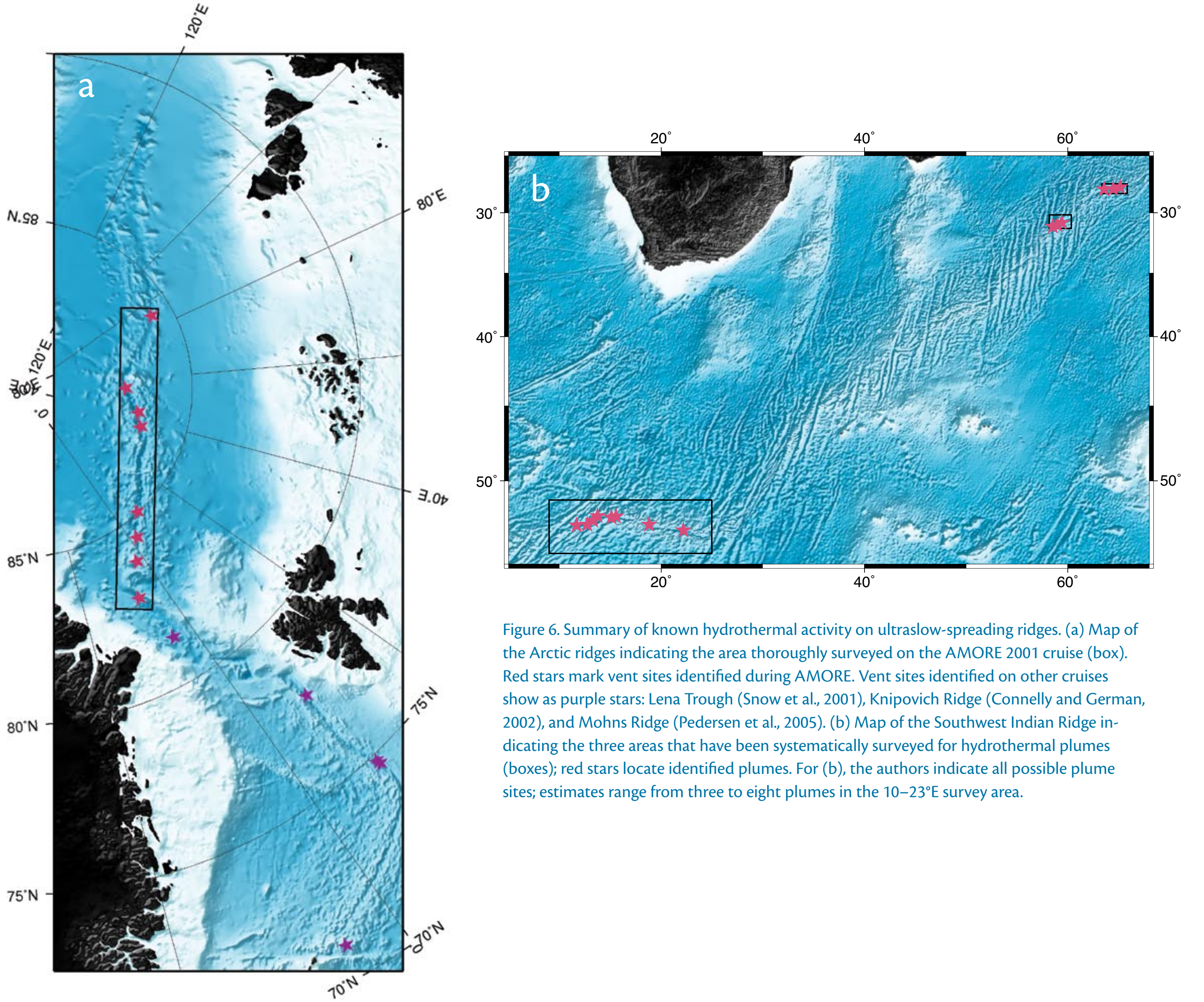

Figure 6. Summary of known hydrothermal activity on ultraslow-spreading ridges. (a) Map of the Arctic ridges indicating the area thoroughly surveyed on the AMORE 2001 cruise (box). Red stars mark vent sites identified during AMORE. Vent sites identified on other cruises show as purple stars: Lena Trough (Snow et al., 2001), Knipovich Ridge (Connelly and German, 2002), and Mohns Ridge (Pedersen et al., 2005). (b) Map of the Southwest Indian Ridge indicating the three areas that have been systematically surveyed for hydrothermal plumes (boxes); red stars locate identified plumes. For (b), the authors indicate all possible plume sites; estimates range from three to eight plumes in the 10–23°E survey area.

the Pacific Oceans (through the Bering Strait) and between the Arctic and the Atlantic Oceans (through the passages of the Canadian Arctic Archipelago and the sills between Greenland and Scotland). At no time since the inception of spreading on these northern ridges has there been a deep (thousands of meters) connection between the Arctic basins and the North Atlantic, and thus it is quite possible that endemic vent fauna of the Arctic ridges have followed an evolutionary path quite separate from any other yet studied. A return expedition planned for 2007 should answer some of these intriguing questions for the Gakkel Ridge.

The SWIR, meanwhile, occupies a crucial gap between known vent biogeographic provinces: no vent sites have yet been characterized in terms of their faunal communities between the Rodriguez Triple Junction (southern Central Indian Ridge, Edmond and Kairei fields) and the northern Mid-Atlantic Ridge. The Central Indian Ridge communities exhibit affinities with both the Atlantic and the western Pacific biogeographic provinces but are most similar overall to the western Pacific (Van Dover et al., 2001). The exploration of vent fields on the southern Mid-Atlantic Ridge (e.g., German et al., 2005; Haase and M64/1 Scientific Party, 2005) and the SWIR thus holds promise for exciting new discoveries regarding vent organism ecology and dispersal.

SUMMARY

Ultraslow-spreading ridges have recently emerged as a unique, new class of mid-ocean ridge spreading center. Observations made on these ridges have brought tremendous advances in understanding the tectonics, magmatic architecture, and hydrothermal evolution of oceanic crust at all spreading rates, and are continuing to do so. In addition, there is a growing realization that ultraslow-spreading ridges provide an analog to processes that govern the breakup of continents along nonvolcanic rifted margins. The ultraslow-spreading ridge community has set several near-term goals on which to focus its activities, beginning with two workshops/conferences held in Europe in the fall of 2006. There will be a major effort to push ridge mapping and sampling at the slowest spreading rates into new regions using new technologies that mitigate both the effect of permanent ice cover and the thick sediments that cover the Gakkel Ridge at the slowest spreading rates near the Siberian continent. In addition, many observers have recently had their eyes opened to the many relevant, ultraslow-spreading-ridge observations that can be made high in the Alps where Harry Hess and Gustav Steinmann worked before them.

ACKNOWLEDGEMENTS

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