CONTRIBUTION OF MULTIBEAM BATHYMETRY TO UNDERSTANDING THE PROCESSES THAT SHAPE MID-OCEAN RIDGES

BY Marie-Helene Cormier
Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA

Abstract

With the emergence in the 1980's of multibeam bathymetric systems, comprehensive two-dimensional maps of the seafloor became available that changed our view of the mid-ocean ridges. Multibeam bathymetry reveals a fine-scale segmentation of the ridge axis, with ridge offsets as small as a few hundred meters. Ridge segments are 10-100km long and generally correspond with individual volcanic systems. While the morphology of the ridge axis depends primarily on spreading rates, it also varies predictably from the center to the ends of a ridge segment and with local supply of magma. Discordant features on the ridge flanks provide a continuous record of the tectonic evolution of the mid-ocean ridges and reveal that the plate boundary is commonly reorganizing in response to minor changes in plate motion and variations in the thermal structure of the lithosphere. Emerging deep-submergence technologies now provide microbathymetric maps with a vertical resolution of a few cm, sufficient to accurately map individual lava flows, eruptive vents, fissures, and faults. A strategy of repeating microbathymetric surveys may offer the potential to precisely characterize seafloor spreading events.

Introduction

Much of the volcanic and seismic activity on earth occurs along the 75,000 km of mid-ocean ridges that circle the continents, hidden from view beneath 2000 to 4000 m of water (Fig. 1). During the mid-20th century, extensive mapping efforts using conventional echosounders successfully outlined the gross geometry of the mid-ocean ridges. In combination with teleseismic earthquakes and magnetic profiles, a first-order picture of the spreading centers emerged [*Heezen et al.*, 1959; *Menard*, 1967; *Wilson*, 1965]. These were shown to consist of linear ridge segments oriented roughly perpendicular to the spreading directions, offset by transform faults every few tens to several hundreds of kilometers. Echosounding data further highlighted a general correlation between the morphology of the ridge axis and spreading rates [*Macdonald*, 1982]. At slow spreading rates (1 to 5 cm/yr), a rift valley 1-3 km deep and 20-30 km wide marks the axis of accretion, as is observed along the Mid-Atlantic Ridge and the Central Indian Ridge. At intermediate spreading rates (5 to 9 cm/yr), this axial valley is only 50-200 m deep, as is observed along the Galapagos spreading center, the Juan de Fuca Ridge, the Chile Ridge, and the Southeast Indian Ridge. Along the fast spreading East Pacific Rise (9-15 cm/yr), an axial valley is rarely detected and instead the axis of accretion sits atop a 300-800 m topographic high. At all spreading rates, the ridge flanks are characterized by a monotonous succession of abyssal hills, with overall relief and orientation comparable to that of the neighboring ridge axes. Submersible investigations indicated that the "neovolcanic zone", the zone of recent volcanism, is typically on the order of 1-2 km wide regardless of spreading rate.

Thorough examination of magnetic anomaly profiles revealed that mid-ocean ridges commonly reconfigure their geometry through a variety of mechanisms. These mechanisms include asymmetric spreading (where faster accretion occurs for one of the ridge flanks) [*Weissel and Hayes*, 1971], ridge jumps (where ridge segments relocate wholesale on one of the flanks) [*Hey and Vogt*, 1977], ridge propagation (where a new spreading center gradually breaks up the existing plate) [*Hey*, 1977] and formation of microplates [*Anderson et al.*, 1974]. Changes in relative plate motions and proximity to hot spots are thought to be dominant factors controlling this evolution of the plate boundaries.

However, geophysical data collected along widely spaced ship tracks are too limited for addressing the finer-scale geological processes that shape the mid-ocean ridges. With the emergence in the 1980's of multibeam bathymetry systems and satellite altimetry, comprehensive two-dimensional views of the seafloor became routinely available. These changed the focus of research. For the water depths characteristic of mid-ocean ridges, multibeam systems achieved a resolution of about 10m vertically and 100m horizontally, a resolution sufficient to highlight most fault scarps and volcanic edifices on the ridge flanks. New maps unambiguously outlined the scars produced by the reorganization of the plate boundary, revealed systematic along-axis variations in morphology, and exposed new types of "non-transform" ridge offsets. The following summarizes new insights that multibeam bathymetry contributed to our understanding of accretionary processes.

Segmentation of the mid-ocean ridges

The first-order segmentation of the ridge axis consists of transform faults and occasional "non-transform offsets" at least 30km wide (Figs. 2, 3, and 4). Multibeam bathymetric data further revealed the widespread occurrence of smaller "non-transform offsets", defining a hierarchy of ridge offsets [*Macdonald*, 1998]. Along the fast spreading East Pacific Rise, overlapping spreading centers accommodate ridge offsets 1-30 km wide [*Lonsdale*, 1983; *Macdonald and Fox*, 1983]. Overlapping spreading centers are produced where two ridge segments curve toward each other and overlap by a distance roughly comparable to the ridge offset (Figs. 2 and 4). With both segments accommodating seafloor spreading, this overlapping geometry is inherently unstable. Ridge tips are regularly abandoned and rafted off-axis as a ridge tip either relocates inside the overlap zone, propagates and overtakes the adjacent ridge tip, or on the contrary retreats before the propagating tip of the adjacent segment. Along the slower-spreading Mid-Atlantic Ridge, non-transform offsets correspond to broad, oblique shear zones (Fig. 3) which are also unstable with time [*Grindlay et al.*, 1991]. This instability of non-transform discontinuities results in the formation of broad corridors of seafloor with oblique fabric. These discordant zones are often wider than a fracture zone. The chemistry of lavas collected between non-transform offsets suggests that they delimit primary volcanic systems 10 to 100 km long [*Langmuir et al.*, 1986; *Sinton et al.*, 1991]. Finally, offsets smaller than 1 km are commonly detected with multibeam bathymetry. These are located within the neovolcanic zone and merely offset the eruptive vents comprised within one volcanic system; they do not produce recognizable off-axis traces.

Multibeam bathymetry also confirms that the style of volcanic accretion is strongly dependent on spreading rate. Along the East Pacific Rise, at the resolution of the multibeam data, the ridge crest generally corresponds to a smooth plateau, suggesting accretion by effusive fissure eruption [*Macdonald and Fox*, 1988]. Along the Mid-Atlantic Ridge, a volcanic ridge occupies the floor of the rift valley that consists of stacked volcanic constructs with bulbous contours [*Smith et al.*, 1999]. Recent surveys along ultra-slow spreading ridges (<1 cm/yr) such as the Gakkel Ridge and the Southwest Indian Ridge suggest that eruptive activity corresponds to point-fed (rather than line-fed) volcanic vents [*Edwards et al.*, 2001; *Sauter et al.*, 2001]. The Reykjanes Ridge is an exception, as its magma supply is influenced by the proximity to the Iceland hot spot [*Searle et al.*, 1998].

At slow spreading rates, inactive fracture zones systematically preserve the deep trough that characterizes the active transform domain. Extreme topography, sometime in excess of 4000-5000m, develops at ridge-transform intersections (the "inside corner high" and its associated "nodal deep"). This is interpreted to result from low-angle detachment faults that accommodate a large component of the spreading near segment ends. This model is supported by multibeam data revealing subtle corrugations and striations on top of the inside corner highs that are oriented parallel to the plate spreading direction [*Cann et al.*, 1997]. The largest transform faults display broad, complex transform domains that might include slivers of seafloor that are much older than predicted by conventional seafloor spreading [*Ligi et al.*, 2002]. At fast and intermediate spreading rates, a smooth region of shallow topography occupies the ridge-transform intersection. This broad high is curved toward the active transform and extends from the ridge axis onto the older plate (e.g., Fig. 4). It is interpreted to form as excess volcanism at the ridge axis extends across the ridge-transform intersection onto the older plate. This process effectively fills the transform valley and smooth out its trace before it is transferred past the ridge-transform intersection. Hence, most fracture zones in the eastern Pacific Ocean do not produce prominent fracture zone traces, except for the largest ones.

Changing geometry of the mid-ocean ridges

Magnetic data have long provided the primary evidence for the tectonic evolution of the ridge axis. Reversals of the magnetic field occur every several 100,000yr, and magnetic anomalies frozen in the oceanic crust record the geometry of the ridge axis for each of these reversal events. In contrast, the reorganization of a plate boundary produces diagnostic features on the ridge flanks that provide a continuous record of the tectonic evolution, and detailed off-axis bathymetric surveys have elucidated many of the precise mechanisms through which a spreading center reconfigure itself.

Changes in the direction of plate motion are recorded in the fabric of the seafloor in several ways. Active transform faults are aligned with present relative plate motion, while the trend of their fracture zone extensions records past plate motion direction [*Menard and Atwater*, 1968]. The direction of the change in relative motion also produces distinctive features within the transform domain. Extensional opening encourages the development of multiple parallel transform faults separated by short intra-transform spreading centers [*Searle*, 1983]. Closing motion across the transform may cause the growth of a transform-parallel compressional ridge [*Pockalny et al.*, 1997; *Searle*, 1983], or even the birth of a microplate [*Bird and Naar*, 1994]. In addition, abyssal hills form perpendicular to spreading direction, except near axial discontinuities where they record local perturbations to the regional stress field. Hence, accurate mapping of abyssal hill trends can reveal subtle changes in spreading directions [*Cormier et al.*, 1996].

Spreading centers typically relocate through a mechanism of ridge propagation, producing diagnostic features on the ridge flanks. As a ridge segment progressively breaks through older lithosphere, it creates a V-shape discordant zone on the seafloor which points in the direction of propagation [*Courtillot*, 1982; *Hey et al.*, 1980]. If the propagating ridge segment overtakes an adjoining ridge segment, it progressively transfers the seafloor caught between the two segments from one plate to the other, resulting in apparent asymmetric spreading. At fast and intermediate spreading rates, side-scan and multibeam surveys indicate that failing ridges retreat stepwise, and propagating ridges advances continuously [*Wilson*, 1990]. While ridge propagation is best exposed a fast and intermediate spreading rates where deformation is distributed over broad accreted areas, detailed survey of the Mid-Atlantic Ridge show much evidence for ridge propagation [*Gente et al.*, 1995]. Propagating ridges are also ubiquitous in back-arc spreading centers, where they accommodate the rapid evolution of an assemblage of small plates [*Auzende et al.*, 1995; *Lagabrielle et al.*, 1997]. Ridge segments always propagate away from shallowest sections of a ridge, and propagator tips represents some of the deepest points along the ridge axis [*Phipps Morgan and Sandwell*, 1994]. Ridge propagation seems facilitated by the presence of a thinner (warmer) lithosphere in the axial region, such as occurs at faster spreading rates, in proximity to hot spots, and in back arc basins. The evolution of oceanic microplates presents some extreme cases of ridge propagation. Microplates nucleate at transform faults, possibly in response to a nearby hot spot or changes in relative plate motion [*Bird and Naar*, 1994], and at triple junctions [*Lonsdale*, 1988]. Microplate boundaries evolve continuously and are characterized by a suite of nested propagators, compressional ridges and deep rifts, while their interiors rotate rapidly. Full coverage of microplates with sidescan imagery reveals their complex evolution [*Larson et al.*, 1992; *Searle et al.*, 1989], but to date, none has been thoroughly mapped with multibeam bathymetry.

Indicators of volcanic-dominated or tectonic-dominated activity

Areas dominated by either tectonism or volcanism display distinctive fabrics in the shipboard multibeam bathymetry. Linear fault scarps are commonly detected within the plate boundary zone and average a few to several tens of kilometers in length. In contrast, terrain dominated by volcanic activity is characterized by clusters of circular volcanic edifices, bulbous depth contours (indicating stacked lave flows), or smooth areas overprinting the surrounding abyssal hill topography (indicating effusive lava fields). Fault scarps and volcanic constructs are both well imaged, provided that their relief exceeds 50m [*Alexander and Macdonald*, 1996; *Smith and Cann*, 1990]. Clues about the freshness of the volcanic activity is provided by the acoustic backscatter routinely collected with newer multibeam systems, as unsedimented volcanic terrains produce strong acoustic returns.

A general correlation between the segmentation of the ridge axis and the supply of magma has been documented from various methods [*Macdonald*, 1998]. This relation indicates higher magma supply near the centers of ridge segments and a decreasing magmatism toward segment ends. There are notable exceptions however [*Sinha*, 1995], which may reflect temporary adjustment. In terms of bathymetry, a robust supply of magma is manifested by a shallower ridge axis. At fast spreading rates, it also correlates with a broader axial high [*Scheirer and Macdonald*, 1993], and smaller fault throw [*Carbotte and Macdonald*, 1994]. At slow spreading ridges, faults develop larger vertical throws near the shallow center of ridge segments (Fig. 3) [*Thibaud et al.*, 1999]. Careful, systematic analysis of variations in abyssal hill morphology down the flanks of a ridge axis might reveal some cyclicity in magma supply.

Multibeam surveys further indicate that local melt anomalies strongly control axial morphology. Hence, the ultra-slow spreading Reykjanes Ridge is highly influenced by its proximity to the Iceland hotspot and displays a relatively smooth topography [*Searle et al.*, 1998], not unlike the morphology of the fast-spreading East Pacific Rise. Local melt anomalies can lead to some extreme variations in axial morphology between adjacent ridge segments. Hence, the ridge segment north of the Orozco transform fault is located proximal to a prominent volcanic ridge. That segment is one of the shallowest and broadest for the entire East Pacific Rise, while the segment south of the Orozco transform fault is one of the deepest, and display a morphology akin to that of the slow spreading Mid-Atlantic Ridge (Fig. 4).

Characterizing accretionary events with microbathymetry

While shipboard multibeam bathymetry delineates volcanic systems at the kilometer scale, emerging deep-submergence technologies offer the potential to characterize eruptive vents and individual lava flows at scales of a few meters. High resolution multibeam systems mounted on remotely operated vehicles, autonomous underwater vehicles, or manned submersibles can survey anywhere from a few meters to 100 m above the seafloor and achieve very high vertical resolution and spatial sampling of seafloor features. Such recent surveys produced microbathymetric maps with vertical resolution of 10cm and pixel size of a few meters [*Chadwick et al.*, 2001; *Cormier et al.*, in press; *Johnson et al.*, 2002]. The microbathymetric data precisely outlines field relations between subtle volcanic features, faulting, and hydrothermal vents (Fig. 5). For example, they revealed systems of drained lava lakes and their associated networks of lava channels and lava tubes, and small volcanic constructs on pervasively fissured seafloor. In combination with direct observations from a submersible or a video camera, this new type of data finally makes it possible to carry out underwater geology at the same resolution that is possible on land.

Ultimately, repeated microbathymetric surveys over the same sections of ridge axis could reveal subtle changes. Such repeated surveys may precisely quantify seafloor events such as emplacement of new lava flows, tumescence or subsidence resulting from subsurface magma movements, mass wasting on steep escarpments, and fault slip or opening of fissures. Possibly, repeated microbathymetric surveys may represent an excellent strategy to achieve reliable underwater geodetic measurements.

On-going and future mapping efforts

To date, multibeam surveys have yielded an irregular patchwork of maps, with significant portions of the mid-ocean ridges remaining unsurveyed. Large sections of the Pacific-Antarctic Ridge, the southern Mid-Atlantic Ridge, the Arctic Ridge, the Southwest, Southeast, and Central Indian Ridges, the Red Sea, and the Gulf of California are only crudely charted. Most back-arc spreading centers in the western Pacific are incompletely surveyed with multibeam [*Auzende and Collot*, 1996]. The several microplates and paleo-microplates known to exist in the eastern Pacific are partially mapped with multibeam bathymetry, and detailed mechanisms controlling their evolution are not well known. Few transform faults and their fracture zone extensions are thoroughly mapped, and how they accommodate and may control changes in plate motion is debatable. Altogether, the flanks of the mid-ocean ridges remain largely unsurveyed, even though the 100-200 km of seafloor nearest the axis record the detailed tectonic history over the past 1-10 Myr. This information would be invaluable for interpreting today's axial morphology and segmentation, especially in areas where mantle plumes are proximal to the mid-ocean ridges. A complete database of multibeam bathymetry of the mid-ocean ridge would provide the necessary base maps for focused near-bottom investigations of accretionary events (volcanic, tectonic, seismic, and hydrothermal) when they are detected.

Several initiatives are underway to coordinate investigations at mid-ocean ridges. InterRidge, an initiative to facilitate international research associated with mid-ocean ridges, maintains a database of past and upcoming expeditions (http://triton.ori.u-tokyo.ac.jp/~intridge). GOMaP (Global Ocean Mapping Project; http://mp-www.nrl.navy.mil/marine_physics_branch/gomap.htm), an ambitious initiative to facilitate and coordinate the multibeam survey of the entire ocean floor, would require a firm commitment from the international community for decades to come [*Vogt et al.*, 2000]. Mapping efforts in remote areas are largely guided with the predicted bathymetry derived from satellite altimetry and scant depth soundings [*Smith and Sandwell*, 1997]. An initiative to support a dedicated altimeter mission that would double the resolution of the present data is in the planning stage (http://topex.ucsd.edu/workshop). Finally, state-of-the-art archiving of multibeam data is critical to ensure that oceanographic expeditions are planned in a cost- and time-efficient manner. GEBCO (http://www.ngdc.noaa.gov/mgg/gebco/gebco.html) and the NGDC (http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html) have a long history of compiling and maintaining such archives. More recently, national initiatives have been established to compile multibeam data acquired along the mid-ocean ridges. For example, the US RIDGE initiative (http://ocean-ridge.ldeo.columbia.edu/) and the French DORSALES initiative (http://www.ifremer.fr/sismer/program/dorsale) maintain such databases.

Acknowledgements: Bathymetric maps compiled prior to the advent of multibeam technology have inspired and guided all ensuing expeditions to the mid-ocean ridges; thanks are due to GEBCO in general and Marie Tharp in particular for their emblematic efforts. Numerous national and international funding agencies have supported mapping expeditions over the years, and the expertise of the captains and crews of research vessels around the world have guaranteed their success. Figures in this paper have been produced with the freeware GMT [*Wessel and Smith*, 1998]

Biography: Marie-Helene Cormier is associate research scientist at Columbia University's Lamont-Doherty Earth Observatory. She received her Ph.D. in 1994 from the University of California, Santa Barbara. Her work focuses on mapping the mid-ocean ridges at a variety of resolutions, and more recently, on mapping coastal areas for assessing seismic hazards.

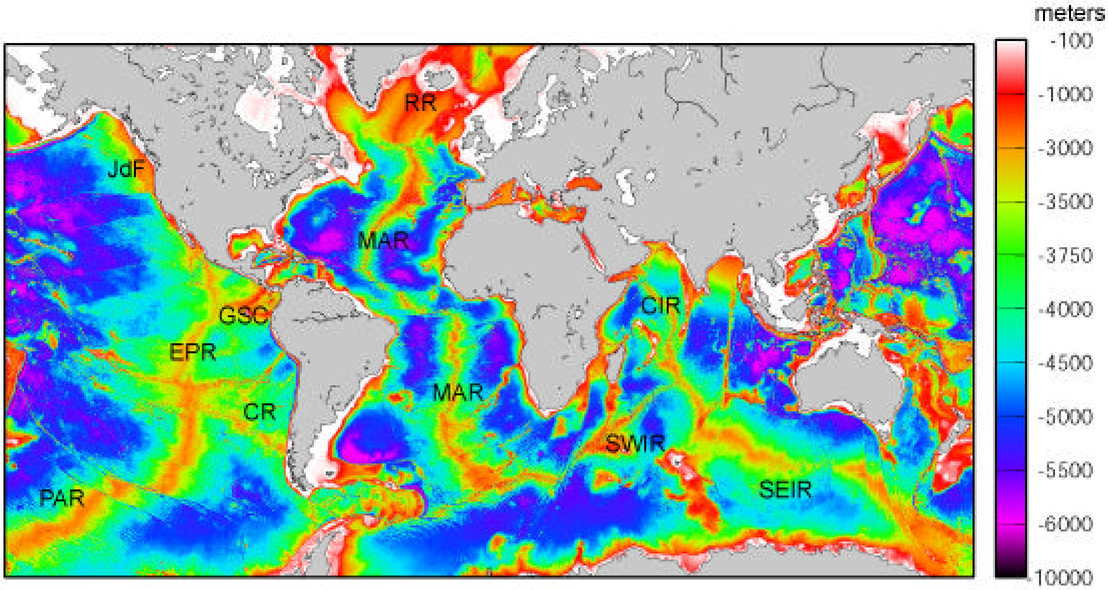

Figure 1. Predicted bathymetry of the oceans [Smith and Sandwell, 1997]. The major mid-ocean ridges are highlighted in orange. MAR = Mid-Atlantic Ridge; EPR = East Pacific Rise; SEIR = Southeast Indian Ridge; SWIR = Southwest Indian Ridge; CIR = Central Indian Ridge; JdF = Juan de Fuca Ridge; RR = Reykjanes Ridge; PAR = Pacific-Antarctic Ridge; GSC = Galapagos Spreading Center.

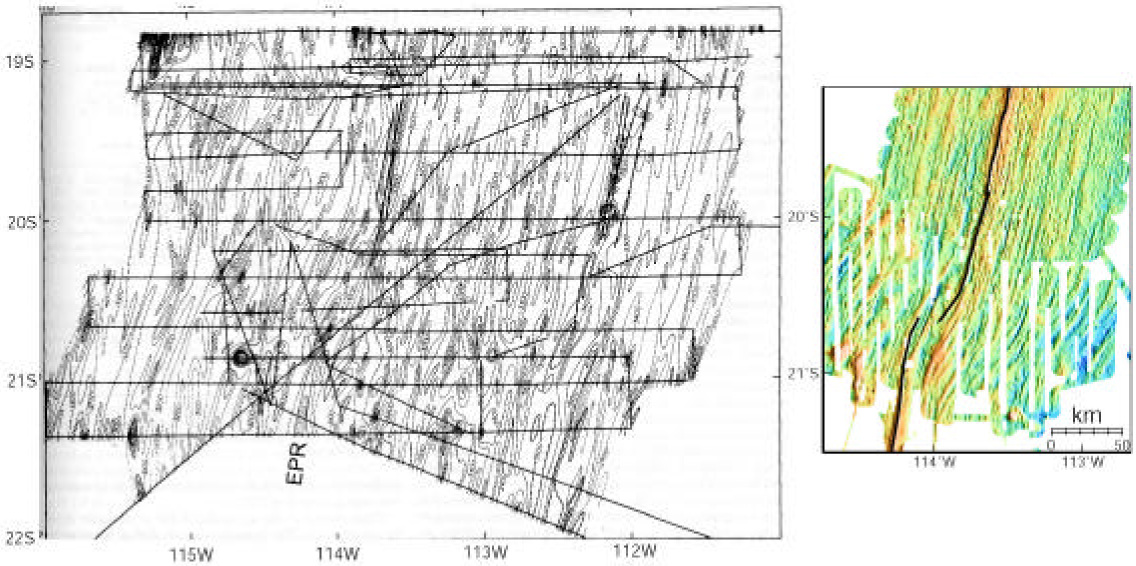

Figure 2. Comparison of conventional and multibeam bathymetry maps for the southern East Pacific Rise. (Left) A 30-km-wide non-transform offset was detected from conventional data [Rea, 1978]. (Right) Multibeam bathymetry shown at same scale reveals a large overlapping spreading centers (solid line). This discontinuity has slowly migrated southward, producing a 100-km-wide corridor of discordant seafloor fabric in its wake [Perram et al., 1993].

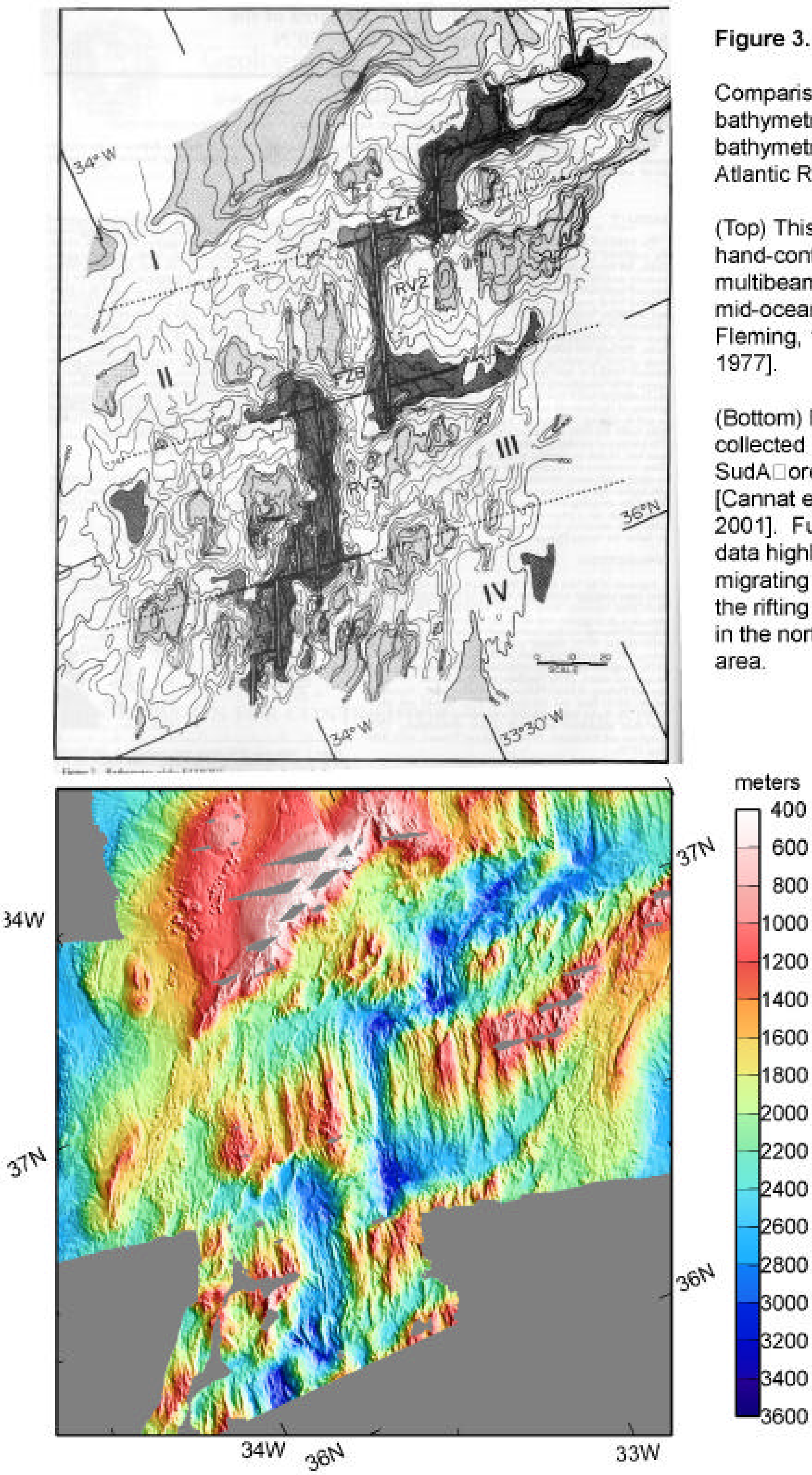

Figure 3.

Comparison of hand-contoured bathymetry and multibeam bathymetry along the northern Mid-Atlantic Ridge.

(Top) This bathymetry map was hand-contoured from one of the first multibeam bathymetric survey at a mid-ocean ridge [Phillips and Fleming, 1978; Ramberg et al., 1977].

(Bottom) Multibeam bathymetry collected recently during the SudA□ores cruise of RV L'Atalante [Cannat et al., 1999; Escart'n et al., 2001]. Full resolution multibeam data highlight fault patterns, migrating non-transform offsets, and the rifting of a large volcanic plateau in the northern half of the surveyed area.

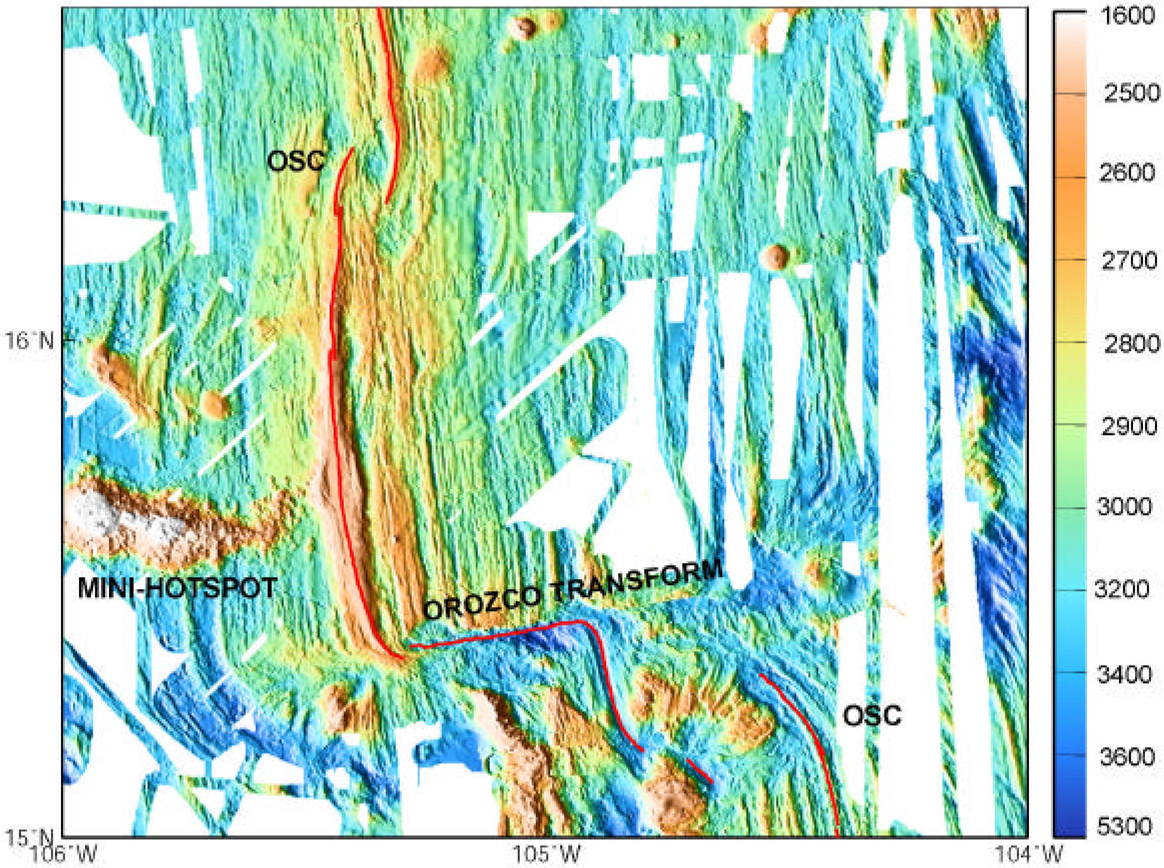

Figure 4.
Multibeam bathymetry of the northern East Pacific Rise (red lines) compiled from disparate surveys spanning the past 20 years. Map highlights the complexities of the area.
The ridge segment north of the Orozco transform fault is one of the shallowest and broadest, and has jumped westward toward a prominent volcanic ridge on at least three occasions during the past 0.5Myr. The short segment south of the Orozco transform fault is one of the deepest along the East Pacific Rise, and is display a rift valley rather than an axial high. It is overlapped to the east by another propagating ridge segment. All these ridge segments spread at sensibly the same rate of 8cm/yr. Note the lack of any well defined fracture zone trace adjacent to the active transform fault. (OSC = overlapping spreading centers).

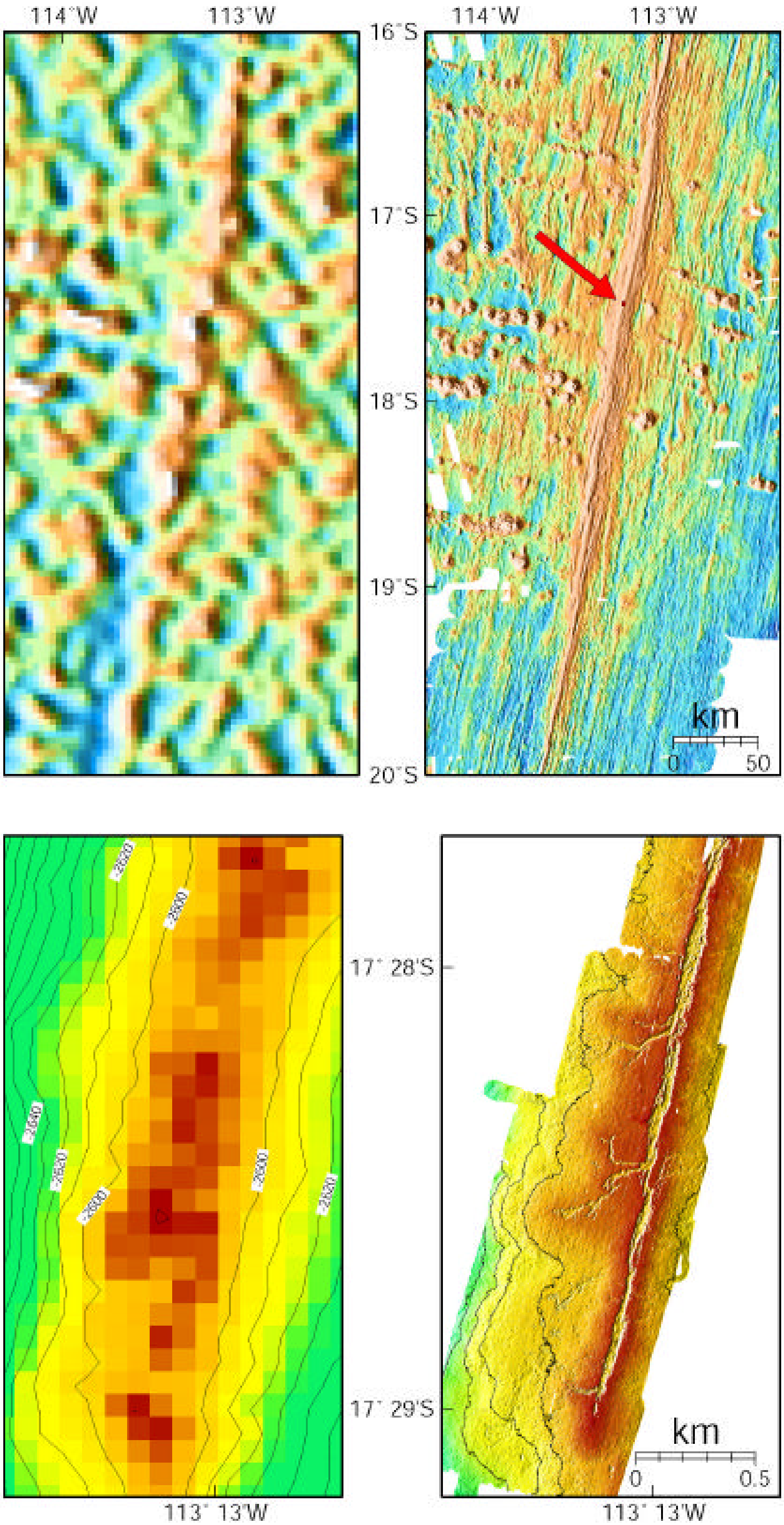

Figure 5.

Resolution of various mapping methods over the southern East Pacific Rise.

(Top left) Gravity anomaly derived from satellite altimetry [Smith and Sandwell, 1997]. Map outlines the East Pacific Rise (oreinted NNE across the map) and some EW-striking volcanic ridges on its flanks.

(Top right) Shipboard multibeam bathymetry for the same area. Map reveals a staircase of small discontinuities offsetting the ridge axis, the detailed pattern of the flanking abyssal hills, and numerous seamounts on the ridge flanks [Cormier et al., 1996]. Arrow points to small area displayed in lower two panels.

(Bottom left) Shipboard multibeam map of the rise crest. Maximum resolution is 10m vertically and 100m horizontally. Contour interval is 10m.

(Bottom right). Microbathymetry collected only 40 m from bottom for same area [Cormier et al., in press]. The narrow trough at the center is a system of drained lava lakes that developed above an eruptive fissure. The drainage pattern of the lavas issued from the system of lava lakes is clearly outlined with the microbathymetry. Contour interval is 10m.

References

Alexander, R.T., and K.C. Macdonald, Sea Beam, SeaMARC II and ALVIN-based studies of faulting on the East Pacific Rise 9°20'N-9°50'N, *Marine Geophysical Researches*, *18*, 557-587, 1996.

Anderson, R.N., D.W. Forsyth, P.T. Molnar, and J. Mammerickx, Fault plane solutions on the Nazca plate boundaries and the Easter plate, *Earth and Planetary Science Letters*, *24*, 188-202, 1974.

Auzende, J.-m., and J.-Y. Collot, Seafloor mapping in the west, southwest and south Pacific: foreword, *Marine Geophysical Researches*, *18*, 119-121, 1996.

Auzende, J.-M., R.N. Hey, B. Pelletier, D. Rouland, Y. Lafoy, E. Gràcia, and P. Huchon, Propagating rift west of the Fiji Archipelago (North Fiji Basin, SW Pacific), *Journal of Geophysical Research*, *100* (17823-17835), 1995.

Bird, R.T., and D.F. Naar, Intratransform origins of mid-ocean ridge microplates, *Geology*, *22*, 987-990, 1994.

Cann, J.R., D.K. Blackman, D.K. Smith, E. McAllister, B. Janssen, S.L.M. Mello, A. Avgerinos, A.R. Pascoe, and J. Escartín, Corrugated slip surfaces formed at ridge-transform intersections on the Mid-Atlantic Ridge, *Nature*, *385*, 329-332, 1997.

Cannat, M., A. Briais, C. Deplus, J. Escartín, J.E. Georgen, J. Lin, S. Mercouriev, C.M. Meyzen, M. Muller, g. Pouliquen, A. Rabain, and P. da Silva, Mid-Atlantic Ridge-Azores hotspot interactions: along-axis migration of a hotspot event of enhanced mamatism 10 to Ma ago, *Earth and Planetary Science Letters*, *173*, 257-269, 1999.

Carbotte, S.M., and K.C. Macdonald, Comparison of sea floor tectonic fabric at intermediate, fast, and ultra-fast spreading ridges: Influence of spreading rate, plate motions and ridge segmentation on fault patterns, *Journal of Geophysical Research*, *99*, 13609-13631, 1994.

Chadwick, W.W., D.S. Scheirer, R.W. Embley, and H.P. Johnson, High-resolution bathymetric surveys using scanning sonars: Lava flow morphology, hydrothermal vents, and geologic structure at recent eruption sites on the Juan de Fuca Ridge, *Journal of Geophysical Research*, *106*, 16075-16099, 2001.

Cormier, M.-H., W.B.F. Ryan, A.K. Shah, W. Jin, A.M. Bradley, and D.R. Yoerger, Waxing and waning volcanism along the East Pacific Rise on the millennium timescale, *Geology*, in press.

Cormier, M.-H., D.S. Scheirer, and K.C. Macdonald, Evolution of the East Pacific Rise at 16°-19°S since 5 Ma: Bisection of overlapping spreading centers by new, rapidly propagating ridge segments, *Marine Geophysical Researches*, *18*, 53-84, 1996.

Courtillot, V., Propagating rifts and continental break up, *Tectonics*, *3*, 239-250, 1982.

Edwards, M.H., G.J. Kurras, M. Tolstoy, D.R. Bohnenstiehl, B.J. Coakley, and J.R. Cochran, Evidence of recent volcanic activity on the ultraslow-spreading Gakkel ridge, *Nature*, *409* (6822), 808-812, 2001.

Escartín, J., M. Cannat, g. Pouliquen, A. Rabain, and J. Lin, Interaction of the Mid-Atlantic Ridge (36°-39°N) and the Azores hot spot, *Journal of Geophysical Research*, *106* (B10), 21719-21735, 2001.

Gente, P., R.A. Pockalny, C. Durand, C. Deplus, M. Maia, G. Ceuleneer, C. Mével, M. Cannat, and C. Laverne, Characteristics and evolution of the segmentation of the Mid-Atlantic Ridge between 20°N ands 24°N during the last 10 million years, *Earth and Planetary Science Letters*, *1229*, 55-71, 1995.

Grindlay, N.R., P.J. Fox, and K.C. Macdonald, Second-order ridge-axis discontinuities in the south Atlantic: Morphology, structure, evolution and significance, *Marine Geophysical Researches*, *13*, 21-49, 1991.

Heezen, B.C., M. Tharp, and M. Ewing, The floor of the oceans: 1. The North Atlantic, *Geological Society of America Special Paper*, *65*, 1-122, 1959.

Hey, R.N., A new class of "pseudofaults" and their bearing on plate tectonics: A propagating rift model, *Earth and Planetary Science Letters*, *37*, 321-325, 1977.

Hey, R.N., F.K. Duennebier, and W.J. Morgan, Propagating rifts on Midocean Ridges, *Journal of Geophysical Research*, *85*, 3647-3658, 1980.

Hey, R.N., and P.R. Vogt, Spreading center jumps and sub-axial asthenosphere flow near the Galapagos hotspot, *Tectonophysics*, *47*, 41-52, 1977.

Johnson, H.P., S.L. Hautala, M.A. Tivey, C.D. Jones, J. Voight, M.J. Pruis, I. Garcia-Berdeal, L.A. Gilbert, T. Bjorklund, W. Fredericks, J. Howland, M. Tsurumi, T. Kurakawa, K.-I. Nakamura, K. O'Connell, L. Thomas, S. Bolton, and J. Turner, Survey studies hydrothermal circulation on the northern Juan de Fuca Ridge, *Eos Transactions AGU*, *83* (8), 73 and 78-79, 2002.

Lagabrielle, Y., J. Goslin, H. Martin, J.-L. Thirot, and J.-M. Auzende, Multiple active spreading centres in the hot North Fiji Basin (southwest Pacific): a possible model for archean seafloor dynamics?, *Earth and Planetary Science Letters*, *149*, 1-13, 1997.

Langmuir, C.H., J.F.F. Bender, and R. Batiza, Petrological and tectonic segmentation of the East Pacific Rise, 5°30'-14°30'N, *Nature*, *322*, 422-429, 1986.

Larson, R.L., R.C. Searle, M.C. Kleinrock, H. Schouten, R.T. Bird, D.F. Naar, R.I. Rusby, E.E.E. Hooft, and H. Lasthiostakis, Roller-bearing tectonic evolution of the Juan Fernandez microplate, *Nature*, *356*, 571-576, 1992.

Ligi, M., E. Bonatti, L. Gasperini, and A.N.B. Poliakov, Oceanic broad multifault transform plate boundaries, *Geology*, *30* (1), 11-14, 2002.

Lonsdale, P., Overlapping rift zones at the 5.5°S offset of the East Pacific Rise, *Journal of Geophysical Research*, *88*, 9393-9406, 1983.

Lonsdale, P., Structural pattern of the Galapagos microplate and evolution of the Galapagos triple junctions, *Journal of Geophysical Research*, *93*, 13551-13574, 1988.

Macdonald, K.C., Mid-Ocean Ridges: Fine scale tectonic, volcanic and hydrothermal processes within the plate boundary zone, *Annual Review of Earth and Planetary Sciences*, *10*, 155-190, 1982.

Macdonald, K.C., Linkages between faulting, volcanism, hydrothermal activity and segmentation on fast spreading centers, in *Faulting and Magmatism at Mid-Ocean Ridges*, edited by W.R. Buck, P.T. Delaney, J.A. Karson, and Y. Lagabrielle, pp. 27-, American Geophysical Union, Washington D.C., 1998.

Macdonald, K.C., and P.J. Fox, Overlapping spreading centers: New accretion geometry on the East Pacific Rise, *Nature*, *302*, 55-58, 1983.

Macdonald, K.C., and P.J. Fox, The axial summit graben and cross-sectional shape of the East Pacific Rise as indicators of axial magma chambers and recent volcanic eruptions, *Earth and Planetary Science Letters*, *88*, 119-131, 1988.

Menard, H.W., Sea floor spreading, topography and the second layer, *Science*, *157*, 923-924, 1967.

Menard, H.W., and T.M. Atwater, Changes in direction of sea-floor spreading, *Nature*, *219*, 463-467, 1968.

Perram, L.J., M.-H. Cormier, and K.C. Macdonald, Magnetic and tectonic studies of the dueling propagating spreading centers at 20°40'S on the East Pacific Rise: Evidence for crustal rotations, *Journal of Geophysical Research*, *98*, 13835-13850, 1993.

Phillips, J.D., and H.S. Fleming, Multi-beam sonar study of the Mid-Atlantic Ridge rift valley, 36°-37°N, Geological Society of America, Boulder CO, 1978.

Phipps Morgan, J., and D.T. Sandwell, Systematics of ridge propagation south of 30°S, *Earth and Planetary Science Letters*, *121*, 245-258, 1994.

Pockalny, R.A., P.J. Fox, D.J. Fornari, K.C. Macdonald, and M.R. Perfit, Tectonic reconstruction of the Clipperton and Siqueiros fracture zones: Evidence and consequences of plate motion change for the last 3 Myr, *Journal of Geophysical Research*, *102*, 3167-3181, 1997.

Ramberg, I.B., D.F. Gray, and R.G.H. Reynolds, Tectonic evolution of the FAMOUS area of the Mid-Atlantic Ridge, lat 35°50'N to 37°20'N, *Geological Society of America Bulletin*, *88*, 621-636, 1977.

Rea, D.K., Asymmetric sea-floor spreading and a nontransform axis offset: The East Pacific Rise 20°S survey area, *Geological Society of America Bulletin*, *89*, 836-844, 1978.

Sauter, D., P. Patriat, C. Rommevaux-Jestin, M. Cannat, A. Briais, and Gallieni Shipboard Scientific Party, The Southwest Indian Ridge between 49°15'E and 57°E: focused accretion and magma redistribution, *Earth and Planetary Science Letters*, *192*, 303-317, 2001.

Scheirer, D.S., and K.C. Macdonald, Variations in cross-sectional area of the axial ridge along the East Pacific Rise: Evidence for the magmatic budget of a fast spreading center, *Journal of Geophysical Research*, *98*, 7871-7885, 1993.

Searle, R.C., Multiple, closely spaced transform faults in fast-slipping fracture zones, *Geology*, *11*, 607-610, 1983.

Searle, R.C., J.A. Keeton, R.B. Owens, R.S. White, R. Mecklenburgh, B. Parsons, and S.-M. Lee, The Reykjanes Ridge: structure and tectonics of a hot-spot-influenced, slow-spreading ridge, from multibeam bathymetry, gravity and magnetic investigations, *Earth and Planetary Science Letters*, *160*, 463-478, 1998.

Searle, R.C., R.I. Rusby, J.F. Engeln, R.N. Hey, J. Zukin, P.M. Hunter, T.P. LeBas, H.-J. Hoffman, and R.A. Livermore, Comprehensive sonar imaging of the Easter microplate, *Nature*, *341*, 701-705, 1989.

Sinha, M.C., Segmentation and rift propagation at the Valu Fa ridge, Lau Basin: Evidence from gravity data, *Journal of Geophysical Research*, *100*, 15025-15043, 1995.

Sinton, J.M., S.M. Smaglik, J.J. Mahoney, and K.C. Macdonald, Magmatic processes at superfast Mid-Ocean Ridges: Glass compositional variations along the East Pacific Rise 13°-23°S, *Journal of Geophysical Research*, *96*, 6133-6155, 1991.

Smith, D.K., and J.R. Cann, Hundreds of small volcanoes on the median floor of the Mid-Atlantic Ridge at 24°-30°N, *Nature*, *348*, 152-154, 1990.

Smith, D.K., M.A. Tivey, H. Schouten, and J.R. Cann, Locating the spreading axis along 80 km of the Mid-Atlantic Ridge south of the Atlantis Transform, *Journal of Geophysical Research*, *104*, 7599-7612, 1999.

Smith, W.H.F., and D.T. Sandwell, Global sea floor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1956-1962, 1997.

Thibaud, R., O. Dauteuil, and P. Gente, Faulting pattern along slow-spreading ridge segments: a consequence of along-axis variations in lithospheric rheology, *Tectonophysics*, *312*, 157-174, 1999.

Vogt, P.R., W.-Y. Jung, and D. Nagel, Meetings Report: Global Ocean Mapping Project (GOMaP), *Eos Transactions AGU*, *81*, 254 and 258, 2000.

Weissel, J.K., and D.E. Hayes, Asymmetric spreading south of Australia, Nature, 231, 1971.

Wessel, P., and W.H.F. Smith, New, improved version of Generic Mapping Tools released, *Eos Transactions AGU*, *79* (47), 579, 1998.

Wilson, D.S., Kinematics of ovelapping rift propagation with cyclic rift failure, *Earth and Planetary Science Letters*, *96*, 384-392, 1990.

Wilson, J.T., A new class of faults and their bearing on continental drift, *Nature*, *207*, 343-347, 1965.