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INSIDE

It's Only Topography: Part 2

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Editor's Note

The science article in this issue is the second of two parts, the first part of which was published in January. The article summarizes much recent work on mapping the ocean floor. Because this article represents a major synthesis of a great deal of new information, and because of space limitations in *GSA Today,* we elected to publish the paper in two parts. We do not plan to make a habit of having articles appear in two installments, however. Accordingly, the space limitations on articles for *GSA Today* will remain as they have been.

—*Eldridge M. Moores*

VOLCANISM ON MID-OCEAN RIDGES

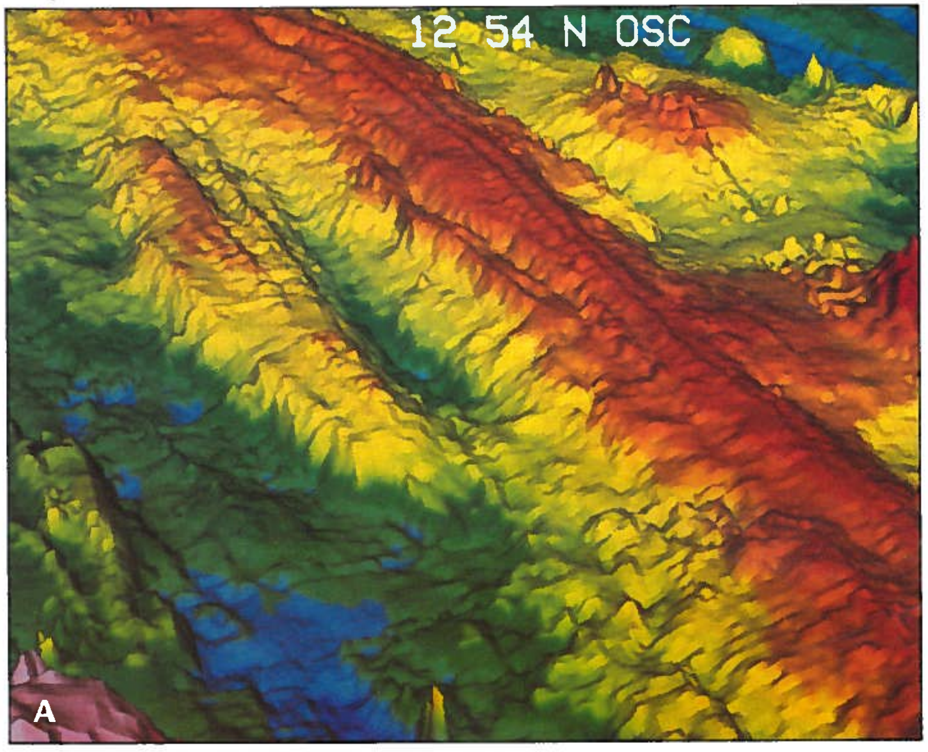
The narrow ribbon of active volcanism along spreading axes is called the neovolcanic zone (e.g., Macdonald, 1982). The neovolcanic zone is characterized by elongate axial highs tens of kilometres long at fast-spreading centers (Searle, 1984); generally shorter (depending on local magmatic budget), discontinuous volcanoes at intermediate-rate spreading centers (Luyendyk and Macdonald, 1985); and a coalesced patchwork of hundreds of small conical to slightly elongate volcanic constructions at slow-spreading centers (Smith and Cann, 1992). The zone is so narrow (~1–3 km) that axial volcanoes are occasionally split in two and rafted away as the plates separate (Macdonald et al., 1980, 1983; Kappel and Ryan, 1986). Yet the most extensive high-resolution study of a fast-spreading ridge to date shows that there are very few structures on the flanks of the East Pacific Rise which resemble the 300–400 m axial high or split halves of it. The axial elevation of the rise seems to disappear completely off-axis (Fig. 4). How can this be? The answer to this question becomes clear when one considers how the neovolcanic zone varies with spreading rate and magma supply.

The axial high on fast-spreading centers indicates that the supply of magma is steady and robust and is able to keep up with the rate of plate separation (Fig. 4). The shape and cross-section area of the axial high are sensitive indicators of the local magma supply. The reduction in cross-section area and change in shape to a narrow, triangular cross section near many discontinuities indicates a reduction in magma supply near the ends of ridge segments; conversely, magma supply is generally greater along the midsections of segments (Macdonald and Fox, 1988; Scheirer and Macdonald, 1993). Active volcanism is dominated by linear fissure eruptions along the crest of the rise and extensive outpourings of sheet flows (e.g., Choukroune et al., 1984; Macdonald et al., 1989). These lavas erupt from a long, linear trough that lies along the crest of the axial high (Figs. 4, 6A, 6B, 7). This trough is referred to as an axial summit caldera, because it is produced by collapse of the frozen volcanic carapace when underlying magma drains away, rather than by block faulting (Haymon et al., 1991a). The caldera is tens of kilometres long and typically ~50-500 m wide (Macdonald et al., 1984; Searle, 1984). Presence of the axial summit caldera (Macdonald and Fox, 1988) coincides almost perfectly with a bright, phase-reversed seismic reflector (e.g., Detrick et al., 1987; Harding et al., 1993), which is interpreted to be the roof of a crustal magma chamber beneath the rise. The caldera is also restricted to 60% of the rise where the shape and cross-section area indicate a robust magmatic budget—i.e., not near discontinuities of orders 1–3.

The axial high on fast-spreading centers has been compared to terrestrial shield volcanoes (e.g., Lonsdale, 1977). While this is a fruitful analogy for understanding the structure and morphology of many submarine volcanic products, it can be misleading, because the axial high is not a volcanic construction clear down to the Moho as is Hawaii, for example. Rather, as outlined above, the elevation of the axial high is created primarily by the buoyancy of hot rock and magma which upwell beneath the rise. For example, if the magma supply to Hawaii were cut off, the island would sink beneath the waters of the Pacific because of subsidence of the lithosphere on which it rides; however, it would not disappear if it follows the evolutionary path of its predecessors along the Hawaii-Emperor seamount chain. In contrast, the axial high at fast-spreading centers will disappear if cut off from its magma supply (Macdonald, 1990). The thickness of the accumulated volcanics is actually thinnest along the axis where the elevation is greatest (Christeson et al., 1992). Thus, while the axial high looks like a shield volcano, it is actually more akin to a long, skinny, magma-filled balloon whose diameter is a sensitive measure of magma supply. This is why we see little vestige of the axial "volcano," split or whole, on the flanks of the East Pacific Rise. As it splits in two, moves off axis and cools, most of it disappears. Only a muted representation of the axial neovolcanic zone survives off-axis (Figs. 3A, 4) (Tighe and Fox, 1991), most commonly within the discordant zones of second-order discontinuities where tips of abandoned ridges may be supported by thicker lithosphere (Fig. 4).

In contrast, significant volcanic constructional edifices may develop on the ridge axis at intermediate-rate spreading centers (40–90 mm/yr.). A more episodic magma supply (Macdonald, 1982), combined with thicker zero-age lithosphere (Purdy et al., 1992), allows axial volcanoes to be constructed and supported along the spreading axis. This thicker zero-age lithosphere also provides sufficient overburden so that normal faulting may occur right along the spreading axis (as opposed to tensional failure and collapse along the axes of most fast-spreading centers where the lithosphere is not sufficiently thick for normal faulting to occur until it has moved 2–5 km off-axis [e.g., Carbotte and Macdonald, 1990]). Thus, as spreading continues, the episodically forming axial volcano on intermediate-rate spreading centers splits by normal faulting, and the two halves of the volcano are rafted away and preserved on the flanks (Fig. 8), creating the "bow forms" found by Kappel and Ryan (1986). A direct test of this split-volcano hypothesis is that the volcanic section (layer 2A) of the oceanic crust should be thicker beneath abyssal hills than the intervening valleys at intermediate-rate spreading centers but

Topography *continued on p. 30*



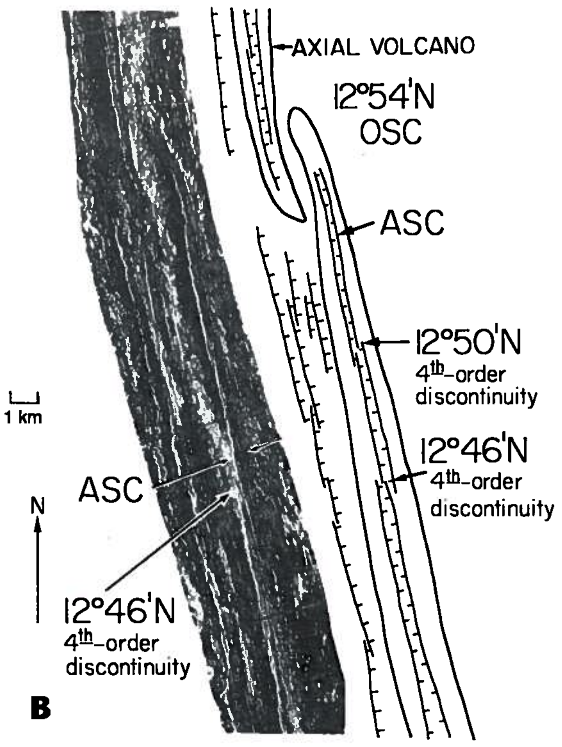


Figure 6. A: Enlarged shaded relief image (location in Fig. 3A) of the fast-spreading East Pacific Rise, 12°35'– 13°N. The 12°37'N overlapping spreading centers (OSC) is in the foreground; 12°54'N OSC is in the background. The axial summit caldera is large enough here (~500 m wide x 50 m deep) to show up as a small axis-parallel trough at the crest of the East Pacific Rise (image produced at University of California, Santa Barbara by S. P. Miller based on data from Macdonald et al. [1992]). B: Sidescan sonar image and tectonic sketch of East Pacific Rise, 12°40'–13°N showing axial summit caldera (ASC) and examples of third-order (12°54'N OSC) and fourth-order (12°50'N, 12°46'N) discontinuities.

Note: Figure 1 (in Part I of this article, *GSA Today,* January 1993, p. 1) is from National Geophysical Data Center data announcement 91-mgg-07, relief globe slides (1991).

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should have a relatively uniform thickness independent of abyssal hills on fast-spreading centers. Seismic data at fast-spreading centers (Kappus et al., 1992; Harding et al., 1993) and at intermediate-rate spreading centers (Rohr et al., 1992) support this hypothesis. These data also support topographic observations that some of the abyssal hill topography flanking intermediate-rate spreading centers may have a volcanic constructional component, whereas the relief associated with lineated hills flanking the fast-spreading East Pacific Rise developed primarily because of faulting (Lonsdale, 1977; Bicknell et al., 1988; Carbotte and Macdonald, 1990).

In contrast to magmatically robust fast- and intermediate-rate spreading centers, magmatically starved intermediate- and slow-spreading centers are characterized by a rift valley and an axial neovolcanic zone that are discontinuous (Figs. 5A, 5B) (e.g., Macdonald, 1986). Some have argued that the rift valley disappears episodically on slow-spreading ridges, so we included one of the touted examples of this disappearance in Figure 5A. The rift valley does not disappear along the entire segment; it is more than 400 m deep along 80% of its length. Near mid-segment, however, the valley shoals to a 200-m-deep half-graben, but even there it does not vanish. At slow-spreading ridges, the axial rift valley disappears along entire segments only near hot spots (e.g., Azores and Iceland) and where rare occurrences of seamount volcanism along the axis overprint the rift valley (e.g., near lat 26°S; Grindlay et al., 1991).

Sea Beam charts show that the neovolcanic zone within the rift valley inner floor is dotted by numerous small, conical volcanoes averaging 60 m in height (Fig. 5C) (Kong et al., 1988; Smith and Cann, 1992), and less commonly by long, linear volcanic ridges (Pockalny et al., 1988). In contrast to the buoyantly supported axial high at fast-spreading centers, these edifices are true volcanic constructions whose elevations are produced entirely by lava flows, primarily pillow flows (Bryan and Moore, 1977). These discontinuous conical volcanoes suggest point-source volcanism from many isolated pockets of magma, in contrast to the remarkably continuous magma reservoir beneath fast-spreading centers. Smith and Cann (1992) suggested that hundreds of these volcanoes coalesce to create the volcanic layer on slow-spreading ridges. If so, then the crust created at slow-spreading centers is a heterogeneous patchwork of lozenge-shaped volcanic units, in contrast to the more continuous "conveyor-belt" style of volcanism at fast-spreading centers. As at intermediate-rate spreading centers, some of these volcanoes split in two (Atwater, 1979), but more commonly they are dismembered, only parts of the volcanoes being preserved as "lips" at the edges of large fault blocks (Macdonald and Luyendyk, 1977; Ballard and van Andel, 1977).

USING TOPOGRAPHY TO FORECAST SEAFLOOR VOLCANIC ERUPTIONS AND AXIAL MAGMA CHAMBERS

On the basis of Sea Beam maps of the East Pacific Rise between lat 9° and 13°N, we suggested that the shape and cross-section area of a fast-spreading rise is an indirect measure of its magma supply (Macdonald et al., 1984). A narrow "triangular" cross section indicates a starved magma supply, whereas a broad dome- or rectangular-shape cross section indicates a robust supply of magma. In 1987, Detrick et al. published multichannel seismic results that were consistent with this hypothesis. A bright, phase-reversed reflector, interpreted to be the roof of a narrow crustal magma chamber, was observed 1.2–2.0 km beneath the seafloor where the rise axis is domed or rectangular in cross section, but this reflector was absent where the profile is triangular. Furthermore, we found an excellent correlation between the presence of an axial summit caldera (then called an "axial summit graben") and the magma

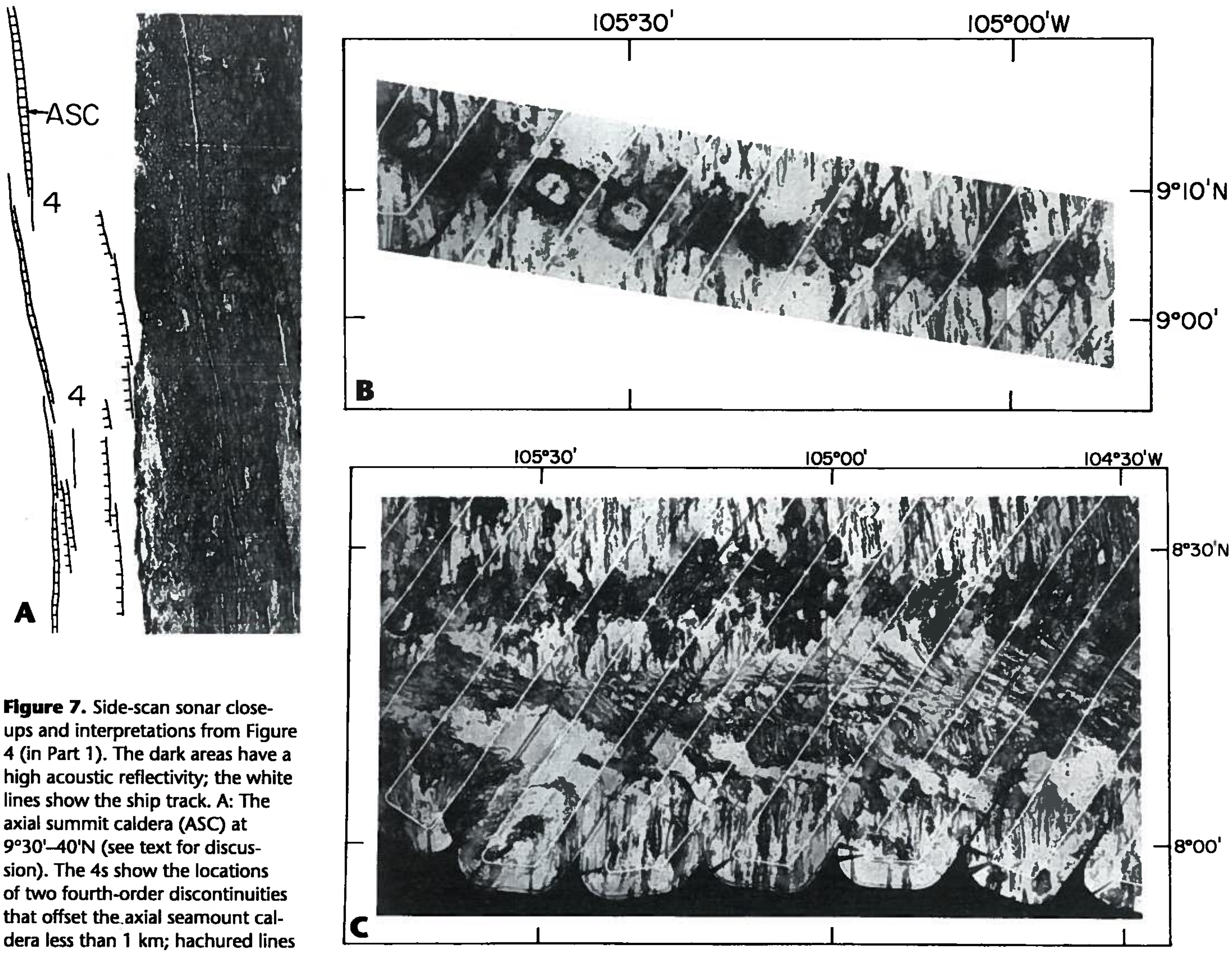

Figure 7. Side-scan sonar close-ups and interpretations from Figure 4 (in Part 1). The dark areas have a high acoustic reflectivity; the white lines show the ship track. A: The axial summit caldera (ASC) at 9°30'–40'N (see text for discussion). The 4s show the locations of two fourth-order discontinuities that offset the axial seamount caldera less than 1 km; hachured lines indicate faults; the hachures are on the down-dropped side. B: OCP seamount chain; the highly reflective hollows around the seamounts indicate lava flows that are younger than the crust they lie upon. C: The west flank of the Siqueiros Fracture Zone showing history of intratransform spreading and southward propagation of East Pacific Rise cutting across the transform, consuming one of the intratransform spreading centers (near 8°15'N, 104°40'W). Also shown is the 8°20'N seamount chain.

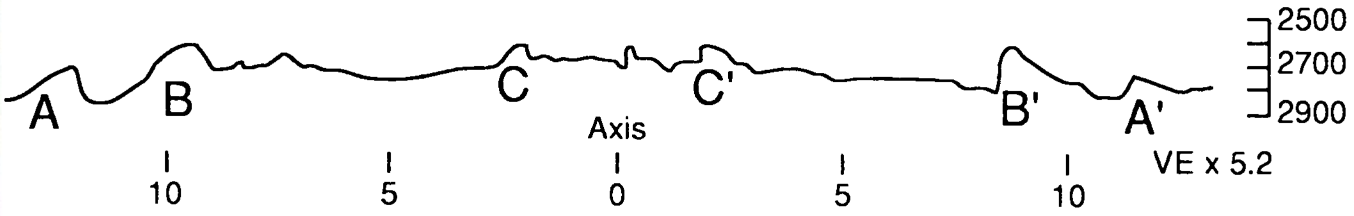

Figure 8. Deep-tow profile of the intermediate spreading rate East Pacific Rise near 21°N (Normark, 1976). A–A', B–B', C–C' represent possible split volcanic edifices, common at intermediate-rate spreading centers but rare at fast-spreading centers (see Fig. 4 and text for discussion).

chamber reflector (Macdonald and Fox, 1988). In only two locations between 9° and 13°N (9°42'–55'N and near 10°00'N) did we observe a magmatically robust, domed ridge cross section, underlain by a bright magma-chamber reflection, that was lacking a summit caldera (Fig. 9). We reasoned that these two anomalous locations were in a magmatically robust phase, swollen with underlying magma and smoothed by fresh lavas that had not yet collapsed to form a caldera. Such a location seemed to be a good candidate for a ridge that is in an active eruptive phase of its evolution (Macdonald and Fox, 1988).

In 1989, Haymon et al. (1991a) conducted a detailed ARGO visual survey of the East Pacific Rise from 9°09' to 54'N for an Ocean Drilling Program site survey. Where we had noted the absence of an axial summit caldera in 1987, there existed in 1989 a narrow caldera (40–70 m wide). Our SeaMARC II survey in 1987 did not detect the feature, indicating either that it was too small to detect with SeaMARC II (unlikely) or that caldera collapse had occurred between 1987 and 1989. During a return to the same area in April 1991, divers in the submersible *Alvin* witnessed many indications that an eruption was occurring beneath and around them (Haymon et al., 1991b and unpublished). Thriving colonies of tube worms documented during the 1989 ARGO survey were mostly buried in fresh glassy lava, but a few scorched corpses were scattered about. Crabs and other mobile predators were absent in April 1991 but were voraciously feasting on broiled tube worms in May (Haymon et al., 1991c). Large (~100 m^2) white bacterial mats grew around new hydrothermal vents. High-temperature fluids issued directly from cracks in the fresh lava flows; there had been no time for fast-growing sulfate-sulfide edifices to form. On the basis of ^{210}Po/^{210}Pb dating, the basalt samples collected at 9°50.6'N from *Alvin* during April 1–14, 1991, must have erupted during March 26–April 6, 1991 (Rubin and Macdougall, 1991). Evidence of eruption was found at several sites extending throughout the 9°42'–55' interval forecasted in 1988 (Haymon et al., 1991c), and appeared to have propagated along an eruptive fissure north to at least 9°54'N.

Buoyed by this one apparent forecast success, we inspected our southern East Pacific Rise SeaMARC II data and found two more sites where we believe eruptions are occurring or will occur very soon: near 14°30'S and between 17°20' and 30'S (Macdonald, 1991). The significant maximum in cross-sectional area (Fig. 10) and a stretch of ~20 km where the axial summit caldera is filled and not yet collapsed convinced us that the case for 17°20'-30'S was particularly compelling, so that area was presented as our next forecast at the December 1991 American Geophysical Union meeting. In the same AGU session, Detrick and Harding presented the first multichannel results for the very fast spreading East Pacific Rise at 13°–20°S (Detrick et al., 1991; Harding et al., 1991). They showed that the magma-chamber reflection is bright and narrow, and present along approximately 60% of the rise, very similar to the East Pacific Rise 9°–13°N observations. However, the reflector is shallower than the one at 9°–13°N (~1 km) and at 17°20'S, the reflector almost reaches the seafloor! When we presented the analysis of our first forecast for 9°42'–55'N and the reasoning behind our next forecast for 17°20'–30'S, Vince Renard, who had conducted three reconnaissance dives with the French submersible *Cyana* in 1984 near 17°25'-27'S (Renard et al., 1985), related how they had seen large areas of fresh glassy lava, the same mysterious white bacterial mats blowing out of fissures in the lava carapace, and hydrothermal fluids venting straight out of cracks in the lava flow, but no sulfide edifices developed yet; most of these were the same indicators of active eruption observed near 9°50'N (Haymon et al., 1991b). The sulfate-sulfide edifices grow in height at a rate of about 10 cm/day (Hekinian et al., 1984), so this limits the age of the eruption to being very recent or ongoing. We think this is a second successful forecast (of sorts) of a deep-seafloor volcanic eruption. Subsequently, a preliminary analysis of March 1992 *Alvin* dive observations near 10°N indicates that dike injection and minor volcanism may have occurred since 1991 in the 10°–10°02'N area (Macdonald, unpub. cruise report).

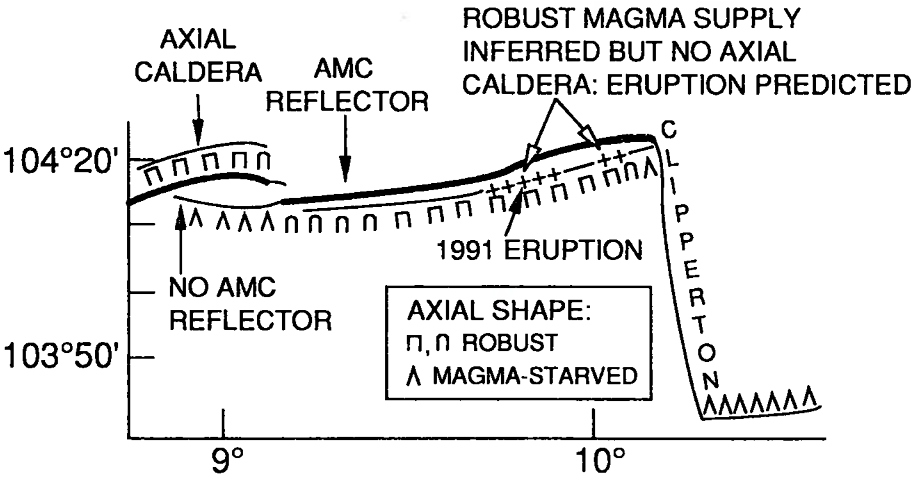

Figure 9. Enlargement of Macdonald and Fox's (1988) Figure 2 showing basis for forecast of 1991 eruption. The thick line shows the location of the axial magma chamber seismic reflector (from Detrick et al., 1987), the axial shape indicative of robust or starved magma supply as shown; the thin line parallel to the axis shows where an axial caldera is present, the plus symbol shows the regions where a cross-sectional shape indicates a robust magma supply but absence of an axial summit caldera, presumably due to recent flooding by lavas. There are only two plus regions on the East Pacific Rise between 9° and 13°N; these are the locations where volcanic eruptions were forecast (Macdonald and Fox, 1988). Most of the 9°42'–55'N region has undergone post-1989 volcanism (Haymon et al., 1991c), and a documented eruption occurred in late March–early April 1991 near 9°51'N (Haymon et al., 1991b). *Alvin* dives near 10°N in March 1992 document evidence for very recent volcanic activity here as well.

Recent seismic results also provided an opportunity to test our prediction of where axial magma chambers should be found between 3° and 23°S on the East Pacific Rise (Fig. 10) (Macdonald and Fox, 1988). We refined this prediction by making a sequence of cross-section area calculations for the rise crest at 1 km intervals along strike using our digital bathymetric data base (Scheirer and Macdonald, 1991). At the December 1991 AGU meeting, Detrick showed where the magma chamber had been imaged between 13°and 20°S (Detrick et al., 1991). In Scheirer's talk, immediately following Detrick's, the predicted magma-chamber locations, based on excessive or maximum cross-section area and shape, had a better than 80% agreement with seismic detection of a magma-chamber reflector (we had only predicted presence, not depth or width of the magma chamber). Our earlier magma-chamber prediction, based solely on shape of the axial high and presence of an axial summit caldera, was almost as successful, and the predicted locations were published in Macdonald and Fox (1988) for comparison with the seismic results. Some of the axial relief we measure may be caused by variations in the thickness of the volcanic carapace (especially at ridges that spread at an intermediate rate), reflecting a longer term average of the magma supply than is measured seismically (Harding et al., 1993). This is the most likely explanation for the 10%–20% of the ridge where our prediction method fails. In general, our forecasting method for axial magma chambers and volcanic eruptions will not work for intermediate-rate- and slow-spreading ridges, but it should work for most fast-spreading cases.

Although it is exciting to forecast submarine eruptions and the locations of magma chambers on the basis of such a simple analysis of seafloor topography, the real scientific importance is not in the forecast itself but in the successful test of two important hypotheses: (1) a distinctive morphology of the ridge axis is linked to the local magma supply, and (2) the fine-scale structure of the axial summit caldera on fast-spreading ridges is linked to the recent eruption history.

In summary, precise mapping of the shape of the seafloor near mid-ocean ridges, in concert with other studies, has revealed a great deal about the creation and tectonic processes responsible for the creation and evolution of oceanic crust. The mid-ocean ridge is segmented in a pattern that reflects magma supply. There is a hierarchy of segmentation such that short segments (~10 km) tend to be short-lived (10^2–10^5 yr), whereas long segments may last for millions of years. Presumably, the longer the segment, the deeper the source (i.e., 1000-km-long hot-spot centers tap the lower mantle, intermediate-wavelength expressions of segmentation several tens to hundreds of kilometres long tap sources in the upper mantle ~50–60 km deep). The axial high at fast-spreading centers is characterized by an axial summit caldera along its crest. The 300–400 m elevation of the high is produced by the buoyancy of hot rock and magma beneath the newly created edges of the spreading plates. The elevation is not a volcanic construction, so there is little vestige of it off-axis. At intermediate spreading rates, there is

Topography *continued on p. 34*

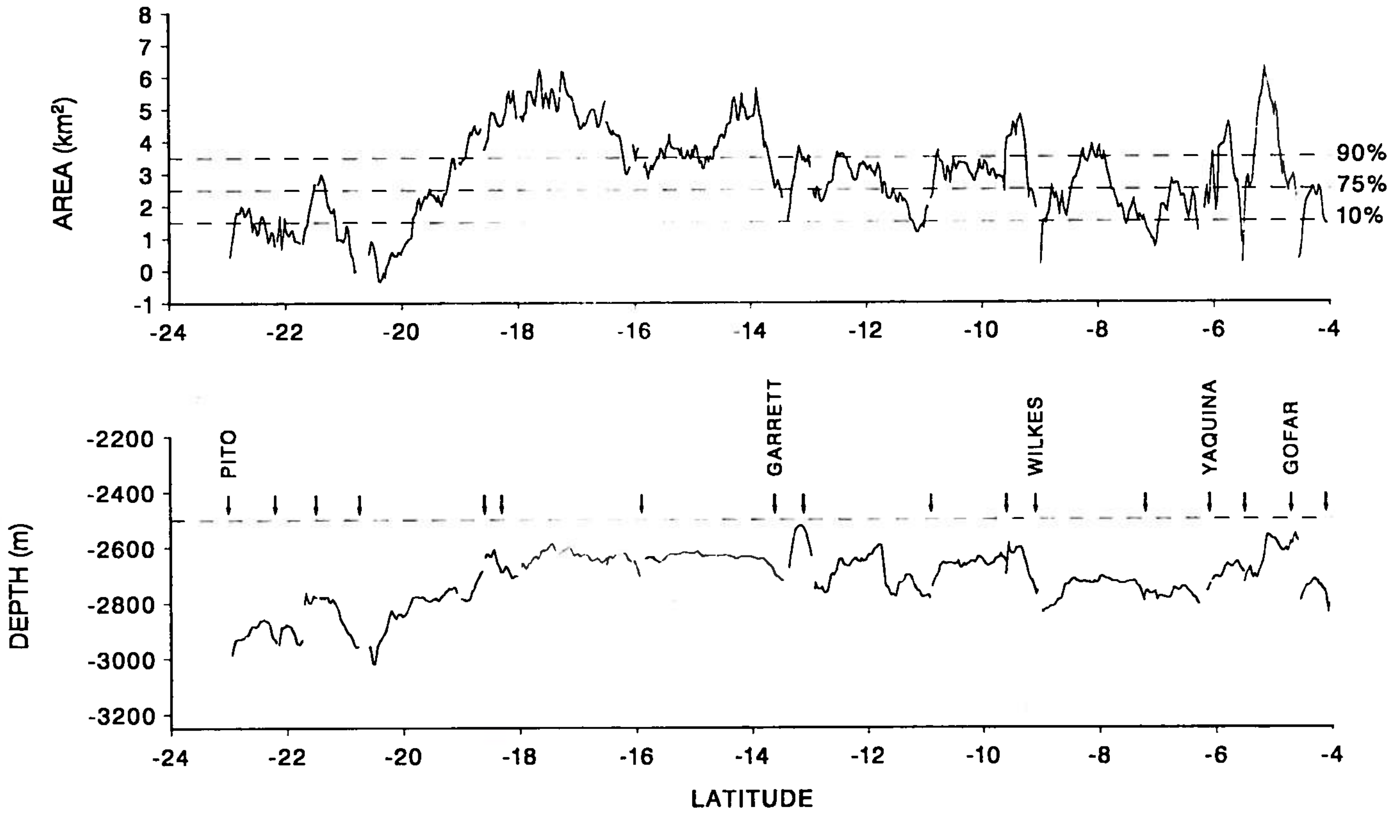

Figure 10. Axial cross-sectional area (top) and depth (bottom) profiles of the East Pacific Rise between 3° and 23°S from SeaMARC II and Sea Beam records; measurements were taken every 1 km along strike (after Scheirer and Macdonald, 1993). The arrows indicate first- and second-order ridge axis discontinuities. On the basis of the documented relation between the presence of an axial magma chamber vs. cross-sectional area for 8.8°–13°N, parts of the ridge whose cross-sectional areas fall above the 90% line (3.5 km^2) have a 90% probability of having an axial magma chamber; the same applies to the 75% and 10% lines. The prediction agrees very well with recent multichannel seismic results from the 13°–20°S area (Detrick et al., 1991).

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sufficient cooling for a volcanic edifice to develop and sufficient thickening of the lithosphere on-axis for accumulation of strain and true normal faulting to occur. Splitting of axial volcanoes and axial grabens occurs under these circumstances. Half-volcanoes, with their steep fault-bounded sides facing the spreading axis, are preserved on the flanks of the ridge. Where axial rift valleys occur, at slow-spreading centers and magma-deficient intermediate-rate spreading centers, the neovolcanic zone lies within the inner floor of the rift valley. Numerous small conical volcanoes, which may coalesce into larger edifices, and elongate ridges created by fissure eruptions contribute to volcanic constructional terrain. On fast-spreading ridges, the morphology and fine-scale structure of the ridge are sufficiently sensitive to magma supply to permit forecasts of magma-chamber locations and even eruptions.

These are only a few examples, taken mostly from our own research, of how useful precise measurements of seafloor topography can be. Many other examples could be cited; determining the history of and changes in plate motion; determining the relative importance of faulting, volcanism, sedimentation, and mass wasting in shaping the ocean floor; exploring the causes of linear seamount chains, and so on (e.g., Searle, 1992). Satellite measurements have also provided low-resolution glimpses of large uncharted areas of the seafloor (Marks et al., 1991). While we have emphasized the importance of topographic measurements, marine geology–geophysics is very much an interdisciplinary area of research, and the charts and structural maps reviewed here provide a common base that draws together geochemists, seismologists, structural geologists, and even biologists and chemists. We hope to catch up, before the end of the millennium, with the successful mission to map the surface of Venus. The long-term goal is the construction of a global-scale-high resolution map of the seafloor that will define patterns of crustal evolution during the past 200 m.y. and provoke fundamental insights into processes that shape the planet in space and time.

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CALL FOR NOMINATIONS

Officers and Councilors

The GSA Committee on Nominations requests your help in compiling a list of GSA members qualified for service as officers and councilors of the Society. The committee requests that each nomination be accompanied by basic data and a description of the qualifications of the individual for the position recommended (vice-president, treasurer, councilor).

Nominations for 1994 officers and councilors must be received at GSA headquarters no later than **FEBRUARY 15, 1993.** Please send nominations and back-up material to the Administrative Department, Geological Society of America, P.O. Box 9140, Boulder, CO 80301.

Penrose and Day Medals, and Honorary Fellowship

Nominations for GSA's Penrose and Day Medals and for Honorary Fellowship in the Society are due at headquarters by **FEBRUARY 1, 1993.**

For procedures and additional information, please refer to the October 1992 issue of *GSA Today,* or call headquarters at (303) 447-2020.

Send your nominations and required back-up material to the Administrative Department, Geological Society of America, P.O. Box 9140, Boulder, CO 80301.

Young Scientist Award (Donath Medal)

The Young Scientist Award was established in 1988 to be awarded to a young scientist (35 or younger during the year in which the award is to be presented) for outstanding achievement in contributing to geologic knowledge through original research that marks a major advance in the earth sciences. The award, consisting of a gold medal called the Donath Medal and a cash prize of $10,000, was endowed by Dr. and Mrs. Fred A. Donath.

For the year 1993, only those candidates born on or after January 1, 1958, are eligible for consideration. In choosing candidates for the Young Scientist Award, scientific achievement and age will be the sole criteria. Nominations for the 1993 award must include

- biographical information,
- a summary of the candidate's scientific contributions to geology (200 words or less),
- a selected bibliography (no more than 10 titles),
- supporting letters from five scientists.

Nominations for the 1993 Young Scientist Award must be received at GSA headquarters by **FEBRUARY 1, 1993.** For procedures and additional information, please refer to the October 1992 issue of *GSA Today,* or call headquarters at (303) 447-2020.

Distinguished Service Award

The GSA Distinguished Service Award was established by Council in 1988 to recognize individuals for their exceptional service to the Society. GSA Members, Fellows, Student Associates, or, in exceptional circumstances, GSA employees may be nominated for consideration. Any GSA member or employee may make a nomination for the award. Awardees will be selected by the Executive Committee, and all selections must be ratified by the Council. Awards may be made annually, or less frequently, at the discretion of Council. This award will be presented during the Annual Meeting of the Society. Nominations and any supporting information may be addressed to Executive Director, Geological Society of America, P.O. Box 9140, Boulder, CO 80301. Deadline for nominations for 1993 is **MARCH 1, 1993.**

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