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FINAL REPORT
ONR Grant N00014-90-J-1043**Variations in Tectonic Extension Along Slow-Spreading Ridge Axes: Implications for the Internal Structure and Bathymetry of Oceanic Crust****Jeffrey A. Karson**Department of Geology
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(919) 684-2731**Introduction**

In contrast to fast-spreading mid-ocean ridge segments where a more or less continuous magma supply exists, slow-spreading ridges are characterized by variable periods of amagmatic plate separation. This results in mechanical extension that is very similar in geometry and kinematics to that of well studied continental extensional terranes. The longer the period of amagmatic spreading, the greater the degree of mechanical extension. In some places on slow-spreading ridges, for example the FAMOUS area, the sputtering magma supply may almost completely bury and heal the disruption accomplished by faulting and ductile deformation processes. Elsewhere, for example parts of the MARK Area, long periods of amagmatic spreading, "magmatic droughts", result in highly extended terranes similar to those found in "metamorphic core complexes" of back-arc basins and the most highly stretched continental rifts. Mechanical extension typically reaches sufficient magnitudes to expose even lower crustal and upper mantle lithologies in regions of very low magma supply.

Exposures of coarse-grained plutonic rocks (i.e., gabbroic rocks and serpentized peridotites) are now known to exist along some portions of the median valley wall of the Mid-Atlantic Ridge and also along several ridge-parallel escarpments in older lithosphere. Furthermore, DSDP and ODP crustal drilling in lithosphere created at slow-spreading ridges has revealed similar lithologies at crustal depths of only a few tens to hundreds of kilometers. By analogy with ophiolite complexes and other basaltic igneous provinces such as Iceland and the East African Rift, such coarse-grained rocks have probably been exhumed from depths of at least 1.5 km. Such exposures can only result from tectonic unroofing caused by faulting. The geometry, kinematics and chronology of this faulting can be constrained by geologic maps of plutonic rock exposures, the examination of their fine-scale structures (shear zones, foliations, lineations, etc.), petrographic and petrologic characteristics and the integration of these geological data with morphological and geophysical data. This study has sought to demonstrate the importance of these geological details in the long-term goal of understanding the nature of faulting along spreading centers.

New morphologic maps of the Mid-Atlantic Ridge clearly show the segmented form of the plate boundary with symmetrical and asymmetrical rift segments separated by a variety of discontinuities completely analogous to the accommodation zones of continental rifts. A major outstanding question that

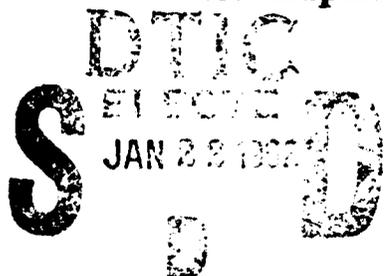
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arises concerns how faults are related to the differently shaped rift segments and the intervening discontinuities. From these observations and the results of the present study it is clear that focussing on a single study area that can be dissected and analyzed in great detail would probably yield a wealth of new information, but still leave much work to be done. This is because the style and magnitude of tectonic extension varies so dramatically along strike. Again drawing on modes of crustal deformation observed in continental terranes, different ridge segments require linking structures referred to generally as *transfer zones*. The extensional and transfer structures probably interact as *extensional systems* with complex 3-D geometries and kinematic histories. One of the most important future contributions to the understanding of seafloor spreading on slow-spreading ridges is to establish the surface geology within the morphologic framework. Similar studies are proceeding in parallel in continental rifts and there is a great potential for the cross-pollination of new ideas from these two domains.

Only hints of the fault structure of slow-spreading ridge axes are found in multi-narrow beam bathymetric and side-scan sonar morphologic maps. Models for the creation of mid-ocean ridge morphology and off-axis seafloor bathymetry typically disregard the types of geological data such as exposures of plutonic rocks and major fault zones with kilometers of horizontal displacement. Realistic models must be consistent with all available geological and geophysical data.

Project Objectives

In several localities, detailed near-bottom investigations of the geology of slow-spreading mid-ocean ridges have been carried out. These have made available a substantial amount of information regarding the fault geometry and kinematics in these isolated areas. The objective of this project is to synthesize these data with available constraints from geophysics to document the style of tectonic extension at various points along spreading centers and to elucidate the 3-D form of extensional systems that accommodate mechanical extension. These data have been integrated into models for the development of rift valley and off-axial seafloor bathymetry. The structural geometry of continental rifts with different magnitudes of mechanical extension and elastic parameters provide important guides for these interpretations.

Results

During the first year of this project a significant amount of time was committed to gathering necessary data from mid-ocean ridge spreading centers and to making some first attempts to create a family of models for structures that are likely to exist along slow-spreading ridges. This resulted in number of papers and presentations that present likely structural geometries for parts of the Mid-Atlantic Ridge.

The second year of the project concentrated on integrating various data sets and writing up the results. New multichannel seismic data from the ridge axis in the MARK Area (24°N) as well as some older parts of the Central North Atlantic have provided a window into the internal structure of the oceanic crust. Along with Dr. J.C. Mutter of Lamont-Doherty Geological Observatory, the integration of geologic and seismic structures in these areas have provided compelling new evidence of the complex development of extensional systems at the ridge axis and their role in the architecture of mature oceanic crust. Linking the surface geology

of the Mid-Atlantic Ridge to this multichannel seismic data has provided a 3-D view of slow seafloor spreading through time and some very surprising new considerations. These include the following points. 1. Major low-angle detachment faults are very common in slow-spread crust but absent in fast-spread crust. 2. The implied extension factors demand that either much of the oceanic crust is serpentinite or that very thick crust created at the ridge axis has been reduced in thickness by stretching. 3. Accommodation (transfer) zones are not necessarily steep fault zones, but in fact are more likely to be much more complex structures ranging from simple monoclines to gently dipping strike-slip faults ("lateral ramps"). 4. Symmetrical segments of the Mid-Atlantic Ridge can be created in at least three very different ways with very different structural histories. 5. The volcanic budget and periodicity varies dramatically along the ridge axis (major eruptions at <10,000 yr to >200,000 yr) and controls the structural style. 6. Ridge transform intersections are regions of typically low magma budget and hence areas where extreme faulting and crustal unroofing typically occur; thus plutonic rocks found in fracture zones are probably exposed by extensional faulting at ridge-transform intersections rather than strike-slip tectonics.

Two papers reporting these results are in the final stages of preparation and will be submitted to *Science* and *Reviews of Geophysics* in January 1992. From these results, it is clear that traditional views of processes along slow-spreading ridges that assumed only small amounts of mechanical extension on steep faults and a simple volcanic/tectonic cycle of activity are at best gross oversimplifications.

Publications

1. Papers submitted to reviewed journals:

Karson, J.A. Accommodation Zones and Transfer Faults: Integral Components of Mid-Atlantic Ridge Extensional Systems, *Proceedings of the Oman Ophiolite Symposium, Ophiolite Genesis and Evolution of Oceanic Lithosphere, Tectonophysics* (in press).

Karson, J.A. and Winters, A.T. Along-Axis Variations in Tectonic Extension and Accommodation Zones in the MARK Area, Mid-Atlantic Ridge 23°N Latitude, *Geological Society of London* (in press).

2. Chapters in books:

Karson, J.A. and Fox, P.J. The Distribution of Rocks in Oceanic Fracture Zones: Implications for Crustal Structure, In: *The Tectonics of Oceanic Fracture Zones*, edited by P.J. Fox, Academic Press, London (in review).

3. Presentations at Scientific Meetings (speaker underlined):

Cannat, M., Mevel, C. and Karson, J., 1990. Direct evidence for lithospheric stretching at present day slow spreading ridges, *Symposium on Ophiolite Genesis and Evolution of Oceanic Lithosphere (Sultanate of Oman)*, Abstract Volume.

Karson, J.A., 1990. Accommodation Zones in Oceanic Lithosphere: Kinematic Requirements of Seafloor Spreading, Symposium on Ophiolite Genesis and Evolution of Oceanic Lithosphere (Sultanate of Oman), Abstract Volume.

Karson, J.A., 1990. Extensional Systems on the Mid-Atlantic Ridge, Symposium on Ophiolites and Their Oceanic Analogues, Geological Society of London, Abstract Volume.

Karson, J.A., 1990. Tectonic Disruption of Volcanic Units of the Oceanic Crust, Workshop on the Physical Properties of Volcanic Seafloor, Woods Hole Oceanographic Institution, April 1990 (extended abstract).

Karson, J.A., 1990. Submersible Observations of Oceanic Crust Produced at Fast- and Slow-Spreading Ridges, Symposium on the Evolution of Oceanic Lithosphere, Institute of the Lithosphere, Academy of Sciences U.S.S.R., Dagomys, November

Mevel, C., Auzende, J.-M., Cannat, M., Gente, P., Karson, J.A., Marion, E., and Tartarotti, P., 1990. Variation of Crustal Thickness Along Axis: The Example of the MARK Area (23°N, M.A.R), Symposium on the Evolution of Oceanic Lithosphere, Institute of the Lithosphere, Academy of Sciences U.S.S.R., Dagomys, November 1990.

Karson, J.A., 1991. Magmatic Droughts on the Mid-Atlantic Ridge: Plutonic Rocks Exposed by Intervals of Amagmatic Spreading, American Geophysical Union, Fall Meeting (San Francisco), EOS, v. 72, p. 471.

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4. Non-referred papers and technical reports:

Karson, J.A., 1992. Tectonics of Slow-Spreading Mid-Ocean Ridges, *Oceanus* (in press).

Karson, J.A., 1991. Tectonic Disruption of Volcanic Units of the Oceanic Crust, In: Proceedings of a Workshop on the Physical Properties of Volcanic Seafloor, edited by G.M. Purdy and G.J. Fryer, Woods Hole Oceanographic Institution, p. 138-142.

Karson, J.A., 1991. Geologic Processes Along Slow-Spreading Ridge Axes and Their Potential as Seismic Sources, In: Characterization of Mid-Ocean Ridge Earthquake Activity Using Acoustic Data from U.S. Navy Permanent Hydrophone Arrays, convened by G.M. Purdy, **Ridge Inter-Disciplinary Global Experiments**, Woods Hole Oceanographic Institution, p. 26-29.

5. Papers in preparation:

Karson, J.A., 1992. Geometry and Kinematics of Extensional Systems on the Mid-Atlantic Ridge. *Reviews of Geophysics* (to be submitted in January 1992).

Mutter, J.C. and Karson, J.A., 1992. Structural Processes at Slow-Spreading Ridges. (to be submitted to *Science* in January 1992).