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SEAFLOOR CHARACTERIZATION / GALAPAGOS PROPAGATING RIFT

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Long-Range Scientific Objectives

Our goal is to better understand the system that produces the oceanic crust. Because the seafloor is a product of this system we believe that fundamental insight can be gained through the study of seafloor topography and the spatial variation in its characteristics.

Project Objectives

Our project has focused on applying and further developing our techniques for analyzing seafloor topography and combining our techniques for seafloor characterization with other data sources (e.g., seismicity) and models.

Accomplishments

1. Fault Patterns and Ridge Segmentation

Recognizing that normal faulting is one of the most significant processes that modifies oceanic lithosphere and contributes to seafloor topography, we have developed an analysis for identifying individual normal faults. Both normal faults and volcanism are capable of creating steep topographic slopes; however, only faulting produces sharp edges characteristic of the upthrust foot-wall block. We identify faults by measuring topographic curvature within a small analysis patch: a threshold set to match the sharp fault corners but exclude constructional volcanism. This method allows topography from these two processes to be separated. The distribution of faults identified in this manner provides key information regarding the tectonic origin and history of a region of seafloor.

A number of insights into the formation of the Galapagos propagator are revealed by this type of analysis. The propagator tip is itself a fault that cracks into "normal" lithosphere. The pseudofault wakes are also composed of a series of en echelon faults, although this is more well-developed in the northern pseudofault. Associated with this asymmetry is the marked difference in the normal faulted abyssal hills created to the north and south of the propagating tip, with the abyssal hills to the south cut by much larger and well-developed faults than to the north. In the region of transferred lithosphere, individual faults are seen to rotateas the shearing process modifies the lithosphere, reactivating the faults in a system of bookshelf tectonics. Less pronounced faults are found in the lithosphere that has passed through the shear zone, as reverse faulting and/or mass-wasting processes subdue the relief. Significant along-axis variations exist in the spatial dimensions of faults, such as their throw and horizontal spacing; these are readily quantified using a suite of curvature measurements at different spatial scales. The largest faults occur at the ends of ridge segments, most notably at the "inside corners" discussed by Tucholke and Lin (JGR, in press, 1993). Normal faults thus appear to be a reliable indicator of lithospheric strength, with the largest-throw faults occurring at the coldest, strongest lithosphere. The large faults in the Galapagos region are mapped using a window of 1.3 k. Highlighted faults occur at the "inside corner" of the active ridge segment. The large failed rift tips also are prominently highlighted at this scale.

We applied our earlier-developed slope analysis techniques to bathymetry from the Galapagos 95°W propagator system. This both confirmed the value of the methods (and led to insights into mechanisms of lithospheric deformation, as described in part in the next section). We compared the determination of seafloor fabric by rapid automated slope analysis and by thorough, but painstaking, manual interpretation (from Kleinrock and Hey, JGR, 1989). The automated method did an excellent job of characterizing the complex seafloor fabric in this region. We also use these quantified characteristics to perform automated strain analysis.

2. Lithospheric Transfer, Rheology, and Faulting

We have extended our work studying the deformation mechanisms involved with lithospheric transfer at propagators and other non-transform offsets to include seismicity and theoretical models, as well as seafloor structural analysis.

In Wetzel, Wiens, and Kleinrock (Nature, 1993), we show that there is a strong correlation between the distribution of teleseismic earthquakes, faulting mechanisms determined from these quakes, and structural lineaments on the seafloor. Combined earthquake and morphological data are compatible only with the "bookshelf tectonics" model for lithospheric transfer promoted by Kleinrock and Hey (J. Geophys. Res., 1989) and Phipps Morgan and Kleinrock (Tectonics, 1991), and incompatible with several other proposed styles of lithospheric transfer. Similar patterns are observed wherever there is significant seismicity at large non-transform offsets at medium to fast spreading ridges. The observed strike-slip earthquakes with fault planes oblique to plate motion constitute a new type of fault geometry for earthquakes along mid-ocean ridges, distinct from well-known strike-slip transform and ridge-parallel normal faulting. These results suggest that bookshelf faulting is the dominant mode of lithospheric deformation within large non-transform offsets of medium- and fast-spreading ridges.

Having documented the dominance of the bookshelf faulting at large non-transform offsets of the faster ridges, we compared the mechanism of lithospheric transfer at these offsets with the mechanism of transfer at larger and smaller ridge offsets. There is a clear break in the style of lithospheric transfer as a function of age offset across the ridge offset. The bookshelf faulting mechanism ("B") occurs at large offsets. A "chunking" mechanism ("C"), wherein episodic extension of one spreading segment tears pieces of crust off one plate and leaves them undeformed on the other plate, occurs at smaller age offsets. Microplate tectonics ("M"), involving long-term overlap of two spreading systems with progressive growth and rotation of a rigid microplate before the ultimate abandonment of one of the ridges, occurs at very large age offsets (greater than ~2 m.y.)

At Galapagos 95°W, our analysis indicates that bookshelf tectonics has been the dominant mechanism of transfer since ~0.9 Ma. Prior to that, when the ridge offset was less than about 10 km (~0.3 Myr), chunking appears to have been dominant. This corresponds to the transition observed between the chunking and bookshelf regimes observed in the Pacific compilation. Similarly, the change from bookshelf to microplate modes at the East Rift of the Easter Microplate seems to have occurred at the corresponding transition in the Pacific compilation. For at least medium and fast spreading environments, age offset is a critical parameter for predicting deformation style, and hence characteristics of basement topography, at a migrating ridge axis discontinuity.

This pattern is inferred to result from changes in physical properties of the lithosphere as it ages. Consider the magnitude and anisotropy of lithospheric strength as a function of depth for different lithospheric ages. When accreted initially at the ridge axis, upper crust is fairly strong and isotropic, and is decoupled from the mantle by a weaker, ductile lower crust. If most of the lithosphere being transferred has this rheology, chunking may transfer this rigid lithosphere. Faulting that generates abyssal hills imposes a rheological anisotropy on the lithosphere, weakening it in a direction perpendicular to the faults. This allows bookshelf tectonics to pervasively shear lithosphere during transfer. With age, the brittle-ductile boundary deepens, and no ductile lower crust remains. Brittle, strong, rheologically isotropic mantle is accreted to the bottom of the plate, significantly strengthening the whole lithosphere. Such lithosphere cannot deform, so microplate tectonics dominates.

3. Seamounts andVolcanic Knobs on Abyssal Hills

Sea Beam bathymetry data show that the floor of the median valley of the slow-spreading Mid-Atlantic Ridge (MAR) is covered with small seamounts: 481 seamounts with heights between 50-650 m were identified in 6000 km^2. The summit height distribution of the MAR population (Figure 2) is consistent with the exponential frequency-size distribution model for off-axis eastern Pacific seamounts [Jordan et al., JGR, 1983; Smith and Jordan, JGR, 1987]. According to the exponential model one thousand square kilometers at the MAR contains, on average, approximately 195 seamounts of all sizes, with the characteristic height of the seamount population being about 60 m. For comparison, Smith and Jordan [1988] estimated for the eastern Pacific a density of about 5 seamounts per thousand square kilometers, and a characteristic height of approximately 285 m. We conclude that the large abundance of seamounts on the median valley floor of the slow-spreading MAR indicates that seamount volcanism plays an important role in the accretionary processes along the ridge. The fact that the characteristic height of the MAR population is about one-fourth the size of the off-axis eastern Pacific population probably reflects the fact that most large seamounts are formed away from the axis presumably because as the lithosphere thickens with crustal age its strength increases sufficiently to support larger edifices or because magma sources lie at deeper levels.

Characterization of volcanic knobs observed in Sea Beam bathymetry near the 95°W Galapagos propagator system on the Cocos-Nazca spreading axis provides insight into volcanic and tectonic processes at propagators and mid-ocean ridges, as discussed in Kleinrock and Brooks (Geophys. Res. Lett., in press, 1993). A quantitative analysis of the seamount population at the medium-spreading Galapagos propagating rift indicates that the exponential height distribution model also well approximates the Galapagos seamount data. Despite evidence suggesting a higher magma supply rate at the propagator axis, crust accreted there contains fewer knobs than crust created at the failing or doomed spreading axes. Fissure-fed flows rather than seamount construction are more important along the propagator. The process of transferring lithosphere via bookshelf faulting from one plate to another as this ridge offset migrates through a region destroys about half of the knobs on preexisting crust. Sparse data tentatively suggest that at slow and intermediate spreading rates on-axis volcanic cones increase in size and contribution to crustal construction but decrease in abundance with decreasing spreading rate.

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4. Magma Bodies

Kilauea Iki is an extensively studied passive lava lake formed during the 1959 eruption of Kilauea Volcano. The lava lake magma body has been the site of a time-series of boreholes, with core recovery near 100% for each of the 23 deep holes drilled since 1967. Geophysical studies including active and passive seismics and electromagnetic profiling have yielded remotely-gathered images of the lake contents. In Barth, Kleinrock, and Helz (J. Geophys. Res., in press, 1993), we present an overview of the geological and geophysical observations from the lava lake, including some new data, and a reinterpretation of the results. Despite the fact that the analogy is imperfect, observations at Kilauea Iki lead to insights into processes at mid-ocean ridge magma chambers. The data suggest fine structure at the top of the mid-ocean ridge magma body in the form of horizontal segregation veins (e.g., sills) and indicate that sustained convection at a mid-ocean ridge magma chamber is highly unlikely. The lava lake also exhibits a dry-out zone above the magma body and below the deepest penetration of hydrothermal circulation; a similar zone may exist under mid-ocean ridge conditions. Physical and petrologic constraints at the lava lake and at mid-ocean ridges strongly suggest very rapid and frequent replenishment of mid-ocean ridge magma chambers at high magma supply ridges where quasi-steady-state melt zones are present.

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