

Ocean Drilling and Exploring a Heterogeneous Ocean Crust

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Abstract

Exploration of the ocean crust at slow and ultraslow spreading ridges over the last decade has transformed the paradigm for the ocean crust. While most scientists hold to a model for a layered Pacific crust of a thick gabbro layer overlain by dikes and basalts, this is not true for slower ridges. At the latter, we find that spreading occurs in new modes by detachment faulting and amagmatic rifting. This creates large regions where mantle is exposed on the sea floor, regions where lower crust consists of isolated magma bodies intruded into peridotite, and regions with layered ocean crust. While more crust is created at the EPR, slower ridges are the largest class by length, and ~half of the extant ocean crust formed at them. Due to tectonics, rough topography, and variation in crustal structure, large areas of the sea floor at slower ridges are paved by mantle peridotite and deep crustal rocks that are far more reactive than the basaltic floor of the Pacific. Thus, hydrothermal circulation and weathering may have greater impact on ocean chemistry. Due to long-lived faults, hydrothermal deposits are far larger than at the EPR, with a greater range in composition, and economic potential. The lower crust must differ significantly from the overlying basalts, yet nowhere in the oceans is its composition known. At the same time, accretionary processes at slower ridges are very different, even as erupted basalts differ. Thus understanding the diversity of crustal structure and composition across the full oceanic spectrum is a fundamental to understand the Earth, with significant human impacts. This requires a full penetration of the lower crustal in a magmatically robust environment to determine its composition and the nature of Moho at slow spreading ridges, and drilling short (~500-m) holes into crust in regions of strongly contrasting seismic structure in tectonic windows to validate the combined use of sea floor mapping and sampling and seismic refraction to explore crustal variability.

Ocean Drilling and Exploring a Heterogeneous Ocean Crust

Crust formed at the mid-ocean ridges extends across some three fifths of the planet and comprises approximately 30% of the Earth's crust. Ocean ridges constitute the major locus for the exchange of heat, mass and volatiles from the Earth's interior to the crust, oceans and atmosphere through magmatism, hydrothermal circulation and sea floor weathering, and ocean crust represents the major input recycled back to the Earth's interior at subduction zones. Thus knowledge of the composition and variability of the ocean crust is key to understanding the Earth's geochemical cycle. While the rate of crustal production is significantly larger at the fast-spreading East Pacific Rise, slow and ultra slow spreading ridges by length are the largest class of ocean ridge, and about half of the extant ocean crust has formed at them. Moreover, due to far greater tectonic activity, rough topography, and variation in crustal structure and composition, extensive areas of the sea floor at slow and ultraslow spreading ridges are paved by mantle peridotite, and deep crustal rocks that are far more reactive than the basalt flooring the Pacific. Due to the long-lived faults at the slow and ultraslow spreading ridges, hydrothermal deposits found along them are far larger than at the EPR, with a great range in geochemical composition, and significant economic potential. Thus understanding the diversity of crustal structure and composition across the full oceanic spectrum is a fundamental problem for understanding the Earth system, with significant human impacts.

The average composition of MORB is not in equilibrium with the olivine that makes up the majority of the shallow upper mantle. Magma parental to the ocean crust must have a ratio of $Mg \times 100 / (Mg + Fe)$ close to 73 to be in equilibrium with mantle olivine. An average of 3087 MORB glasses from the PetDB database gives an average Mg# of 59 requiring that MORB has undergone substantial chemical differentiation in the lower crust, and that the latter has a bulk composition substantially different from the shallow crust. The composition of the lower ocean crust has not been determined for any ocean basin, and remains one of the principle unknowns in the global geochemical cycle.

The general model for formation of the lower crust thirty years ago was a 4-5 km high magma chamber, 5 to 10 km wide where the lower crust accreted by crystallization on the roof and walls, and floor. Fractionated melts, erupted from this chamber to form basaltic crust. This model was inferred from three primary observations: 1) seismic refraction which indicated a uniform layered structure across the ocean basins, 2) sections of fossil ocean crust (ophiolites) where such sequences were preserved, and 3) sampling of a similar sequence of rocks: mantle harzburgite, dunite, troctolite, olivine gabbro, gabbro and gabbro norite from the walls of the great oceanic transform fault valleys, where it was presumed cross sections of the ocean crust were exposed. The latter rocks corresponded well to the sequence of crystallization found by experiment for MORB glasses of olivine (dunite), olivine + plagioclase (troctolite), olivine + plagioclase + Cpx (olivine gabbro), and plagioclase + Cpx + orthopyroxene (gabbro norite). Using these rocks,

Ocean Ridge Crustal Accretion Models

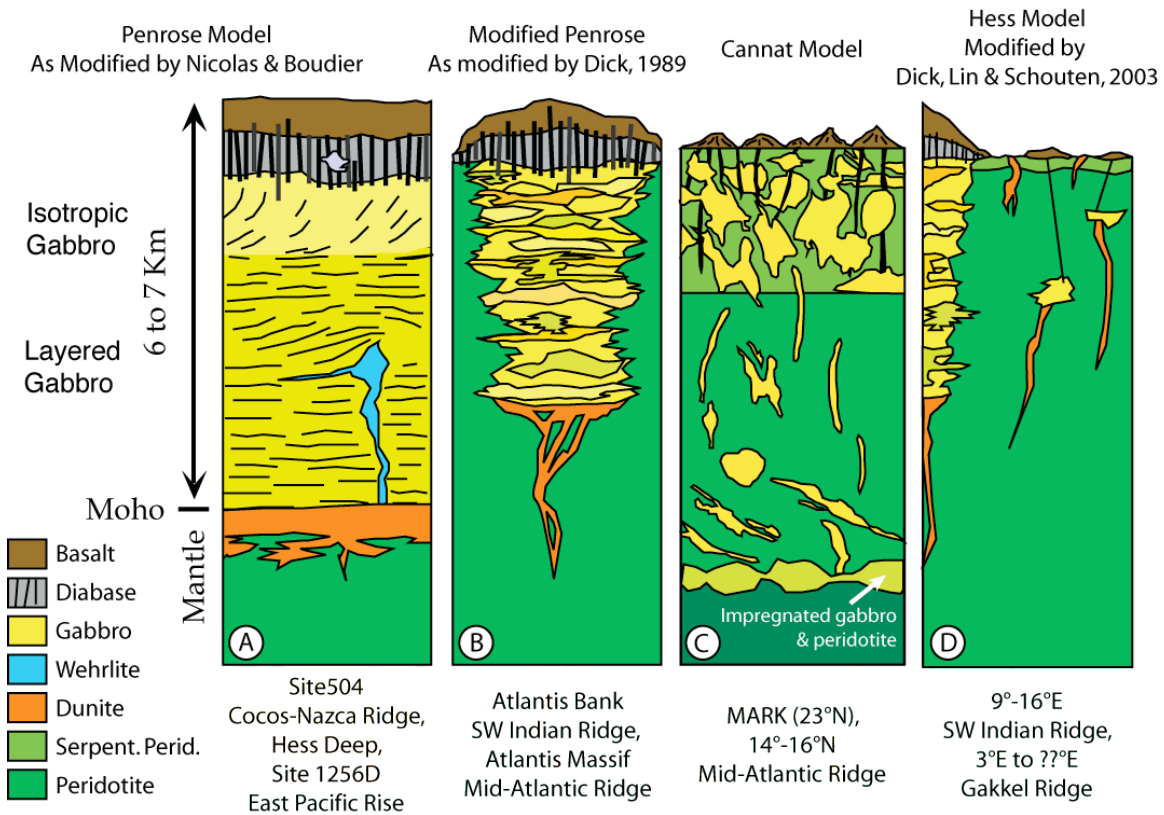


Figure 1 Models for crustal accretion at ocean ridges from Dick et al [2006]. A. Classic interpretation of the Penrose Model for a fast spreading ridge based on the Oman Ophiolite. B. Penrose model as modified for slow spreading ridges based on the abundance of peridotite and frequent absence of gabbro at transforms following focused melt flow models. C. Model for the anomalous 14°-16°N area of the Mid-Atlantic Ridge. D. Model for magmatic and amagmatic accretionary segments at ultraslow spreading ridges.

it was straightforward to construct a simple section of layered rocks similar to the large layered intrusions such as the Skaergaard Intrusion, which provided a physical example for such large magma chambers. The principal role of this magma chamber in the evolution of MORB was to fractionate melts by simple fractional crystallization and for magma mixing [e.g.: *Dungan, 1978*], which would homogenize diverse melts delivered from the underlying mantle.

Models for the lower ocean crust have changed dramatically over the last thirty years (Fig. 1). The large magma chamber model was vanquished by the discovery of the narrow melt lens beneath the EPR, little evidence for a long-lived chamber beneath the MAR [*Detrick et al., 1987*] and the first long sections of lower crust drilled at slow and ultraslow spreading ridges [*Dick, 1991; Sinton and Detrick, 1992*]. Nisbet and Fowler [1978] first proposed that the lower crust at slow spreading ridges consists of many small independent intrusions from geophysical and geochemical observations. This accretion model is strongly supported by the complex stratigraphies of the 1400 and 1500-m sections of gabbro cored at Atlantic

Hole U1309D and Indian Ocean Hole 735B, which require many intrusive events. These sections confirm the existence of locations along slow and ultraslow spreading ridges where a massive gabbro layer formed beneath pillow lavas and sheeted dikes as envisaged by the Penrose ocean crust model. Sampling along the Mid-Atlantic Ridge north and south of the 15°20' fracture zone, however, reveals lower crust comprised of numerous small gabbro intrusions in partially serpentinized peridotite tectonically exposed over large areas of the sea floor, originally overlain by scattered pillow basalt and dikes [Cannat *et al.*, 1997]. ODP Leg 209 recovered some 30-40% gabbroic rock intruded into serpentinized peridotite at numerous locations there, dramatically confirming the existence of such crust [40]. At the same time, exploration along the SW Indian and Gakkel Ridges identified amagmatic accretionary segments extending up to 400 km where nearly the only rock type dredged is peridotite, with only scattered pillow basalt, and a near absence of gabbros [Dick *et al.*, 2003; Michael *et al.*, 2003]. Another crustal variant was found by mapping and seismic refraction in a tectonic window near 23°N on the Mid-Atlantic Ridge, the Kane Megamullion. There, local magmatic centers existed on the time scale of several hundred thousand years where gabbroic crust formed beneath the basaltic layer at different points beneath the ridge axis with intervening large areas where the basaltic layer overlay massive peridotite [Canales *et al.*, 2008; Dick *et al.*, 2008].

This dramatic change in our understanding of the nature of the lower crust formed at slow and ultraslow spreading ridges has been driven by deep drilling and mapping in a few tectonic windows exposing lower ocean crust and mantle at oceanic core complexes. This has revealed geologic relationships, rock distributions and associations inconsistent with that envisioned in the simple layered crust model. Oceanic core complexes, first discovered little over ten years ago [Cann *et al.*, 1997; Tucholke *et al.*, 1996], provide a unique opportunity to explore the lower ocean crust and mantle. It was initially assumed, however, that their formation represented an anomalous mode of sea floor spreading. A second look at sea floor bathymetry for the Atlantic [Escartin *et al.*, 2008], however, together with new data from the SW Indian Ridge [Cannat *et al.*, 2006; Dick *et al.*, 2003] show that large areas of the ocean crust at slow and ultraslow spreading ridges formed by detachment faulting and amagmatic rifting.

Thus, in the last ten years there has been a fundamental paradigm shift in our understanding of the ocean crust that requires a new focus on understanding the crustal structure and architecture of slow and ultraslow spreading ocean ridges. This is required if we are to understand the full global geochemical cycle, and how a large portion of the Earth's crust is formed.

The issue is, how to approach this problem with limited resources. There is no substitute for a full penetration of the lower crust from the sheeted dikes through the crust-mantle boundary into the mantle in a magmatically robust environment at a slow spreading ridge. This is required in order to understand both the full igneous composition of the ocean crust, and the processes that shape the composition of Mid-Ocean Ridge basalt at the slow end of the ridge spreading spectrum, and to

explain the differences in its composition at fast and slow spreading ridges. This site should have a well-characterized MOHO discontinuity, and provide an opportunity to determine if this boundary can be a serpentinization front rather than the transition from mafic to ultramafic rock. It is essential, in evaluating crustal budgets across the ocean basins to know how the Mohorovicic discontinuity can be interpreted.

Addressing the variability of crustal architecture at slow and ultraslow spreading ridges would seem a greater challenge. This can be done, however, to a large extent at a large oceanic core complex with present technology. The discovery that oceanic core complexes expose lower ocean crust in a diversity of environments from magmatically robust to anemic provides a valuable short cut to exploring lower crustal structure at slow and ultraslow spreading ridges. Recent geologic mapping at the Kane Oceanic Core Complex found large lateral heterogeneity in the crust, which varied from large regions where at the point of accretion the crust consisted of mantle peridotite overlain by a carapace of dikes and basalt, to regions with large magmatic complexes and a thick gabbroic section [Dick *et al.*, 2008]. An extensive shallow (1-km) penetration seismic reflection survey over the same core complex showed large variations in seismic velocity that were independently similarly interpreted. Comparison of the results found that the interpretation of crustal structure from the geology and the seismology were essentially identical with the seismic survey extending the results of the mapping into regions where sediment and hanging wall debris obscured the geology [Canales *et al.*, 2008]. Recent seismic and geologic mapping at Godzilla Megamullion in the Parece Vela basin appears to be giving a similar result (Ohara, pers. Comm.). A single drilling leg, penetrating to ~500-m in two or three locations of contrasting seismic velocity would confirm whether using these two tools in combination is a valid approach to exploring lower crustal architecture as well as obtaining key stratigraphic relationships unobtainable by surface sampling. This would effectively leverage one drilling leg into a whole new approach, using alternate methods, to explore crustal architecture across a wide range of spreading rates and ocean basins where seismic structure and geologic sampling could be used hand-in-hand, both to validate seismic interpretation and to extend geologic mapping results into three dimensions, and to guide further sampling .

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