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Article abstract

During the past 25 years much has been learned about the structure and composition of oceanic lithosphère through bathymétrie surveying, seismic experiments, and scientific drilling. Our understanding of the processes by which oceanic lithosphère is generated is still limited, however, by our inability to sample directly the lower crust and upper mantle.This is due to the limitations of available drilling platforms, the technological challenges of drilling on bare rock close to mid-ocean ridges, and the inordinate expense of drilling deep holes through the ocean crust. Exposed ophiolites offer a valuable alternative source of information on oceanic lithosphère but their interpretation is hampered by uncertain provenance, tectonic dismemberment, and overprinting of original features during emplacement. Using data from studies of in situ oceanic lithosphère and ophiolites, numerous models have been developed for the genesis of oceanic crust and upper mantle which involve the interaction of a variety of magmatic, tectonic and hydrothermal processes. These models can only be tested thoroughly by deeper ocean drilling.

Series

OCEANIC LITHOSPHERE 1. The Origin and Evolution of Oceanic Lithosphere: Introduction

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SUMMARY
During the past 25 years much has been learned about the structure and composition of oceanic lithosphere through bathymetric surveying, seismic experiments, and scientific drilling. Our understanding of the processes by which oceanic lithosphere is generated is still limited, however, by our inability to sample directly the lower crust and upper mantle. This is due to the limitations of available drilling platforms, the technological challenges of drilling on bare rock close to mid-ocean ridges, and the inordinate expense of drilling deep holes through the ocean crust. Exposed ophiolites offer a valuable alternative source of information on oceanic lithosphere but their interpretation is hampered by uncertain provenance, tectonic dismemberment, and overprinting of original features during emplacement. Using data from studies of *in situ* oceanic lithosphere and ophiolites, numerous models have been developed for the genesis of oceanic crust and upper mantle which involve the interaction of a variety of magmatic, tectonic and hydrothermal processes. These models can only be tested thoroughly by deeper ocean drilling.

RÉSUMÉ
Au cours des derniers 25 ans, les connaissances sur la structure et la composition des roches de la croûte océanique ont beaucoup progressées, grâce en autres aux levés bathymétriques, à des expériences sismologiques et aux sondages d'exploration scientifique réalisés. Cependant, nos connaissances des géomécanismes qui ont été à l'origine de la genèse de la croûte océanique sont encore limitées, étant donné notre incapacité à échantillonner directement la croûte inférieure et le manteau supérieur. Cela est dû aux limitations intrinsèques des plateformes de forage existantes, aux difficultés technologiques que représentent les forages sur la roche nue d'une dorsale médio-océanique, et à l'énormité de coûts de sondages profonds à travers la croûte océanique. Les affleurements d'ophiolites constituent une source d'information alternative intéressante sur la croûte océanique, mais la qualité des informations que l'on peut en déduire dépend de la provenance, du morcellement tectonique et des caractères hérités du milieu au moment de la mise en place. En utilisant les données provenant d'études sur des croûtes océaniques et des ophiolites en place, de nombreux modèles ont été développés sur la genèse de la croûte océanique et du manteau supérieur à partir de l'interaction d'une variété de géomécanismes magmatiques, tectoniques et hydrothermaux. Seuls des forages plus profonds de la croûte océanique permettront de valider adéquatement ces modèles.

INTRODUCTION

As a boundary layer between the upper mantle and the Earth's surface, the oceanic lithosphere has recorded the complex and interrelated magmatic, tectonic and hydrothermal events that occur around ocean ridges. After it is formed, the oceanic lithosphere is carried away from ocean ridges by sea-floor spreading and, as it ages, it cools, undergoes alteration, and is covered by sediment. Eventually, it is recycled into the mantle at subduction zones where, once again, it becomes part of the mantle geochemical reservoir, thereby completing one of the fundamental geological and geochemical cycles in the Earth system (Fig. 1). This interacts with other global geological systems with profound implications for the chemical and thermal evolution of the mantle, the generation of continental crust, and the buffering of seawater chemistry. For example, the composition of the mantle reservoir must be influenced not only by the removal of magmas, particularly beneath spreading ridges and island arcs, but also by the chemistry of recycled lithosphere. Hydrothermal circulation at the ocean ridges and low temperature reactions between basement and seawater control many aspects of seawater composition, and altered crustal rocks play a major role in the nature and composition of volcanism at convergent plate margins. Thus, knowledge of the processes by which ocean lithosphere is created, modified, and destroyed is crucial to understanding the evolution of planet Earth.

STRUCTURE OF OCEAN RIDGES

Because submarine erosion is limited, the morphology of the sea floor reflects closely the volcanic and tectonic processes acting in the ocean basins. Much of the sea floor, particularly the mid-ocean ridges, has been accurately mapped in the last decade, revealing a high degree of ridge segmentation and significant variations in morphology, which are correlated with sea-floor spreading rates (Macdonald *et al.*, 1991; Macdonald *et al.*, 1993a, b; Weiland *et al.*, 1996). Along-axis ridge segmentation, which appears to be independent of spreading rate, occurs on a variety of scales from a few tens to hundreds of kilometres. First-order segments, usually bounded by transform faults, may be several hundreds of kilometres long and persist for millions of years. Transform faults juxtapose a barrier of old lithosphere against zero-age spreading axes (Fox and Gallo, 1984) and thus greatly affect along-axis accretionary processes. The first-order, large-scale segments are divided into second- and even third- and fourth-order segments that are bounded by a variety of discontinuities, such as propagating rifts, no-offset transforms, overlapping spreading centres, and deviations from axial linearity (devals) (Searle and Laughton, 1977; Macdonald *et al.*, 1991) (Fig. 2), which reflect small changes in spreading direction, asymmetrical spreading rates and perhaps variations in melt generation (Lonsdale, 1989; Perram and Macdonald, 1990; Macdonald *et al.*, 1991; Macdonald *et al.*, 1993a, b). Most ridge segments, regardless of length, have along-ridge bathymetric sections that shallow toward their mid points (Whitehead *et al.*, 1984; Macdonald *et al.*, 1991). These bathymetric highs typically are the *loci* of magmatic and hydrothermal activity and are believed to be underlain by subrift magma chambers or melt pockets, for which there is some evidence from seismic experiments (Detrick *et al.*, 1987; Toomey *et al.*, 1990). Global variations in basalt chemistry, particularly in Na_2O and FeO contents, have been shown to correlate with axial depth and crustal thickness along modern spreading axes (Klein and Langmuir, 1987; 1989; Klein *et al.*, 1991; Brodholt and Batiza, 1989) although many local variations exist (Brodholt and Batiza, 1989; Klein and Langmuir, 1989). Many large-scale ridge discontinuities, particularly transform faults, appear to have lower magma budgets than typical ridge segments and are commonly marked by basalts with lower abundances of incompatible elements (Ti, REE, Zr, Sr) and FeO than those near the centres of ridge segments (*e.g.*, Langmuir and Bender, 1984). Small-scale temporal changes in lava composition are also observed along some ridge segments (*e.g.*, Reynolds *et al.*, 1992; Perfit *et al.*, 1994).

CONSTRUCTION OF OCEANIC LITHOSPHERE

The processes involved in the construction of oceanic lithosphere are poorly understood, chiefly because of the technical difficulties involved in sampling the lower crust and upper mantle, especially on, or close to, ridge systems. Most of what is known and inferred about the composition and structure of the lithosphere comes from studies of lava geochemistry, seismic velocities, and tomography, and by comparison with ophiolites. Only a few samples of the lower ocean crust and upper mantle have been recovered by dredging or drilling in "tectonic windows" where such sections are exposed on the sea floor.

Evidence From Modern Ocean Basins

During the past two decades, increasingly detailed geological and geophysical investigations of active spreading centres have given us a basic understanding of the structure of oceanic crust. Seismic data from the major ocean basins were originally interpreted in terms of a *layered* model (Raitt, 1963) (Fig. 3). Layer 1 is defined by P-wave velocities ranging from about 1.6 $km \cdot s^{-1}$ to 2.5 $km \cdot s^{-1}$ and is clearly composed of sediment. P-wave velocities in Layer 2 range from about 3.3 $km \cdot s^{-1}$ to 6.3 $km \cdot s^{-1}$ and generally increase with increasing age of the crust. Drilling has shown that the upper part of Layer 2 consists of basaltic pillows or sheet flows, and the low velocities in young crust are correlated with highly fractured and porous lavas near the ridge crests. The higher velocities are believed to represent massive lavas and dykes in which pores and cracks have been sealed by secondary minerals. Unlike the other transitions in the ocean crust, the Layer 2–3 boundary is not marked by a distinctive reflector and its nature is uncertain. It may represent either a change in lithology from dykes to gabbros, or it may mark a change in metamorphic grade or intensity. Layer 3 velocities are typically more uniform than those in Layer 2 and range between about 6.2 $km \cdot s^{-1}$ and 7.3 $km \cdot s^{-1}$. Although this terminology is still used to describe the velocity structure of ocean crust, what were originally thought of as sharp boundaries between the layers are now recognized

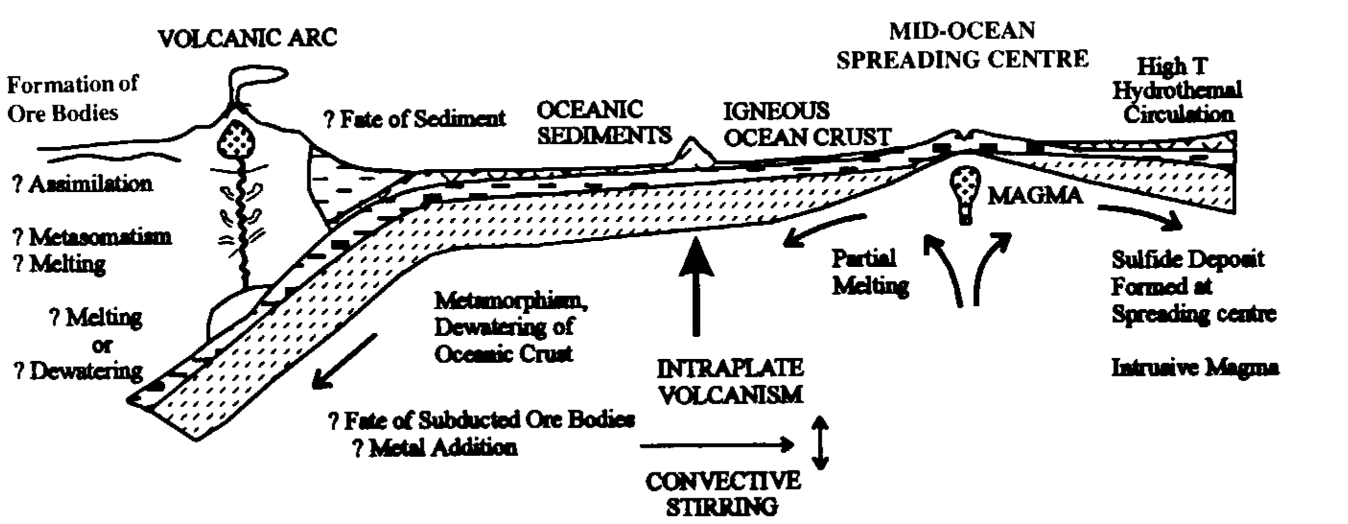

Figure 1 *Schematic cross-section of the oceanic crust and upper mantle illustrating the plate tectonic cycle by which ocean lithosphere is created, modified and destroyed (modified from COSOD II).*

as gradational changes in velocity structure. It is also clear that, although widespread, this seismic stratigraphy is not as laterally continuous as once thought (*e.g.*, Spudich and Orcutt, 1980; Orcutt, 1987). Regional variations in the thickness and character of specific layers are thought to reflect along-strike variations in the nature of the magma supply system along spreading ridges, in positioning and duration of hydrothermal circulation cells, and in the locations of major ridge offsets. In addition, differences may reflect formation of ocean lithosphere in a variety of tectonic settings, such as mid-ocean ridges, propagating rifts, and back-arc basins, and at spreading rates that differ by an order of magnitude. It is clear that crustal construction takes place in extensional environments, however, and involves the close interplay of magmatic, tectonic, and hydrothermal activity. This *first order* observation is valid regardless of where the spreading axis is located, and places constraints upon models for the formation of ocean lithosphere.

In situ igneous ocean lithosphere has been sampled in a great many Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) holes but only a few of these have penetrated more than a few hundred metres. The most important locations where deep samples have been recovered include Sites 504, 894 and 895 in the eastern equatorial Pacific Ocean and Site 735 in the southwestern Indian Ocean.

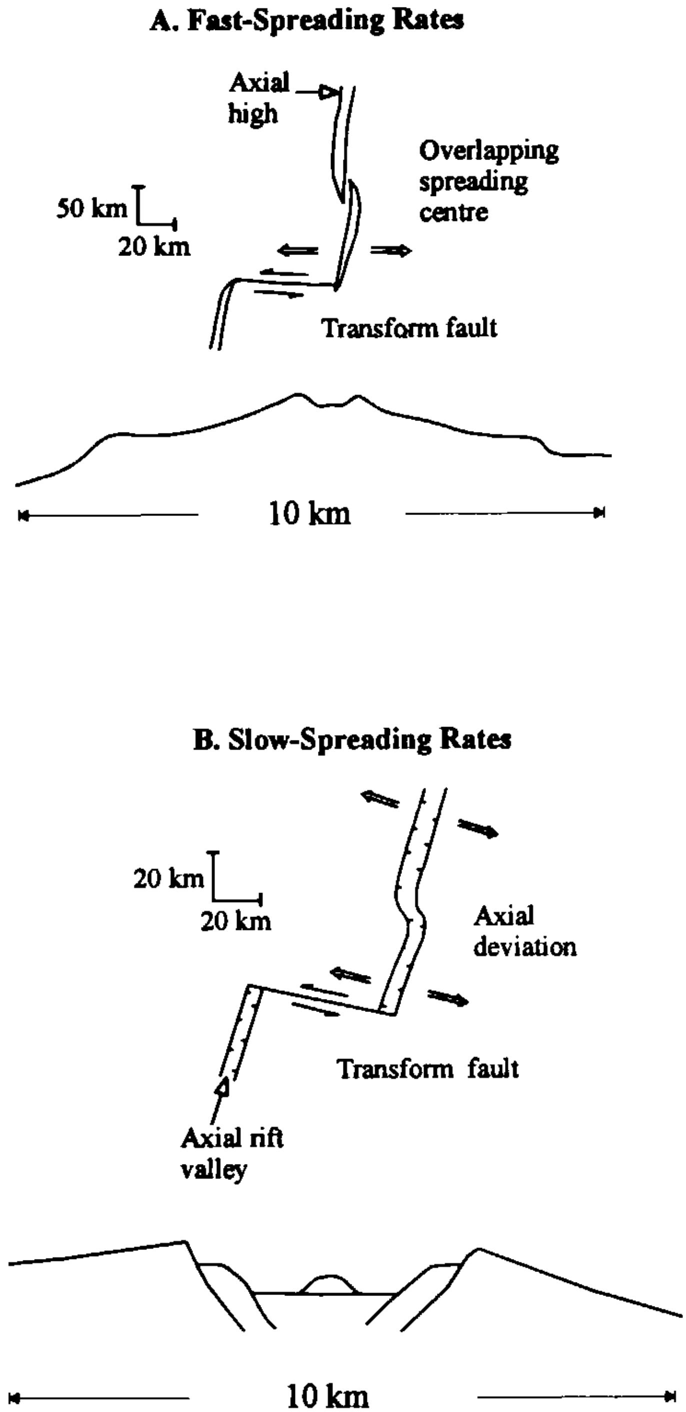

Figure 2 *Map view of ridge segmentation features and schematic cross-sections of fast- and slow-spreading ridges (modified from Macdonald* et al., *1991; Macdonald* et al., *1993a). Along fast-spreading ridges, such as the East Pacific Rise, the ridge is marked by an axial high with a narrow graben and is offset by overlapping spreading centres and transform faults* (**A**). *Along-axis bathymetric highs, located near the middle of major ridge segments, are the loci of volcanism and hydrothermal circulation. Slow-spreading ridges, which are characterized by a lower magma budget, are marked by an axial graben and offset by transform faults. Many also display deviations in axial linearity (devals), even though they are physically continuous* (**B**).

Pacific Ocean

So far Hole 504B is the deepest drillhole into ocean basement and it is the only one interpreted as penetrating a transition between crustal layers (Fig. 4). Site 504 was selected as an area where 5-6 m.y. old ocean crust appears to have reached conductive equilibrium with the underlying mantle, and is thus what one might think of as *normal* ocean crust. After 7 legs of drilling (DSDP 69, 70, 83 and ODP 111, 137, 140 and 148), Hole 504B has been extended to a total of 2111 metres below sea floor (mbsf). The drilled section includes 274.5 m of sediment, 571.5 m of pillow lavas and minor sheet flows, 209 m of breccia, pillow lavas, thin flows and dykes, and 1056 m of dykes. The dykes are mineralogically and chemically similar to the overlying lavas and have compositions consistent with crystallization from a magma produced by partial melting of a slightly depleted mantle source. The rocks are olivine tholeiites with compositions similar to moderately evolved mid-ocean ridge basalt (MORB). A paucity of glassy chilled margins and an increase in grain size in the lower parts of the section suggest that the dyke–gabbro boundary is not far below the bottom of the hole. The lower dyke section in Hole 504B has been pervasively altered by low-temperature rock–seawater interaction, which appears to have occurred in stages.

The low-temperature pervasive alteration is locally overprinted by hydrothermal veins filled with chlorite, chlorite–actinolite, epidote–quartz, and chlorite–pyrite. Most of the dyke rocks in Hole 504B are seriate porphyritic in texture and contain gabbroic clots up to a few centimetres across. Some of these clots contain up to 20% Fe–Ti oxides and are interpreted to be crystallized pockets of trapped Fe–Ti-rich magma.

Downhole changes in physical properties in Hole 504B, including marked increases in density and seismic velocity, suggest that the Layer 2–3 transition has been intersected within the sheeted dyke section (Salisbury and Christensen, 1994; Detrick *et al.*, 1994). If so, this boundary is related to changes in secondary alteration and void filling rather than a lithologic change from dykes to gabbro.

During ODP Leg 147, a number of relatively shallow, offset holes were drilled at two sites (894,895) in the Hess Deep of the equatorial Pacific (ODP Leg 147 Shipboard Scientific Party, 1993). This drilling of offset partial sections is a strategy similar to that employed in Cyprus to sample the complete stratigraphy of the Troodos ophiolite through a series of drill holes rather than through one deep and extremely expensive penetration. In the Hess Deep, lower crust generated 1.2 Ma at the East Pacific Rise has been exposed by the westward propagation of the Costa Rica Rift. The distribution of rock types, which include peridotite, gabbro, diabase, and basalt, indicates that there is severe structural dismemberment of the crust and upper mantle. There appears to be little lateral continuity of rock types, and in places there is a clear reversal of normal lithospheric stratigraphy where harzburgites of the upper mantle sequence overlie cumulate gabbros of crustal Layer 3. Only gabbroic rocks were recovered at Site 894, whereas at Site 895, some 9 km to the southeast, a sequence of ultramafic and mafic rocks was recovered, including dunites and harzburgites with associated troctolites, gabbros, and basalts. Rocks from Site 894 are considered to have formed in the roof zone of an axial magma chamber, and those from Site 895 from the transition zone between Layer 3 of the oceanic crust and the upper mantle.

Igneous rocks recovered in Holes 894F and 894G include gabbro, olivine gabbro, gabbronorite, olivine gabbronorite, and basalt. These rocks have textures very similar to those of varitextured gabbros found in ophiolites generally near the top of the plutonic sequence, *i.e.*, immediately below the sheeted dykes. Although common in ophiolites, such rocks had never before been recovered in significant quantity from *in situ* ocean crust. The geochemistry of these rocks suggests that they formed by the escape of interstitial melt from a crystal mush, followed by the local re-invasion of the crystalline matrix by very evolved, volatile-rich liquid (Pedersen *et al.*, 1996). This interpretation implies that the migration of magma through the upper parts of sub-rift magma chambers, especially in the surrounding mush zone, takes place around and along crystal boundaries rather than through major dyke-like conduits.

Indian Ocean

Hole 735B, located on a transverse ridge along the east side of the Atlantis II Fracture Zone on the Southwest Indian Ridge, penetrated more than 500 m of relatively fresh gabbro, believed to represent the upper portion of oceanic Layer 3 (Fig. 4). Dick *et al.* (1991) concluded that most of the sampled section consists of a single olivine gabbro intrusion that exhibits only minor layering or cryptic variation. This body appears to have intruded a coarse gabbronorite at the top of the section and has itself been intruded at the base of the section by troctolite and troctolitic gabbro. Numerous small lenses and pods of micro-gabbro that crosscut this section formed by crystallization of melts that migrated through the olivine gabbro prior to its complete solidification. The whole section has undergone a process of "syntectonic differentiation" during which intercumulus melts were squeezed out of the crystal mush into ductile shear zones, where they are now represented, in part, by ferrogabbros. The gabbro section appears to have formed in a crystal mush zone like those believed to surround small crustal magma chambers (Sinton and

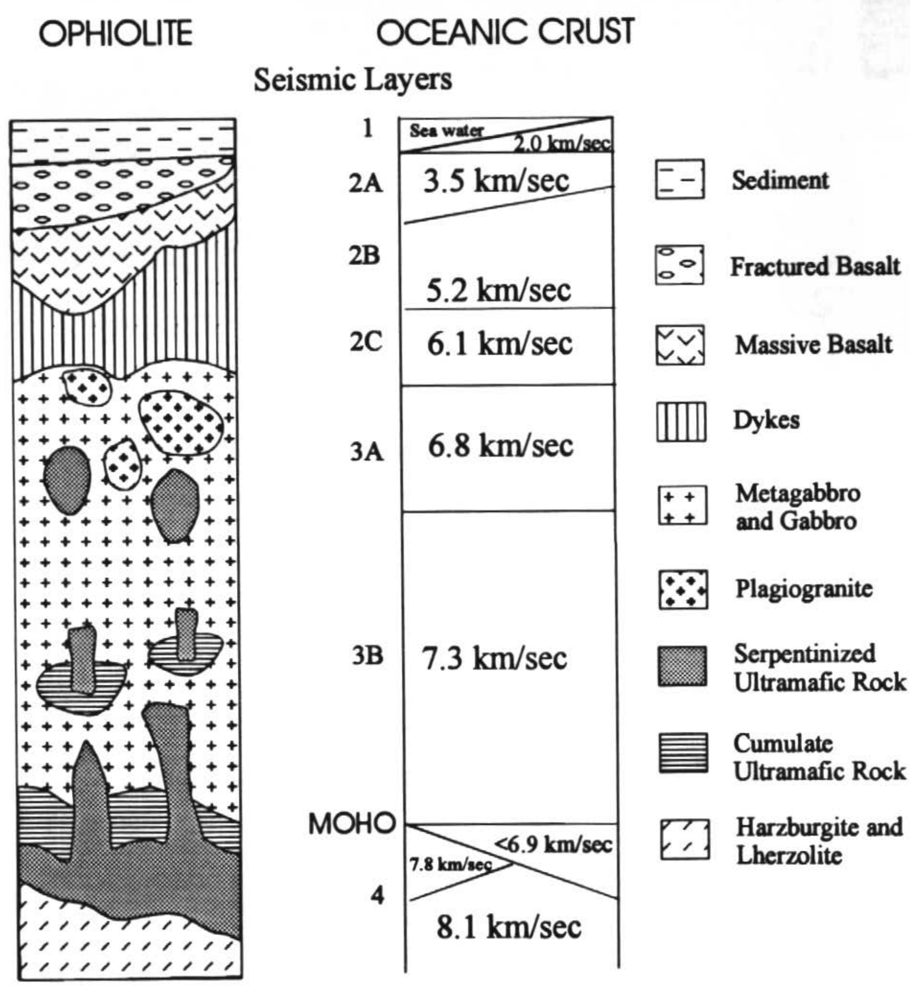

Figure 3 *Generalized composite sections of an ophiolite and* in situ *oceanic crust. Layering in oceanic crust is defined by p-wave velocities which correlate reasonably well with ophiolitic lithologies* (e.g., *Christensen and Salisbury, 1975). Mantle velocities of 6.9 km·s⁻¹ represent serpentinized ultramafic rocks and those of 7.8 km·s⁻¹ correlate with anomalous mantle close to ridge axes.*

Detrick, 1992). The SW Indian Ridge is spreading at the rate of 0.8 $cm \cdot a^{-1}$, not unlike the slow-spreading Mid-Atlantic Ridge. It is believed that such ridges are underlain by small, ephemeral magma chambers, perhaps less than 2 km wide. Generation of the plutonic rocks sampled at Hole 735B in a small magma chamber would explain their poor layering, the limited mixing of magma types, and the considerable degree of fractionation. In addition, the small volumes of magma involved in the intrusive events and the crosscutting relationships displayed in the section suggest that Hole 735B sampled the upper part of oceanic Layer 3.

Evidence From Ophiolite Complexes

Ophiolite complexes are associations of mafic and ultramafic rocks including basalt, gabbro, dunite, and peridotite that crop out in major orogenic belts. Most are highly deformed and dismembered, but well preserved examples have a pseudostratigraphy characterized by tectonized harzburgites at the base, followed upward by dunite, layered gabbro and ultramafic rock, massive gabbro, sheeted dykes, and pillowed and massive lavas. The sheeted complexes consist of dykes that are intrusive into one another with no host rock in between. Such sheeted complexes are taken as evidence of formation in an extensional environment similar to that of a mid-ocean ridge (*e.g.,* Gass, 1968).

Ophiolite complexes have long been interpreted as remnants of ancient ocean lithosphere (Gass, 1968; Moores andVine, 1971; Coleman, 1977; Nicolas, 1989), and have provided information on the lithologies that might correlate with the *in situ* seismic layers (Fig. 3). The "ophiolite model" for ocean lithosphere, as defined at a Penrose Conference in 1972, assumes that ophiolites are fragments of normal ocean lithosphere formed at mid-ocean spreading ridges. The pillow lavas and sheeted dykes of ophiolite complexes are assigned to oceanic Layer 2, the vari-textured and layered gabbros to Layer 3 and the ultramafic rocks to the upper mantle.

Detailed investigations of well-preserved and well-exposed ophiolite sections have provided a wealth of data which can be compared directly with that from *in situ* ocean crust and upper mantle. These studies reveal that although each ophiolite complex has unique features, there are many common characteristics. For example, most ophiolites have a complex lava geochemistry suggesting formation through multiple magmatic events. Most well-preserved ophiolites contain a sheeted dyke sequence and the plutonic rocks show a variety of forms ranging from isotropic to varitextured to layered. In many cases, the gabbroic and ultramafic rocks exhibit a well-developed foliation, indicative of high-temperature, ductile deformation of the type believed to be associated with sea-floor spreading.

On the other hand, most ophiolites have

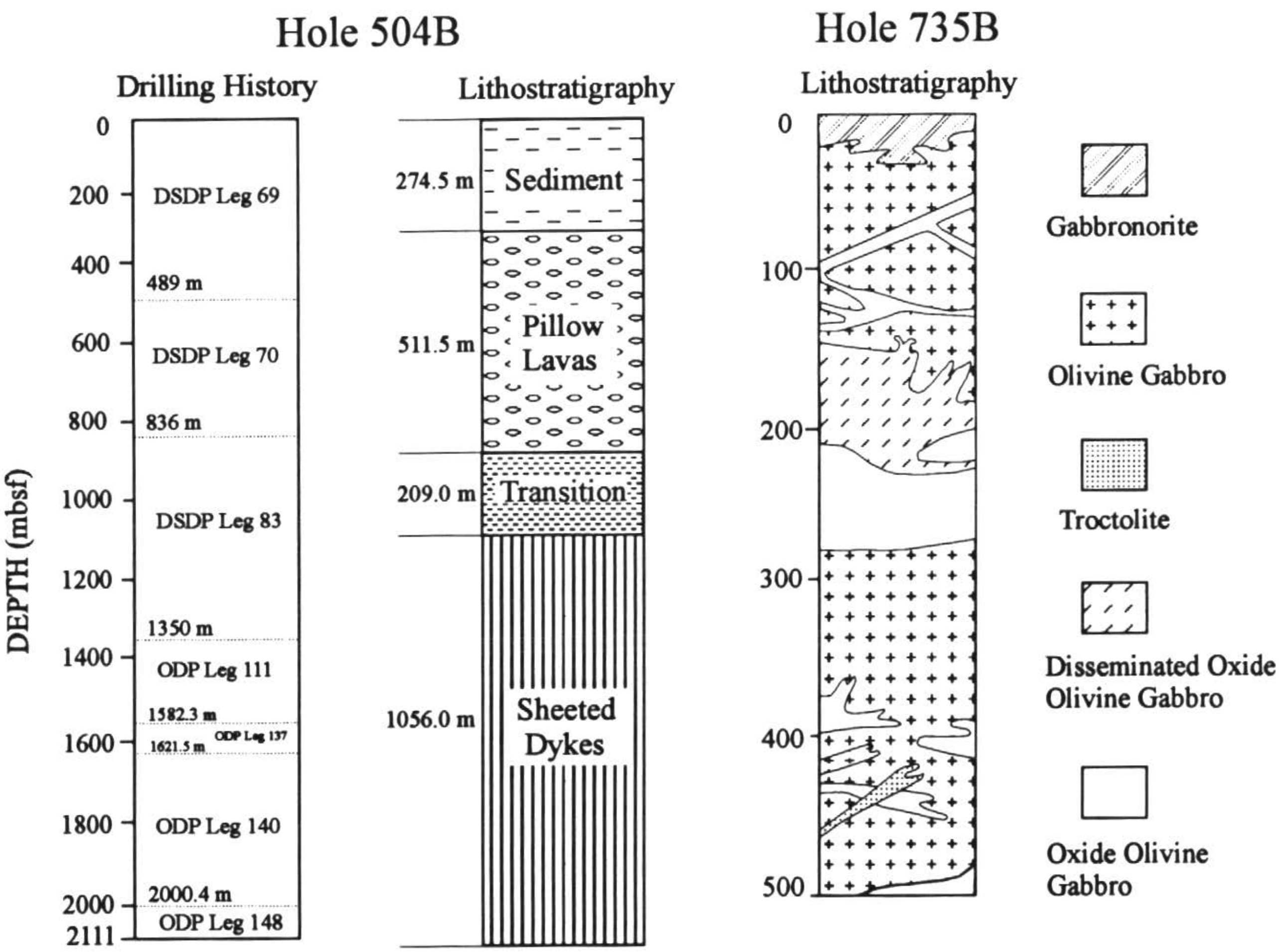

Figure 4 *Generalized lithologic sections of ocean crust sampled in ODP Holes 504B and 735B. Seven drilling legs were required to penetrate 2111 m at 504B, located on the Costa Rica Rift in the eastern Pacific Ocean, and the depths achieved on each leg are shown on the figure. Lithologic data are from DSDP and ODP Initial Reports for each drilling leg. Hole 735B, located on the Southwest Indian Ridge was drilled to a depth of 500 m in two weeks. Lithologic data for Hole 735B are from Dick* et al. *(1991). Mbsf = metres below sea floor.*

magma compositions indicating formation in the mantle slab above a subduction zone (supra-subduction zone environment) (*e.g.,* Miyashiro, 1973; Saunders *et al.,* 1980; Alabaster *et al.,* 1982; Robinson *et al.,* 1983; Jenner *et al.,* 1991). In addition, the large-scale "stratigraphy" observed in many ophiolites is much less regular and areally extensive than the seismically defined layers of *in situ* ocean crust. Therefore, despite fundamental sim-ilarities, questions still remain as to how far the ophiolite analogy may be reasonably taken, and whether one conceptual model can encompass the total spectrum of ocean crust formation.

Three of the best exposed, most complete, and best studied ophiolites in the world are the Troodos complex of Cyprus, the Semail ophiolite of Oman, and the Bay of Islands massif of western Newfoundland. Although they have certain features in common, each is different in significant ways and provides a unique perspective on the origin of oceanic lithosphere.

The Troodos complex has been studied intensively since the early 1950s by the Cyprus Geological Survey and teams of international scientists and has provided much of the information on which our present interpretation of ocean lithosphere is based. A major re-investigation of Troodos was undertaken in the 1980s by the International Crustal Research Drilling Group (see papers in Malpas *et al.,* 1990). Detailed field studies were accompanied by deep drilling in order to construct a 3-D picture of the ophiolite and to obtain continuous sections for comparison with DSDP and ODP samples of *in situ* crust. Five offset holes, with core recoveries ranging from 93% to 99.5%, provided a composite section of the upper 3500 m of the ophiolite sequence (Fig. 5). Study of field exposures and the drillcore has shown that this classic ophiolite formed in a supra-subduction zone environment resulting from the collision of the African and Eurasian Plates in the Late Cretaceous (Moores *et al.,*1984). An arc-tholeiite suite, a depleted tholeiite suite, and a highly depleted boninitic suite have been recognized in the extrusive sequence (Mehegan and Robinson, 1991). Cyprus-type massive sulphide bodies are the products of high-temperature hydrothermal solutions which vented on the sea floor (Oudin and Constantinou, 1984) along axial grabens (Moores *et al.,* 1990, Varga and Moores, 1990). Except in narrow, subvertical zones beneath these ore bodies, the Troodos lavas have undergone only low-temperature interaction with seawater. Secondary mineral assemblages consist chiefly of clay minerals, zeolites and carbonates, and appear to have been controlled largely by variations in permeability, lithology, water–rock ratios and proximity to intrusions (Gillis 1987; Gillis and Robinson, 1990). Such alteration of the lavas is not pervasive, however, and fresh volcanic glass exists throughout the lava pile (Robinson *et al.,* 1983). This fresh glass has yielded primary compositions of the volcanic rocks which show that the ophiolite was generated in a convergent plate margin setting.

The Semail ophiolite (Alabaster *et al.,* 1982) and the Bay of Islands ophiolite (Jenner *et al.,* 1991) exhibit volcanic geochemistry similar to the Troodos massif, suggesting that they also formed in a supra-subduction zone environment. The Semail ophiolite is of Cretaceous age and has been extensively studied by teams from the United States (Journal of Geophysical Research, v. 86, B4, 1981), United Kingdom (Lippard *et al.,* 1986) and France (Nicolas *et al.,* 1988). The ophiolite crops out in a semi-continuous belt 475 km long and up to 80 km wide along the length of the Oman Mountains. The main stratigraphic subdivisions of the ophiolite suite are all well represented, allowing investigation of both lateral and vertical variations.

The mantle sequence of the Semail ophiolite makes up more than 60% of the exposed section and, although estimates are difficult to make, varies in thickness from about 5 km to 12 km. It consists of variably serpentinized peridotite tectonites, dominantly harzburgite and lherzolite with subordinate bodies of dunite, the whole being cut by numerous dykes, veins and pods of ultramafic and mafic rocks. Complicated tectonite fabrics in the mantle section are believed to be the result of divergent diapiric flow, suggesting that the exposed mantle section was derived from the immediate spreading centre (Lippard *et al.,* 1986; Ceuleneer, 1991).

Mantle diapirs about 10 km in size are recognizable in which the upwelling zone consists of homogeneous harzburgite which is interpreted as the residue after partial melting and melt extraction. At the very top of this zone, abundant melt ex-

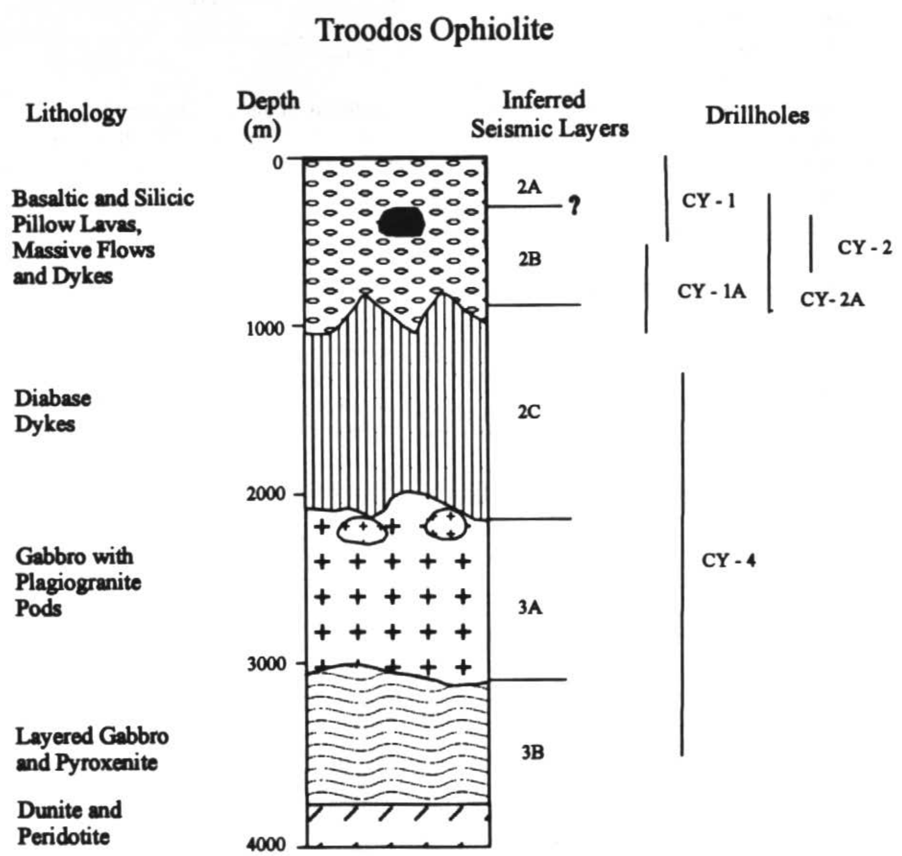

Figure 5 *Generalized lithologic section of the Troodos ophiolite showing penetration of boreholes drilled by the International Crustal Research Drilling Group and the inferred correlation with in* situ *oceanic crustal layers. The black feature in the extrusive section is a massive sulphide ore body.*

traction features in the form of discordant veins and dykes of ultramafic and mafic compositions occur in a dunitic host and point to the existence of a low-viscosity crystal mush horizon correlated with the mantle–crust transition zone. Farther outward, lateral zones of divergent flow are devoid of ultramafic melt extraction features but host numerous gabbro dykes suggestive of lower temperatures (Ceuleneer, 1991). Deformation, related to the effective viscosity of the upper mantle, increases with distance away from the axial zone.

In the Bay of Islands massif of western Newfoundland, the mantle magmatic history involves multiple periods of melt–rock interaction (Edwards and Malpas, 1995). Both mantle composition and magma composition were significantly modified by these processes, which indicate that the simple division of ophiolites into harzburgite and lherzolite types (Nicolas, 1988) is perhaps somewhat oversimplified. The high-temperature tectonite fabrics in the Bay of Islands mantle rocks are all essentially sub-horizontal and there is no evidence of diapirs. This would suggest that the mantle exposed here represents a sample derived some distance from a spreading ridge axis.

These three examples indicate that ophiolites have many first-order similarities, suggesting that oceanic lithospheric segments should also have many commonalities in structure and lithology, regardless of the tectonic environment in which the spreading centre was located. Nevertheless, ophiolites differ from the sampled parts of *in situ* oceanic lithosphere in many respects and the ophiolite model can only be validated by direct sampling of lower crustal layers.

CONCLUSIONS

Knowledge of oceanic crustal and mantle processes is fundamental to comprehending earth history and the formation of oceans and continents. We are still a long way from fully understanding these processes and their complex interaction, however, particularly at ocean ridges. Although the ophiolite analogy has been successful in giving us a first-order model for the origin of the ocean crust and related upper mantle, there are clearly problems inherent in carrying the analogy too far (Malpas, 1993). The main difficulty is that, when detailed geology is investigated, there are clearly different models for different ophiolites. Ophiolites also only provide us with *fossil* sections of the ocean lithosphere, and they are commonly overprinted by processes associated with obduction and post-obduction events.

Geophysical methods offer promise in resolving some of these questions. Without further ocean drilling, however, it is unlikely that we will ever be able to determine the average composition of the ocean lithosphere and develop a more complete understanding of the processes that have led to its evolution. The latter is critical to our evaluation of the lithosphere's economic and environmental importance and to the part it plays in geochemical cycling. It is to be hoped that progress will be made in drilling deep crustal sections. Of fundamental importance is a better understanding the transition zones between the oceanic layers, most particularly, the Moho. Obtaining long, uninterrupted sections of the plutonic part of the oceanic crust and coring a deep hole into the upper mantle will provide us with opportunities to understand magmatic, tectonic, and hydrothermal processes, including those associated with mantle partial melting as well as fractionation, magma mixing, assimilation, and eruption at crustal levels.

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