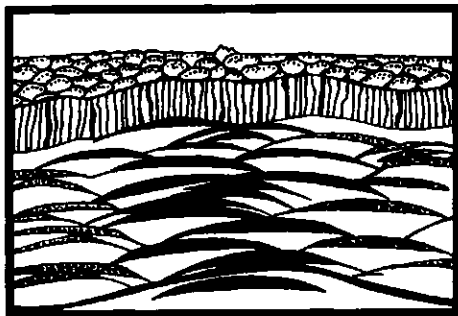


# ARTICLES



## Nature and Origin of the Oceanic Lithosphere: Some Insights from Past Ocean Drilling and Plans for the Future

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### SUMMARY

The Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) have fundamentally changed our understanding of the Earth system. Drilling in the south Atlantic Ocean provided the critical test of the theory of plate tectonics and initiated innovative programs to investigate the products, fluxes, and processes associated with the creation, evolution, and recycling of the oceanic lithosphere. Key findings include a new and evolving understanding of the range and complexity of processes of oceanic lithosphere creation, and their probable importance in global geochemical cycles and seawater composition over time. Major questions remain about details, rates, and significance of lithospheric processes and fluxes. The expanded

capabilities of the Integrated Ocean Drilling Program (IODP, to begin in 2003), will offer many exciting opportunities, including a chance to assess the role of lithospheric creation in global geochemical and climatic cycles.

### RÉSUMÉ

Le *Deep Sea Drilling Project (DSDP)* [projet de forages des fonds océaniques profonds] et le *Ocean Drilling Program (ODP)* [programme de forages océaniques] ont changé fondamentalement notre compréhension du système terrestre. Le forage de l'océan Atlantique sud a constitué le test déterminant de la théorie de la tectonique des plaques, et a permis de lancer des programmes d'étude inédits des produits, flux et processus liés à la création, l'évolution et le recyclage de la lithosphère océanique. Parmi les retombées de première importance se trouve cette compréhension nouvelle et en pleine évolution quant à l'étendue et la complexité des processus de création lithosphérique océanique et leur importance probable sur les cycles géochimiques planétaires et la composition de l'eau de mer dans le temps. D'importantes questions demeurent sans réponse quant aux détails, aux taux et à la portée des processus et flux lithosphériques. Les capacités accrues du *Integrated Ocean Drilling Program (IODP)* [programme intégré de forages des fonds océaniques] devant débuter en 2003 offrira de nombreuses perspectives stimulantes, dont une occasion d'évaluer le rôle de la création lithosphérique sur les cycles géochimiques et climatiques planétaires.

### INTRODUCTION

Ocean drilling has provided essential new insights into how the lithosphere, hydrosphere, and biosphere interact as oceanic crust is accreted in different geological

settings (e.g., mid-ocean ridges, oceanic plateaus) and during different stages of the life cycle of an oceanic plate. Over the past 30 years, exploratory drilling evolved into hypothesis-driven programs that developed new innovative technologies, such as bare-rock drilling guidebases and hydrological observatories, to achieve their goals. The Integrated Ocean Drilling Program (IODP) will build on the legacy of the DSDP and ODP through the use of a wide range of drilling platforms, establishment of observatories for long-term monitoring of active processes, and integration with other International Earth System programs. In this brief contribution, I highlight some key discoveries made by recent ocean drilling and introduce examples of the types of new problems to be addressed by the IODP.

### THE LEGACY OF THE OCEAN DRILLING PROGRAM, 1985–2003

The Ocean Drilling Program addressed a wide variety of fundamental lithospheric themes, including the genesis of actively forming ore deposits, emplacement of giant oceanic plateaus, and dynamics of oceanic crustal accretion. ODP developed many innovative drilling approaches in order to recover core from challenging environments, such as tectonic exposures of the lower crust and active hydrothermal systems. Integration, with rock properties, of bore-hole data obtained by down-hole logging has dramatically enhanced our knowledge of the ocean crust, especially in environments where core recovery is low. Another key technological advance was the development of hydrological observatories (Circulation Obviation Retrofit Kits, CORKs) for long-term monitoring of bore-hole properties (see Davis and Becker, 2001). Collectively, new data acquired by ODP have challenged many of our models of how the oceanic litho-

sphere is created and evolves. A selection of key new results and their implications follows.

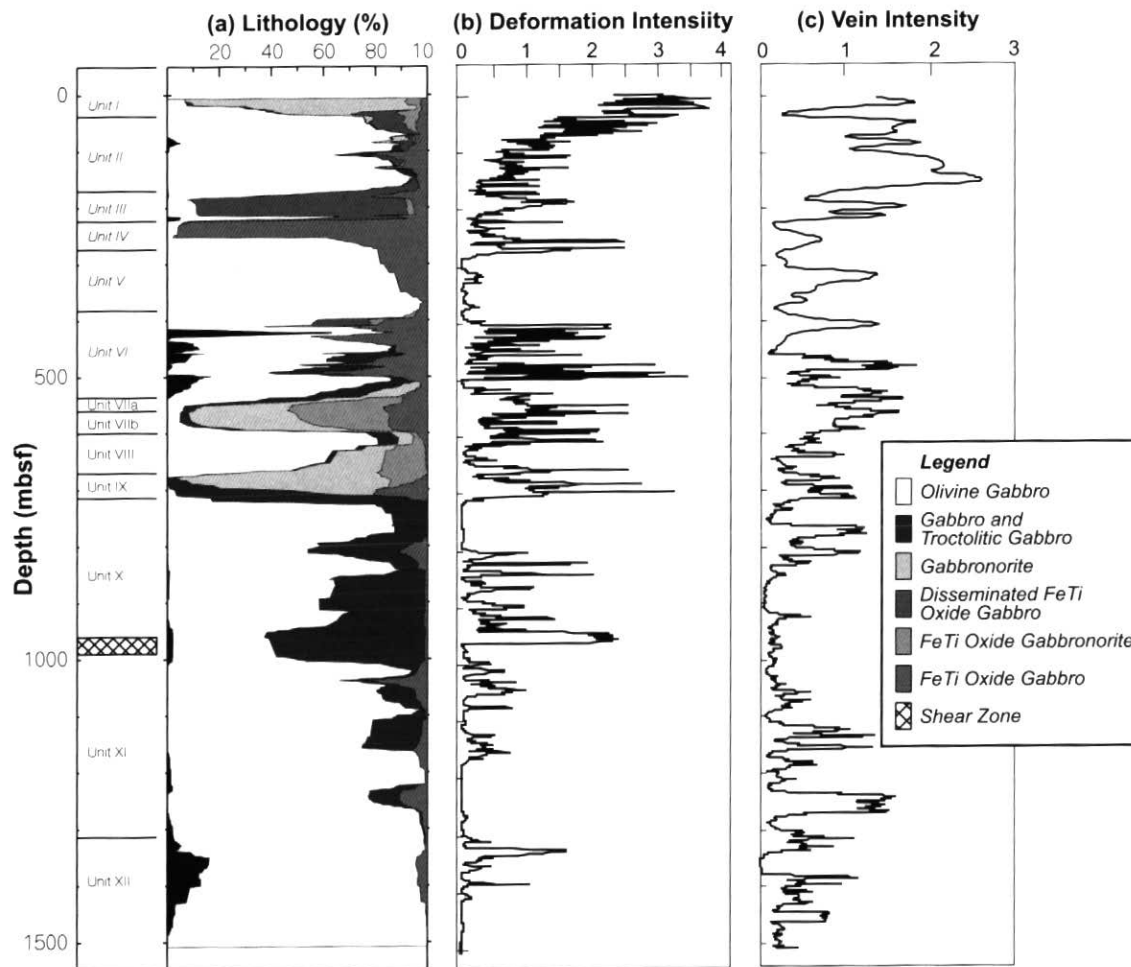
**Layered models for the structure of the oceanic crust are not applicable to slow-spreading ridges.** Field relationships in land-based ophiolites and marine seismic data have led to the broad acceptance of a layered model for the structure of the oceanic crust, in which pillow lavas and sheeted dikes are underlain by gabbro and mantle peridotite. Ocean drilling has shown, however, that such a simplified model is not appropriate for slow-spreading ocean crust. For example, DSDP Holes in young Mid-Atlantic Ridge crust (*e.g.*, Sites 334, 395, 556) show that gabbros and mantle peridotites can be overlain by a thin veneer of basalts, even in wide regions where the seismic structure appears to be “normally” layered

(Cannat *et al.*, 1995). Similarly, drilling in tectonic exposures of the lower crust created at slow-spreading ridges (Southwest Indian Ridge, Hole 735B; Mid-Atlantic Ridge, Holes 921E, 923A) illustrates the heterogeneity of the lower crust in terms of igneous mineralogy, deformation, and alteration (Fig. 1) on a scale that is not observed in most ophiolites (Dick *et al.*, 2000).

**Large Igneous Provinces (LIPs), *e.g.*, oceanic plateaus and volcanic rifted margins, are constructed over a very short time interval and can form by mechanisms that are independent of the plate tectonic cycle.** Drilling of the Kerguelen and Ontong Java oceanic plateaus suggests that major portions of these giant plateaus were constructed over very short time intervals (Frey *et al.*, 2000) and that the oceanic lithosphere

under them can be significantly thickened up to 30 km away from oceanic spreading centres. These results are consistent with the formation of giant plateaus by major mantle melting events that occur episodically in the geological record and are linked with hot mantle plumes that rise toward the surface from deep thermal boundary layers (Coffin and Eldholm, 1994). Drilling along the southeast coast of Greenland has shown that in some instances LIPs are linked with episodes of continental breakup and the initiation of seafloor spreading (see Loudon and Lau, 2001). However, LIPs that formed in intraplate settings, *e.g.* oceanic plateaus and aseismic ridges, resulted from crustal accretion mechanisms independent of plate tectonics.

**Seismic velocity boundaries do not always correlate with lithological**



**Figure 1** Lithostratigraphy of Hole 735B (ODP Legs 118 and 176) which penetrated 1.5 km (with 86% recovery) of 11 Ma lower crust that formed at the Southwest Indian Ridge. (a) Relative abundances of igneous rocks averaged over 20-m intervals. (b) Crystal-plastic deformation intensity from zero (undeformed) to four (ultramylonite). (c) Vein intensity by core % averaged over 2-m interval intensity (modified from Dick *et al.*, 2000).

transitions. ODP Hole 504B, the deepest basement drillhole (2200 m), penetrated the volcanic sequence and most of the sheeted dike complex and validated the ophiolite model for shallow ocean crust formed at intermediate spreading rates. Field and bore-hole seismic experiments, coupled with recovered core, demonstrated that the seismic layer 2/3 boundary in this setting lies *above* the dike-gabbro transition and probably is an alteration front rather than a lithologic boundary (Detrick *et al.*, 1994). In the vicinity of Hole 735B, a deep hole (1500 m) in gabbroic crust initiated in a tectonic exposure, seismic layer 2 velocities are prevalent in the upper 2-2.5 km of the crust rather than the expected layer 3 velocities (Muller *et al.*, 2000).

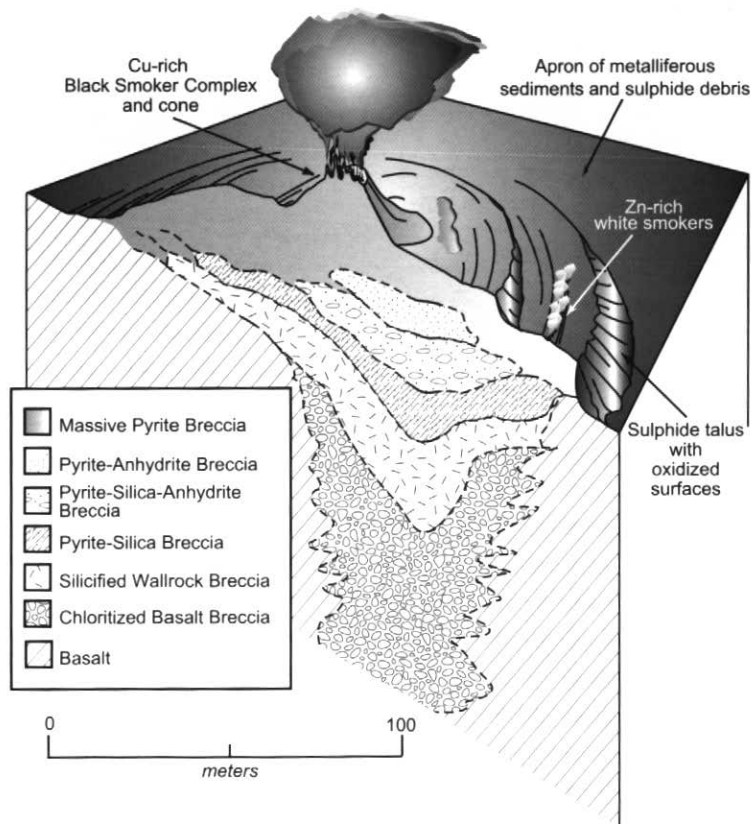
**Topographically driven hydrothermal circulation creates geochemical**

**heterogeneity in the upper ocean crust.** Alteration characteristics of the volcanic sequence at Hole 504B differ markedly from Site 896 situated approximately 1 km away on a topographic high. These 5.9-Ma rocks document considerable heterogeneity in the extent and nature of low-temperature alteration (Alt *et al.*, 1996), and show that the nature and extent of crustal alteration is not simply a function of age. Moreover, correlation of heat flow studies with paleo-seafloor bathymetry and alteration characteristics highlight the importance of topographically driven circulation in the shallow ocean crust (Fisher and Becker, 1995). For further details see Davis and Becker, 2001.

**Anhydrite plays a key role in the formation of Volcanogenic Massive Sulphide (VMS) deposits; surface**

**samples from hydrothermal mounds are not representative of the metal content of the whole deposit.** A series of offset holes drilled into the active Trans-Atlantic Geotraverse (TAG) hydrothermal deposit on the Mid-Atlantic Ridge demonstrated that the evolution of this sulphide mound is intimately linked to the entrainment of ambient seawater and the precipitation of massive anhydrite (Humphris *et al.*, 1995) (Fig. 2). The internal structure of the TAG deposit is strikingly similar to many ancient volcanogenic massive sulphide (VMS) deposits, including the abundance and types of breccia ores and sulphide conglomerates, as well as grade and tonnage (Hannington *et al.*, 1998). Periodic discharge of hot hydrothermal fluids in the same place over at least the last 20,000 years (Lalou *et al.*, 1995) resulted in cyclic growth of the mound and progressive remobilization of base and trace metals from its interior to its outer surface (Humphris *et al.*, 1995). Entrainment of ambient seawater into the mound during intermittent periods of hydrothermal discharge acted to cement sulphide breccias with anhydrite, whereas during periods of quiescence, dissolution of anhydrite contributed to mound collapse and the formation of conglomeratic breccias. These new observations have fundamentally changed our models for the formation of these types of VMS deposits because anhydrite is rarely preserved in ancient deposits (*e.g.*, Petersen *et al.*, 2000).

**Ocean crust buried by sediments at a young age shows significant heat and geochemical fluxes off-axis.** An 80-km drilling transect along the eastern flank of the Juan de Fuca ridge has revealed the extent to which fluid circulation in the flank environment of a sedimented ridge contributes to global geochemical and heat fluxes. Here, young crust spanning 0.5 - 3.5 Ma is buried by glacial turbidites. Seawater enters the crust at the ridge and at isolated basement exposures and flows laterally within permeable layers hosted in the upper volcanic rocks. Basement fluids become progressively more chemically evolved with distance from the ridge and broadly correlate with temperature, which ranges from 16°C to 63°C (Elderfield *et al.*, 1999). Large geochemical fluxes are implied by fluid compositions: the extent to which they



**Figure 2** Simplified cross-section through the TAG mound showing the distribution of different lithological zones as inferred from drilling results of ODP Leg 158. The upper part of the mound consists of massive sulphides and sulphide breccias locally overlain by cherts and Fe-oxyhydroxides and underlain by anhydrite-bearing breccias. Anhydrite is also exposed at the black smoker complex and locally at the surface of the upper platform. The subsurface stockwork is characterized by pyrite-silica breccias grading into silicified wallrock breccias and paragonitized and chloritized basalt at depth (modified from Humphris *et al.*, 1995).

discharge into the oceans is still largely unknown, however. A remarkable finding is that fluid flux rates are on the order of 1-5 m per year (Elderfield *et al.*, 1999), which is significantly faster than fluid flow in sedimentary basins and most other geological environments (Person and Baumgartner, 1995).

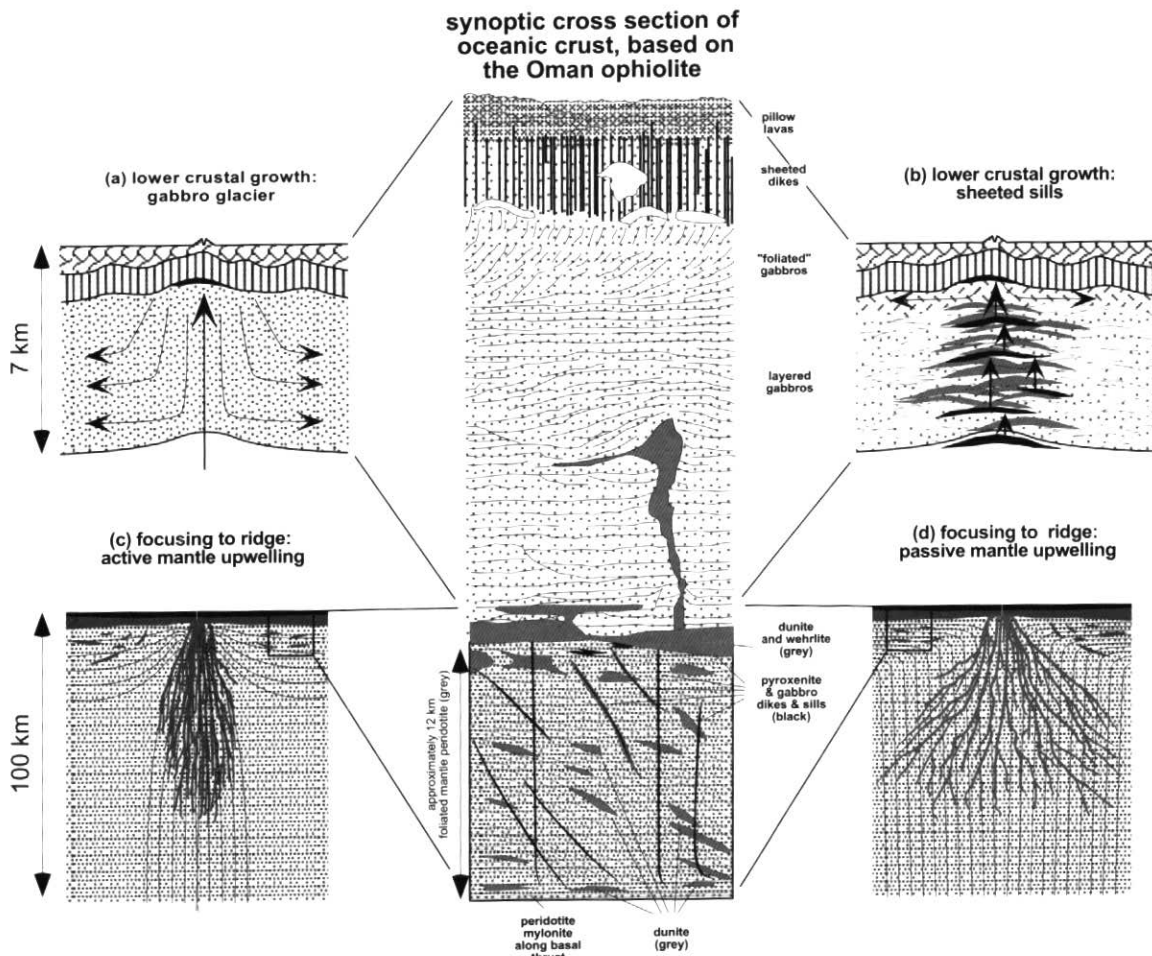
### NEW OPPORTUNITIES WITH THE INTEGRATED OCEAN DRILLING PROGRAM

The recent achievements of lithospheric drilling pose important new questions and lay a solid foundation for future ocean drilling. Newly developed drilling,

sampling, analytical, and *in situ* technologies will make possible innovative experimental approaches as well as the selection of hitherto technically challenging targets such as unsedimented, fractured rocks. The scientific themes for the IODP were developed during international conferences for riser drilling (CONCORD, 1998, = Report of the CONFERENCE on Cooperative Ocean Riser Drilling) and non-riser drilling (COMPLEX, 1999, = CONFERENCE on Multiple Platform EXploration of the ocean). These themes have been formulated into the IODP Initial Science Plan, 2003-2013, that is available from the IODP Web site

(<http://www.iodp.edu>). Here, a selection of these themes, taken primarily from the COMPLEX report, is highlighted in order to illustrate the breadth of new lithospheric problems that IODP will address.

**How is the oceanic lithosphere created?** New oceanic lithosphere is the primary product of plate tectonics. The flux of basaltic melt out of the mantle creates a distinct chemical boundary layer, made of lava flows, dikes, and gabbros. Seafloor basalts are fractionated relative to mantle-derived, parental liquids, and the composition of parental liquids is uncertain. The temperature structure of the



**Figure 3** Schematic illustrations of recently proposed models for igneous accretion of the lower crust at fast-spreading mid-ocean ridges, and for focussing melt extraction assuming channelized melt extraction from a melting region approximately 100 km wide in the mantle to a crustal accretion zone approximately 5 km wide beneath the ridge axis. (a) "Gabbro glacier" model in its simplest form. Ductile flow downward and outward from a single, shallow axial magma chamber constructs the lower crust. (b) "Sheeted sill" model with melt transport by hydrofracture and *in situ* emplacement of the lower crust by on-axis sill intrusions. In this model most gabbros are crystallized at their current depth of emplacement. (c) Focussed solid mantle upwelling (fine lines), due to buoyancy-driven convection, with mainly vertical melt transport. (d) Passive solid-mantle upwelling (fine lines), due to plate spreading, with coalescing melt conduits. Central panel is a summary cross section of the Oman ophiolite, where upper-mantle and lower-crustal exposures allow testing of these hypotheses. It is essential to determine whether specific features of ophiolites are representative of similar features beneath mid-ocean ridges and, if so, at what spreading rate (source: fig. 26, COMPLEX conference report, 1999).



oceanic crust is strongly affected by the depth of latent heat released by crystallization, thus the relative proportion of melt emplaced as lavas, sheeted dikes, and plutonic gabbros is critical to the thermal state of the oceanic lithosphere. Only a complete crustal mass balance can determine the composition of the net magmatic flux from the mantle, including the nature and geometry of newly created ocean crust in a variety of settings (Fig. 3). For this it will be necessary to drill through the entire crust, down to the Mohorovicic discontinuity. Such drilling should be feasible with the combined technology of riser and non-riser drilling. This objective is referred to in the Initial Science Plan as the 21st century "Mo-hole."

The composition and structure of the ocean crust varies with spreading rate as well as on a ridge segment scale. At slow-spreading ridges, drilling in young crust, and rock dredging around transform faults, have largely recovered peridotite and basalt with little gabbro, suggesting that the gabbroic layer is attenuated or absent near the ends of many ridge segments. Moreover, gravity and seismic studies have suggested that the crust thins near transform faults and small ridge offsets. There is also evidence that magmatic crustal production may vary with time at individual ridge segments. Higher rates of mantle upwelling

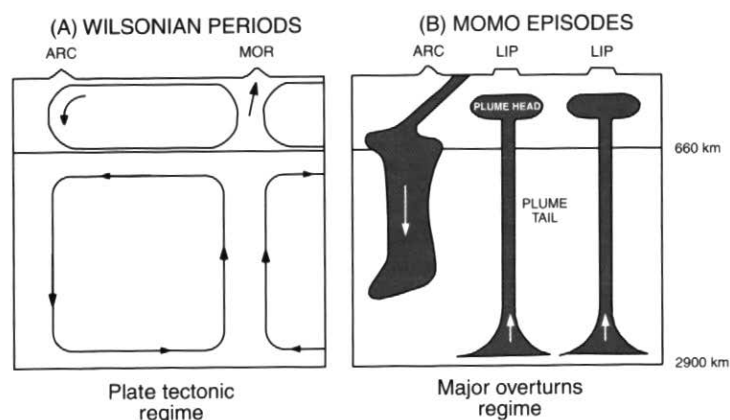
at the East Pacific Rise may lead to a more uniform crustal structure with a nearly steady-state melt lens near the top and bottom of seismic layer 3 (Fig. 3). In contrast, lower rates of mantle upwelling at slow-spreading ridges appear to lead to episodic accumulation of melt in magma chambers and a variable thermal gradient. This variability implies that the internal structure and composition of the lower crust should be different at slow- and fast-spreading ridges, a conclusion supported by the initial results of ODP drilling in tectonic windows, but not yet confirmed. IODP will drill a series of off-set holes in a variety of spreading regimes in order to determine the 3-D character of the lower ocean crust.

**What is the geological nature of seismic velocity structures?** The seismic velocity structure of oceanic crust and upper mantle allows us to make large-scale inferences about their composition and evolution because seismic properties result from a combination of factors, such as bulk mineralogy, pore distribution, alteration, temperature, and pressure. Acquisition of new data and samples from many localities has shown, however, that even the most fundamental correlations must now be questioned. A good example of this is seismic layer 2A, which is interpreted to be the volcanic carapace that hosts vigorous hydrothermal circulation in young crust, and disappears due to

a decrease in porosity caused by alteration processes in old crust (Jacobson, 1991). Re-evaluation of historical seismic data (Carlson, 1998) and new data (Greve-meyer and Weigel, 1996) has shown that layer 2A disappears when the crust is quite young ( $\leq 5-10$  Ma), implying that seawater circulation and crustal alteration cease within this timeframe. In contrast, global heat flow compilations show that significant advective heat loss continues until the crust is at least 65 Ma (Stein and Stein, 1994), and regional surveys indicate that local convection may continue within some of the oldest seafloor. These results emphasize the need to test our interpretations of remote seismic data by direct correlation with rock properties, requiring good recovery, *in situ* measurements, and coupled experiments in several geological settings.

**What are the time-integrated fluxes of fluids, heat, and chemistry associated with lithospheric creation and modification, and what are their impacts on global cycles?** The patterns of heat flow from the Earth's mantle through the ocean crust are fundamentally affected by two phenomena. One is the localization of magmatic processes primarily along constructional plate boundaries. The second phenomenon is the infiltration of seawater into fractured and porous lithosphere, which redistributes heat by advection. This process of advective fluid flow, coupled with chemical reactivity between seawater and oceanic rocks, leads to major fluxes of heat and mass within the lithosphere and between the lithosphere and the overlying ocean.

Alteration budgets for the crust and upper mantle need to be quantified at all stages of the life cycle of an oceanic plate, from its creation at a spreading center until it is subducted into the mantle. The rates of seawater cycling depend fundamentally on plate tectonic rates, so that first-order differences in seafloor spreading rates have profound consequences for seawater chemistry and global ocean-atmosphere cycles. Moreover, recent results indicate that the hydrologic isolation of the crust occurs at various rates and efficiencies depending on the sedimentation rates and sediment types, as well as basement topography (Fisher, 1998). Thus, heat and geochemical fluxes between the lithosphere and



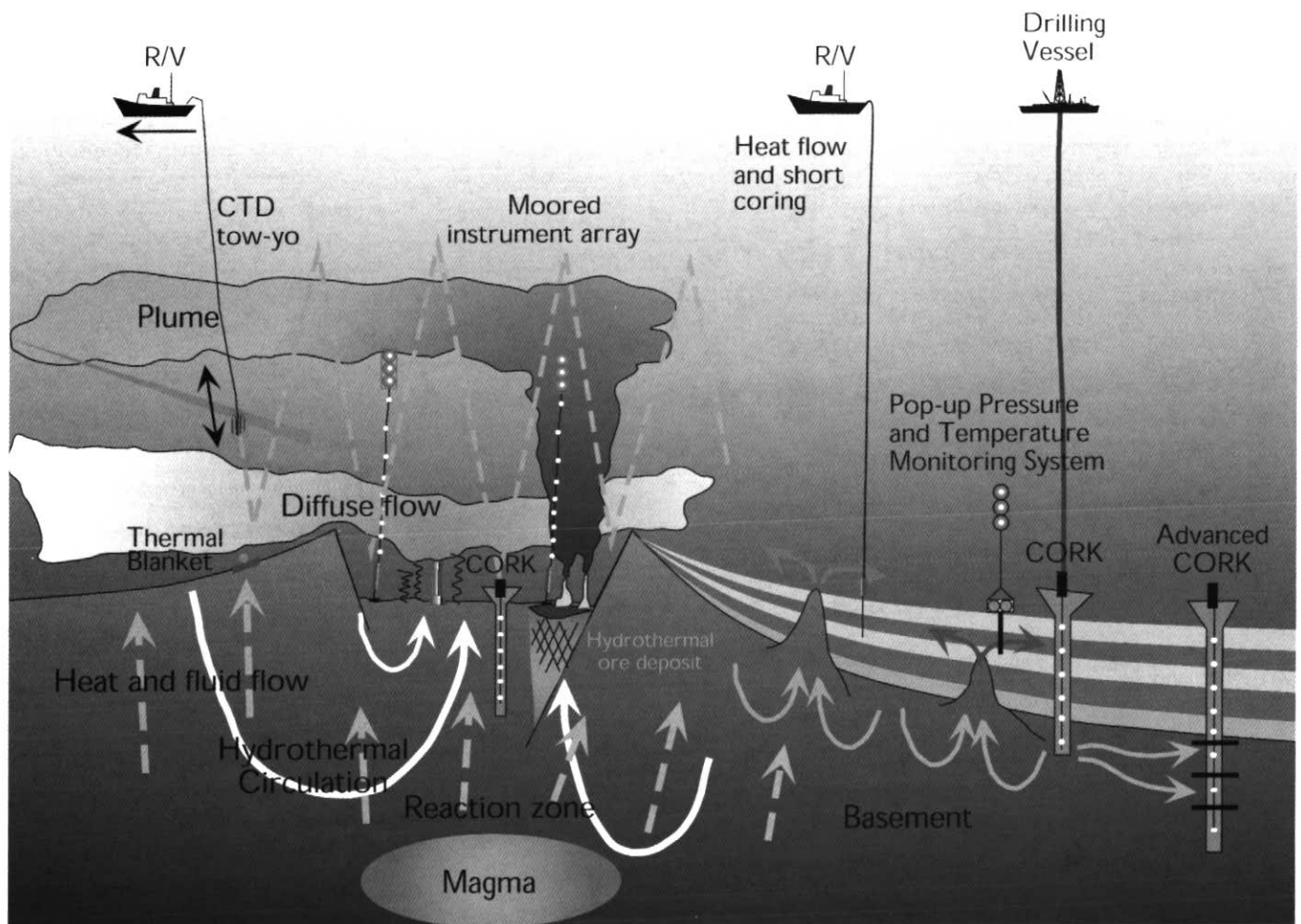
**Figure 4** Model of Wilson Cycle periods and mantle overturn and major orogeny (MOMO) episodes. (A) During Wilson Cycles, the normal mode of plate tectonics prevails, with opening and closing of ocean basins; mantle plumes originate predominantly from the base of the upper mantle layer, and continental growth is dominated by arc accretion. (B) During MOMO episodes, accumulated cold material descends from the boundary layer at 660-km depth into the lower mantle, and multiple major plumes rise from the core-mantle boundary to form large igneous provinces at the surface, creating a major overturn (modified from Stein and Hofmann, 1994).

oceans must be understood in terms of specific lithospheric properties. A “Mo-hole” drilled in older (>5 Ma), fast-spreading ocean crust will provide our first comprehensive data set for the bulk composition of mature crust. Complementary holes representative of the full range of spreading rates and sedimentation regimes must also be explored. These new data are critical for the development of meaningful global geochemical cycles, such as those for subduction zones (Plank and Langmuir, 1998).

**What is the mass and energy flux associated with Large Igneous Plateau emplacement and what is their environmental impact?** Large igneous provinces, including oceanic plateaus, volcanic rifted margins, continental flood basalt provinces, submarine ridges, and seamount chains, have been linked to massive

volcanic events that result from a mode of mantle convection different from that driving plate tectonics (Fig. 4). Today, mid-ocean ridge systems account for 95% of the heat and mass exchange from the mantle to crust, but at times in the past (e.g., Cretaceous period), LIPs may have contributed up to ~50% to these fluxes (Coffin and Eldholm, 1994). The consequences of these huge magmatic fluxes to the Earth’s environment are not well understood, but they have been linked to climate change, mass extinctions, and higher rates of seafloor spreading and hydrothermal activity (Coffin and Eldholm, 1994). LIPs may also have played a significant role in the early formation and evolution of the continental crust. A possible example of this comes from the Canadian Superior Province where Archean greenstone belts

are interpreted as collages of oceanic plateaus, oceanic island arcs, and trench turbidites (e.g., Desroches *et al.*, 1993; Polat and Kerrich, 2000). In order to understand the mantle dynamics associated with LIP formation, it is essential to study modern (Cretaceous and younger) LIPs, because the critical characteristics of many older LIPs have been obscured by collisional tectonics or removed by erosion. Study of modern LIPs will also contribute to our understanding of other planets, such as Venus, whose mass and energy fluxes are attributed to episodes of abrupt mantle turnover rather than plate tectonics. To fully characterize the nature of large oceanic plateaus will require recovery of long stratigraphic sections using a combination of the riser and non-riser technology of the International Ocean Drilling Program.



**Figure 5** Cartoon showing how a wide array of multidisciplinary borehole, seafloor, and sea-surface experiments could be integrated within one or more lithospheric settings. Abbreviations: R/V, research vessel; CTD tow-yo, conductivity-temperature-depth (ctd) instrument that is towed behind a ship so that it moves up and down like a yo-yo to get a detailed map of temperature and salinity (conductivity) in the water column (source: fig. 29, COMPLEX conference report, 1999).

## INTEGRATION WITH OTHER INTERNATIONAL AND MULTINATIONAL PROGRAMS

A key aspect of the new Integrated Ocean Drilling Program will be its integration and collaboration with other international and multinational programs, three of which are highlighted here. The first involves the InterRidge and RIDGE (US; Ridge InterDisciplinary Global Experiments) programs that are aimed at understanding the global mid-ocean ridge system. These programs will require the ability to establish long-term, *in situ* monitoring stations at mid-ocean ridges in order to address scientific questions related to active processes, such as hydrothermal systems and deformation (microseismicity, strain) (Fig. 5). The second program is the International Ocean Network (ION), which maintains a global grid of seismological stations in order to study deep earth structures. IODP will work closely with ION to install borehole seismometers in areas of the Global Seismic Network that are critical to study present-day mantle dynamics. The third program that will potentially work closely with IODP is the NEPTUNE project (North East Pacific Time-series Undersea Networked Experiments), which is currently in the planning phase. The NEPTUNE program will establish a network of underwater observatories within and along the boundaries of the Juan de Fuca plate. A goal of this network will be to provide real-time data for shore-based scientists to address a variety of scientific problems, ranging from intraplate deformation to monitoring of active hydrothermal vent sites. For each of these programs, IODP will play an essential role by drilling holes to house instruments, such as flow meters and seismometers, and providing innovative technology to seal these holes for long-term monitoring of parameters such as temperature, *in situ* pressure, and fluid compositions.

## FURTHER INFORMATION

More information about these programs may be obtained at these World Wide Web sites: 1) Ridge program: <http://ridge.occ.orst.edu/>; 2) InterRidge: <http://triton.ori.u-tokyo.ac.jp/~intridge/>; 3) ION: <http://www.seismo.berkeley.edu/seismo/ion/>; and 4) NEPTUNE: <http://www.neptunecanada.com/>.

Note that the host institution for each program changes on a yearly to bi-yearly basis.

## CONCLUSION

The unique legacy of outstanding scientific findings resulting from more than three decades of past ocean drilling sets the stage for challenging new efforts to understand the range and complexity of linkages between different parts of the Earth system, from lithospheric creation to climatic cycles. The Integrated Ocean Drilling Program, to begin in 2003, will offer a fundamentally new, multiple-platform approach in order to apply the whole range of modern expertise and technology to enhanced exploration of the Earth system.

## ACKNOWLEDGMENTS

I am grateful to Paul Robinson and Shiri Srivastava for their useful comments as journal reviewers of this paper.

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Accepted as revised 30 October 2001

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