

LARGE IGNEOUS PROVINCES

A WORKSHOP TO DEVELOP
SCIENTIFIC DRILLING INITIATIVES ON
VOLCANIC MARGINS AND OCEANIC PLATEAUS

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November 1990

The Large Igneous Provinces Workshop and
this report were sponsored by:

Joint Oceanographic Institutions, Inc.
1755 Massachusetts Avenue NW
Washington, DC 20036

and the

U.S. Science Advisory Committee

When citing this report, it should be referenced as:

Coffin, M.F., and Eldholm, O., eds., 1991, Large
Igneous Provinces: JOI/USSAC Workshop Report.
The University of Texas at Austin Institute for
Geophysics Technical Report No. 114.

Cover photo: Dipping basalt sequences in the Baie
d'Audierne region, Kerguelen Islands, southern Indian
Ocean. The Kerguelen Islands form the largest subaerial
expression of the Kerguelen Plateau, a large igneous
province characterized seismically by extensive horizontal
and dipping reflections within primarily igneous base-
ment. The Kerguelen Plateau was first drilled during
Ocean Drilling Program legs 119 and 120 in 1987/88.
Photo by M.F. Coffin.

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Acknowledgments

First and foremost, I acknowledge the support of the U.S. Science Advisory Committee and the Joint Oceanographic Institutions for supporting the LIPs Workshop and the publication of this report through award JOI 16-90. I thank the Bureau of Mineral Resources (Australia), the Terres Australes et Antarctiques Françaises (France), the National Science Foundation, and the State of Texas for supporting research which led to the idea for this Workshop. I am greatly indebted to Olav Eldholm, who amiably and invaluabley helped run the Workshop and write this report. Keith Cox, Dave Roberts, and Jerry Winterer devoted extraordinary energy and skills in running their respective working groups, and in providing input for this report. Henry Dick provided valuable insight into making a JOI/ USSAC Workshop and report effective. To all other Workshop participants (Appendix 2), as well as non-attendant contributors (Appendix 3), I extend sincere thanks for making the Workshop stimulating and productive, and for input into

this report. Toni Lee Mitchell deserves a very special thanks for her superb preparation, execution, and follow-up of the Workshop, all conducted with warmth and Grace. At UTIG I gratefully acknowledge Eric Rosencrantz and Larry Lawver for final editing; Judeene Blankenship and Tricia Denton for bibliographic entry; Lisa Gahagan, Becky Madsen, and the PLATES project for the production of Figure 1; Judith Haller for layout design and production; Patty Ganey-Curry for production; and Wayne Lloyd for drafting services. Janet Johnson and other Woods Hole staff were magnificent in helping to run the Workshop efficiently and hospitably, with great attention to details which made for a most productive and comfortable atmosphere. The salubrious setting and excellent service of the Swope Center of the Marine Biological Laboratory provided a welcome home, ably hosted and administered by Lou Ann King. Finally, copacetic Cape Cod November weather amazed us all with its benevolence.

Executive Summary

Recent research has documented important temporal, spatial, and compositional relationships among oceanic plateaus, volcanic passive continental margins, and continental flood basalt (CFB) provinces. High quality seismic data and a few scientific drill holes have shown that volcanic margins and oceanic plateaus comprise large extrusive constructions, which in some cases share temporal, spatial, and compositional characteristics with CFBs. Recognition of genetic similarities among these large igneous provinces (LIPs), which previously have been studied by different groups within the earth science community, prompted the JOI/USSAC-sponsored LIPs Workshop.

Much of our knowledge of oceanic LIPs is less than a decade old. LIPs represent major global events, whose genesis and evolution are directly linked to mantle dynamics. Large volumes of lava and associated intrusives are commonly produced in short episodes. Exceptions include some submarine ridges which record persistent extrusion as a plume trail. LIP emplacements may

be related to changes in rate and direction of plate motion, and their episodicity is not well known.

LIPs potentially had major effects on global environment, although these are as yet undocumented. The scale and timing of the large outpourings of lava, gas, particulate matter, and heat may have caused severe regional and global environmental stress that affected the chemistry and circulation of both the hydrosphere and atmosphere, and changed basin geometries, which in turn modified ocean circulation, gateways, and sea level. Nonetheless, little quantitative information is available to constrain mantle and crustal processes, to reliably predict environmental effects of oceanic LIP formation, or to constrain LIP dimensions, duration and rate of emplacement, geochemical and petrological signature, crustal structure, and relationship to tectonism.

Oceanic plateaus and volcanic margins offer excellent laboratories to study the internal processes and external consequences of LIP emplacements. Successful drilling critically

depends on high-quality site survey and other preparatory work. Only drilling will substantially address many fundamental problems. The Workshop recommends that:

- ◆ Volcanic margin and oceanic plateau drilling become an integral part of future drilling programs using an approach reconciling the need for both exploratory and focused, problem-oriented sites. Transect drilling will be the principal strategy, supplemented by holes of “opportunity”, and is compatible with magmatic, tectonic, and paleoenvironmental objectives. Significant advances will be made with present drilling technology integrated with comprehensive logging programs and vertical seismic experiments for deep holes.
- ◆ Each drilling transect sample key sedimentary, igneous, and metamorphic rock units, tied to off-LIP reference holes in normal oceanic crust and/or on the continental margin. Moderately deep (500-1000 m) basement penetration should be achieved to establish the igneous stratigraphy of each oceanic LIP. All other holes should penetrate ~150 m of igneous basement.
- ◆ Conjugate volcanic margin transects include arrays of closely-spaced holes across the margin (4-7 plus reference holes), augmented by single holes to evaluate along-strike variability, such as hotspot influence. North Atlantic margins are targets; areas with thin sediment would allow penetration deep into the extrusive pile.
- ◆ Hotspot/plume source evolution from a CFB across a volcanic margin to an oceanic plume be studied (≤ 10 holes) along the plume trail. Potential targets are the Greenland-Scotland Ridge, Walvis Ridge-Rio Grande Rise, and Deccan-Réunion hotspot tracks.
- ◆ One of the two huge oceanic plateaus, Kerguelen or Ontong Java, be drilled along longitudinal and latitudinal transects (10-15 sites plus reference holes) to examine variations in age and composition; and a purely oceanic plateau, e.g., Manihiki, Shatsky, or Hess, be drilled (~5 holes) to characterize the crustal composition of one LIP end member.
- ◆ Because optimal site density is now unknown, the first phase of drilling be focused on selected holes to estimate variability along the transect; further drilling would be contingent on initial results.

Since the Second Conference on Scientific Ocean Drilling (COSOD II), exciting new research has been undertaken on LIPs. Volcanic passive margins (Leg 104) and oceanic plateaus (legs 119, 120, and 130) have been foci of the Ocean Drilling Program, and CFB provinces have been targets of major geological investigations, especially the Deccan Traps in relation to K-T boundary controversies (e.g., *Macdougall*, 1988). Plume and hotspot models have been recently advanced to account for both oceanic and continental LIPs (e.g., *Duncan and Richards*, 1991; *Hill*, 1991). A prime impetus for convening this Workshop was the realization that scientists working on volcanic margins, oceanic plateaus, and CFB provinces had very little interaction with one another. This Workshop was viewed as a means of resolving that problem, and in particular to direct scientists' attention to developing scientific drilling initiatives on oceanic LIPs.

Aside from this Workshop, high scientific interest in LIPs has manifested itself in other scientific meetings. Within a year, at least three other conferences concerned with LIPs have met or will meet:

- ◆ *Volcanisme Intraplaque. Le Point Chaud de la Réunion*—12-17 November 1990, Réunion. 113 participants.
- ◆ *Caltech Mantle Plume and Hotspot Symposium*—2-4 May 1991, Pasadena. 115 participants.
- ◆ *Magmatism and the Causes of Continental Break-up*—3-4 October 1991, London. Limited to 160 participants.

This intense consideration of LIPs has arisen, in part, from the important reconnaissance drilling of the Rockall, Vøring, Kerguelen, and Ontong Java plateaus over the past 10 years. The *JOIDES Resolution* continues to be a required and valuable geoscientific tool, and can now address specific scientific problems involving magmatic and tectonic processes in the mantle and crust associated with LIP emplacement, as well as the role of LIPs in global change. However, as past exploratory drilling of a few LIPs has proven, we may be missing fundamental data if more such holes are not drilled. The drilling strategies which arose from the Workshop endeavor to address most aspects of LIPs of which we are now aware.

Definitions and Acronyms

- CCD**—Carbonate Compensation Depth—the level in the ocean below which the rate of solution of calcium carbonate exceeds the rate of its deposition.
- CFB**—Continental Flood Basalt—huge volumes of homogeneous tholeiitic magma erupted in a very short time.
- COSOD I**—Conference on Scientific Ocean Drilling I—Austin, Texas, 1981.
- COSOD II**—Conference on Scientific Ocean Drilling II—Strasbourg, France, 1987.
- COT**—Continent-Ocean Transition—the transitional region between continental and oceanic crust at continental margins.
- DMM**—Depleted MORB Mantle—the source of mid-ocean ridge basalts, and a component in magma mixing models.
- DSDP**—Deep Sea Drilling Project—the predecessor (1968-1983) of the Ocean Drilling Program.
- DUPAL**—*Dupré and Allègre* (1983)—a southern hemisphere isotopic anomaly defined by enhanced content(s) of EMI, EMIL, or HIMU.
- EMI**—Enriched Mantle I— $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.5124-0.5125 and $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7050-0.7055, a component in magma mixing models.
- EMII**—Enriched Mantle II— $^{87}\text{Sr}/^{86}\text{Sr} > 0.7065$, a component in magma mixing models.
- ESP**—Expanding Spread Profile—a spatially localized, wide-angle reflection/refraction survey using two ships, a multichannel receiver array, and high-resolution navigation.
- HIMU**—High μ ($^{238}\text{U}/^{204}\text{Pb}$), in which $^{206}\text{Pb}/^{204}\text{Pb} > 20.5$; a component in magma mixing models.
- Hotspot**—a relatively localized region of persistent igneous activity and/or uplift whose cause underlies the lithosphere and does not share its motions. Hotspots may be the expression of narrow, ascending mantle plumes.
- IRD**—Ice-Rafted Debris—material such as boulders or till which is deposited by the melting of floating ice containing it.
- JOI**—Joint Oceanographic Institutions, Inc.—the managing body of the Ocean Drilling Program; the prime contractor to the National Science Foundation; a consortium of ten United States Oceanographic Institutions which provides management support of large, multi-institutional research programs.
- JOIDES**—Joint Oceanographic Institutions for Deep Earth Sampling—an international group of scientists representing United States institutions and international partner nations; provides planning and advice on scientific goals and objectives, facilities, scientific personnel, and operating procedures.
- K-T**—Cretaceous-Tertiary.
- LIP**—Large Igneous Province—a region characterized by transient large-scale intrusive and extrusive activity, including CFB provinces (e.g., Deccan Traps), volcanic passive margins (e.g., Vøring Margin), oceanic plateaus (e.g., Ontong Java Plateau), ocean basin flood basalts (e.g., Caribbean Flood Basalts), and large seamount chains (e.g., Hawaiian-Emperor).
- Plume**—a localized body of magma rising into the crust from the mantle and thought to be the cause of a “hotspot.”

- MCS**—Multi-Channel Seismic—seismic reflection data acquisition and processing in which the data from different hydrophone groups are combined by the common midpoint method.
- MORB**—Mid-Ocean Ridge Basalt—basalt erupted at a seafloor spreading axis.
- NAVP**—North Atlantic Volcanic Province—the area affected by Tertiary and Quaternary volcanism centered on Iceland and including Greenland, Faeroe, United Kingdom, and offshore intrusive and extrusive bodies, including dipping reflection sequences.
- OAE**—Oceanic Anoxic Event—an interval marked by the deposition of sequences of black, organic-rich (1-30%), laminated muds and shales in an oxygen deficient or anoxic environment, overlain and underlain by well-oxygenated biogenic sedimentary sequences.
- Oceanic Plateau**—a broad, more or less flat-topped and ill-defined elevation of the seafloor, generally rising 2000 m or more above the surrounding seafloor and isolated from the major continents and continental islands. Their crustal thickness is anomalously greater than that of adjacent oceanic crust. In this report we do not include microcontinents without major extrusive cover (e.g., Lord Howe Rise, Seychelles Bank) as LIPs.
- ODP**—Ocean Drilling Program—an international effort to explore the structure and history of the ocean basins; its focus is to provide core samples and data from downhole experiments in the ocean basins, and to provide facilities for the study of these samples and data.
- OIB**—Oceanic Island Basalt—basalt erupted on the seafloor away from a mid-ocean ridge spreading axis.
- Seamount**—an elevation of the seafloor, 1000 m or higher, either flat-topped (called a guyot) or peaked (called a seapeak). Seamounts may either be discrete, arranged in a linear or random grouping, or connected at their bases and aligned along a ridge or rise.
- SOPITA**—South Pacific Isotopic and Thermal Anomaly—anomalous Sr, Nd, and Pb isotope signatures of South Pacific islands and seamounts, different from DUPAL and including HIMU, and anomalous thermal character of the South Pacific ocean floor.
- Strangelove Ocean**—an ocean with no carbon isotope gradient, i.e., homogeneous $\delta^{13}\text{C}$ in both deep and surface water masses. This condition existed at the K-T boundary.
- Submarine Ridge**—an elongate, steep-sided elevation of the ocean floor, commonly having rough topography, and created at least in part off the axis of a spreading center.
- Superswell**—a huge, broad, elongate, smooth elevation of the ocean floor (e.g., South Pacific Superswell).
- Swell**—a broad, elongate, smooth elevation of the ocean floor (e.g., Hawaiian swell).
- USSAC**—United States Science Advisory Committee—the group which makes scientific and policy recommendations to the USSSP (United States Science Support Program). Its mandate includes planning, site development, scientists' support, downhole instrument development, and education/public information.
- Volcanic Passive Margin**—a passive continental margin characterized by significant volcanism and uplift during continental breakup. The margin formation is commonly associated with extrusive and intrusive activity, and the lower crust is commonly characterized by high-velocity bodies (e.g., Vøring Margin).
- VSP**—Vertical Seismic Profiling—measurements of the response of a geophone at various depths in a borehole to shots near the sea surface. Where the source is moved to increasing distances from the well head, the result is a "walkaway" VSP.

Sources include *Bates and Jackson (1987)* and *Sheriff (1991)*.

Introduction

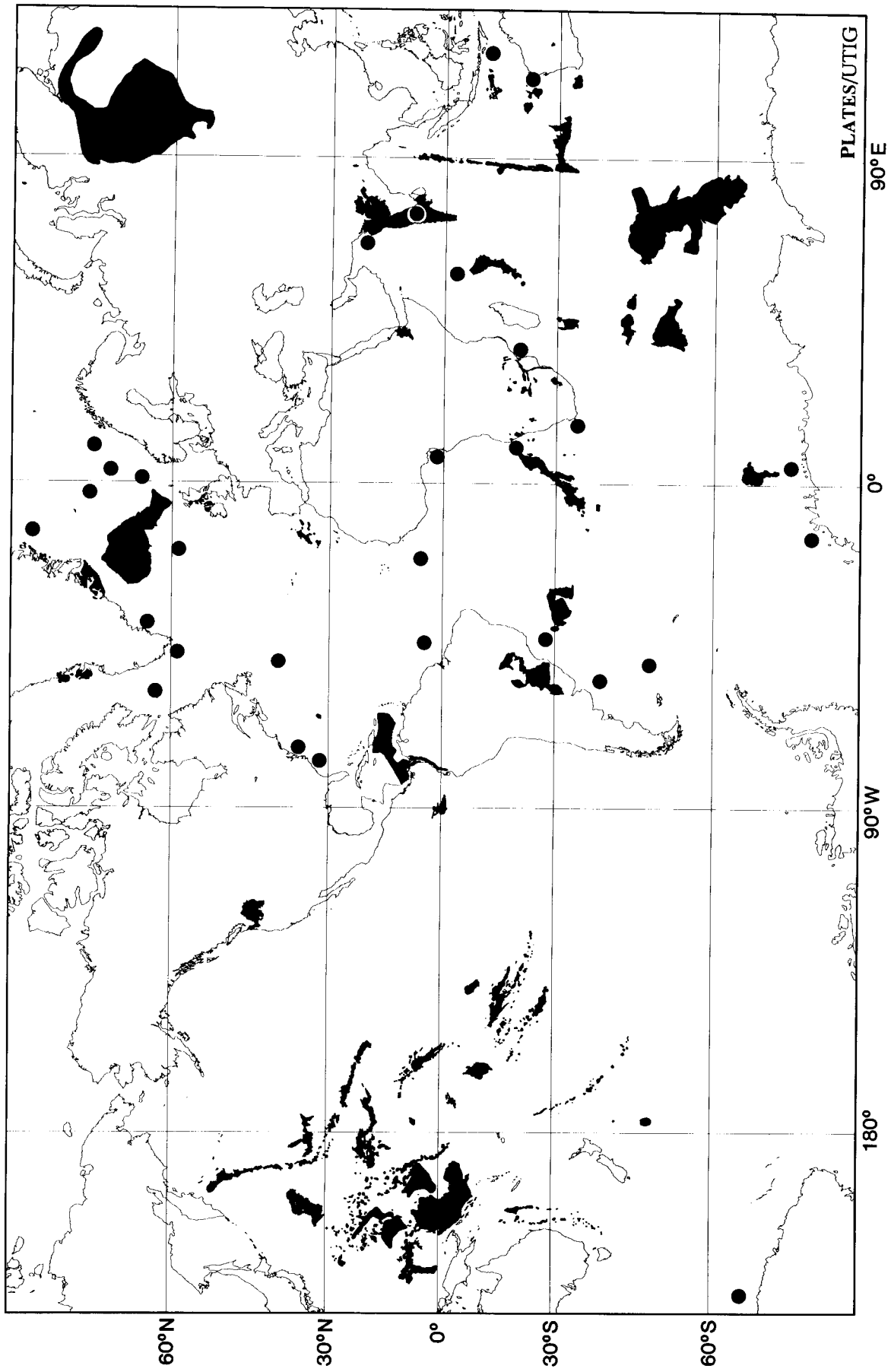
Background

Episodes of magmatism have resulted in the emplacement of LIPs including CFB and associated intrusive provinces; volcanic passive margins; oceanic plateaus; submarine ridges; ocean basin flood basalts; and seamount groups. In the oceanic realm, high-quality seismic data and a few scientific drill holes have shown that volcanic margins and oceanic plateaus comprise extensive constructions of extrusive igneous rock. In some cases volcanic margins and oceanic plateaus share temporal, spatial, and compositional characteristics with CFBs. The sizes and distribution of LIPs on a global scale demonstrates that their emplacements are major geological events (Fig. 1).

Reconnaissance drilling, in conjunction with analysis of seismic data, on volcanic passive margins (Roberts, Schnitker, *et al.*, 1984; Eldholm, Thiede, Taylor *et al.*, 1987) and some oceanic plateaus (Schlich, Wise, *et al.*, 1989) indicates that the upper parts of the basalt sequences in both provinces were commonly emplaced subaerially, similarly to CFBs. On the other hand, basalt cored from three sites on the Ontong Java Plateau was emplaced in a submarine environment (Kroenke, Berger, *et al.*, 1991). Geochemical studies of rocks from plateaus and volcanic margins suggest lower to upper mantle sources for the magma, with regional variations due to mantle heterogeneities and the nature of the crust through which the magma passed (e.g., Macdougall, 1988; Roberts,

Schnitker, *et al.*, 1984; Eldholm, Thiede, Taylor, *et al.*, 1989; Mahoney *et al.*, 1990; Wise, Schlich, *et al.*, in press).

CFB provinces have been studied for many years, and much knowledge has been gained about the nature and composition of their extrusive component (e.g., Macdougall, 1988; Upton, 1988; Reidel and Hooper, 1989). Little, however, is known about the deeper components. Our lack of knowledge of oceanic plateau and volcanic margin igneous rock is still more profound; to date only one drill hole (Site 807, Ontong Java Plateau; Kroenke, Berger, *et al.*, 1991) has penetrated deeper than 100 m into oceanic plateau basement, and only two (sites 553, Rockall Plateau, Roberts, Schnitker, *et al.*, 1984; and 642, Vøring Plateau, Eldholm, Thiede, Taylor, *et al.*, 1989) more than 100 m into volcanic margin basement. In fact, so little is known of all provinces that even volume estimates are difficult to make. It appears, however, that the largest of conjugate volcanic passive margin (Eldholm and Grue, submitted) and oceanic plateau (Coffin, 1991) provinces may include much more igneous rock than most CFB provinces (e.g., Huffman, 1990). Furthermore, the rate of emplacement of the most voluminous LIPs appears to have been comparable to or exceeded that of the contemporary mid-ocean ridge system over time intervals of a few million years (e.g., Coffin, 1991), although only the uppermost extrusive rocks of a few LIPs have been reliably dated.



The realization that LIPs on land and under the sea may share common elements in their origin and evolution, and the fact that interaction among geoscientists working on volcanic margins, oceanic plateaus and swells, and continental igneous provinces has not been extensive, provided strong impetus for convening the LIPs Workshop.

The most salient observations regarding LIPs are the large volumes of lava produced and the short durations of their emplacement phase. As new data have become available, estimates of volumes of extrusive and intrusive magmas have increased. Timing has become more closely constrained, revealing the transient nature of many of these features. Exceptions include some oceanic plateaus and ridges which reflect a more continuous extrusion process along interpreted plume trails. Consequently LIPs preserve a history of mantle circulation patterns and temperatures. Moreover, emplacement of LIPs may be linked to "instantaneous" plate tectonic events such as changes in rate and direction of plate motion. In this context, possible episodicity of eruptive events is highly important. Several models for the emplacement of LIPs, primarily associated with mantle plumes, have been proposed, but are currently poorly constrained.

In addition to recording internal Earth processes, the formation of LIPs may have had significant external consequences. Much geoscientific discussion has focused on causes of extinctions at the K-T and other boundaries. The scale and timing of eruptive activity associated with LIPs formation could have exerted severe regional and global environmental stresses at intervals throughout the geologic record, and may have been a single or a contributing cause of extinction events. Large-scale outpourings of gases and particulate matter may have significantly affected the chemistry and circulation of both the oceans and the atmosphere, and changes in basin geometry have modified gateways, ocean circulation, and sea level.

LIPs Workshop

The JOI/USSAC-sponsored "Large Igneous Provinces: A Workshop to Develop Scientific Drilling Initiatives on Volcanic Margins and Oceanic Plateau" was convened at the Woods Hole Oceanographic Institution from November 4-6, 1990 (Appendix 1). Thirty-eight scientists representing 8 JOIDES member organizations, 14 non-JOIDES academic and governmental institutions, and 2 private industries attended (see Appendix 2). The workshop attracted specialists on volcanic passive margins, oceanic plateaus, and CFBs with the aims of gaining a better understanding of the formation and evolution of LIPs, and of determining how ODP may contribute towards this goal.

The objectives of the Workshop were twofold:

- 1) to develop suites of drilling objectives for volcanic passive margins and oceanic plateaus based on global thematic perspectives tempered by important regional considerations, and
- 2) to widen scientific expertise in developing drilling experiments to solve global thematic problems.

The Workshop did not consider mid-ocean ridges and individual seamounts; these have been foci of previous workshops, and in most cases are easy to distinguish from oceanic LIPs on the basis of transience and scale, respectively. Distinctions between small submarine ridges/plateaus and large seamounts are, however, somewhat arbitrary. The amount of igneous material emplaced is primarily a function of source intensity, lithospheric plate speed over that source, and the thickness and thermal state of the lithosphere. The difference between a seamount and a submarine ridge may in the simplest case be a function of how long a portion of lithospheric plate was situated in the vicinity of ascending asthenosphere. One example of our arbitrary distinction is the inclusion of the Mid-Pacific Mountains, and the exclusion of the New England Seamounts, in our consideration of LIPs.

◀ *Figure 1. Global LIPs. Volcanic passive continental margins along which seaward dipping reflector sequences have been recognized are indicated by circles. Based on Hinz (1981); additional data from Coffin and Eldholm (in prep.), D.G. Roberts (pers. comm.), E. Rosencrantz (pers. comm.), and T. Shipley (pers. comm.). Digital map courtesy of PLATES Project, UTIG (L. Gahagan and B. Madsen).*

The Workshop began and ended with plenary sessions intended to introduce the topic of LIPs and to summarize its proceedings, respectively. For most of the three days, participants attended three working group sessions which focused on particular LIP topics. A detailed agenda appears in Appendix 1. Keynote presentations at the start of the Workshop included overviews of the main types of LIPs, and specific topics addressed were the geochemistry, paleoenvironmental consequences, subsidence histories, and drilling prospects of LIPs. Presentations by Mike Coffin, Keith Cox, Olav Eldholm, Loren Kroenke, Marcia McNutt, Jason Morgan, Chuck Officer, Mark Richards, Dave Roberts, Mike Storey, and Jerry Winterer set the stage for more detailed working group deliberations.

One working group, led by Keith Cox, addressed the petrology, geochemistry, and dating of LIPs. The group examined lithospheric and asthenospheric circulation; the plate settings of LIP emplacement and the relationship to continental breakup; the temporal and spatial distribution of LIPs; and LIP source compositions, partial melting, fractionation history, and lithospheric contamination. A second working group, led by Dave Roberts, concentrated on conjugate volcanic passive margin and plateau development. Topics addressed included heating of the lithosphere and magma production; igneous emplacement mechanisms, location, and timing; pre-, syn-, and post-rift horizontal and vertical movements; and structure of the volcanic margins and the continent-ocean transition. The third working group, chaired by Jerry Winterer, studied global paleoceanography, paleoclimate, and paleoenvironment. Discussions concerning the paleoenvironmental impact of LIPs focused on paleoclimate, ocean warming, and sea level; paleoceanography—circulation, gateways, chemistry, productivity, and evolution; and the

terminal Cretaceous event and other mass extinctions. More than twelve hours of formal working group meetings, plus at times intense refreshment break and mealtime discussions, resulted in effective cross-disciplinary exchange of ideas.

The Workshop clearly documented links among CFBs, volcanic margins, and oceanic plateaus, and showed that their genesis and evolution must be ascribed to fundamental global earth processes. Moreover, it is plausible, though not yet documented, that the emplacement of LIPs has had far-reaching effects on the Earth's environment. Frequent reference was made to the fact that our knowledge of LIPs is at a nascent stage but rapidly growing. More geologic and geophysical work, including both deep drilling and site surveys, are needed to address even the most rudimentary LIP problems.

Oceanic plateaus and volcanic margins form excellent laboratories to study both internal processes and external consequences associated with LIPs. Sampling the igneous rock as well as the relatively undisturbed interbedded and overlying sediment of the volcanic edifices will provide a record of LIP genesis and evolution, as well as calibrate thermal models of the mantle. The Workshop has documented that only drilling will substantially address these fundamental problems which are central in the ODP Long Range Plan (*JOI*, 1990). Several LIPs drilling strategies arose from the working groups, and these recommendations comprise the major result of the Workshop.

This report represents contributions from all 38 scientists who attended the Workshop as well as comments and revisions from 15 additional scientists who were solicited to review the first draft (see Appendix 3). A broad segment of the geoscientific community has had input into this report.

LIPs and the ODP Long Range Plan

Long Range Plan

Major scientific themes associated with LIPs which emerged from the workshop concern their emplacement mechanism(s), emplacement history, spatial and temporal geologic and geophysical evolution, and paleoenvironmental impact. These topics coincide closely with those of the ODP Long Range Plan (JOI, 1990), which summarized the results of the first and second conferences on scientific ocean drilling (COSOD I, 1981 and COSOD II, 1987), as well as the JOIDES thematic panels' white papers (LITHP, 1988; SOHP, 1989; TECP, 1989; SGPP, 1990). As described in the Long Range Plan, scientific interest in ocean drilling falls into four themes, of which three involve LIPs. These three themes, their pertinent sub-themes, and their relevance to LIPs are as follows:

Structure and Composition of the Crust and Upper Mantle

Understanding how the solid earth has evolved through time requires knowledge of the structure and composition of the oceanic crust and underlying mantle. Plate tectonics has provided the basic kinematic framework for these studies, and a process-oriented approach involving quantification and modeling of the actual physics and chemistry involved in this solid earth geochemical system is underway.

Structure of the Lower Oceanic Crust and Upper Mantle

The deep crustal and upper mantle structure of volcanic margins and oceanic plateaus is very

poorly known on both seismic and drill hole scales. Few high-energy, long-receiver, British Institutions Reflection Profiling Syndicate (BIRPS)-style seismic reflection profiles across volcanic margins or oceanic plateaus have been reported on in the literature, and modern seismic refraction experiments have been limited to the Norwegian, Greenland, Rockall, and US East Coast volcanic margins, and to the Kerguelen Plateau. A common lower crustal feature resulting from the few refraction experiments is a 7.2-7.5 kms^{-1} layer which has been variously ascribed to underplating, expanded oceanic crust, or serpentinization of peridotite. No scientific or industrial drilling has penetrated deeper than 914 m (Site 642) into the ~20 km thick igneous crust of a volcanic margin, or deeper than 149 m (Site 807) into the ~40 km thick igneous crust of an oceanic plateau.

Magmatic Processes Associated with Crustal Accretion

Crustal accretion is a complex interaction among magmatic, tectonic, and hydrothermal processes, all of which are poorly understood. Different types of crustal accretion on volcanic margins have been proposed based on seismic reflection data that primarily image the upper igneous crust. Drilling provides a means to distinguish among various models and to develop new models, yet igneous basement has been recovered from only two volcanic margins—Vøring and Rockall. No model has as yet been advanced for the crustal accretion process in large oceanic plateaus, in no small part due to the paucity of high-quality seismic reflection and refraction data

from the features. As for melt generation, quite different models have been suggested to account for extensive volcanism observed at volcanic margins and oceanic plateaus. An important component in testing these models is borehole data, which uniquely allows us to address questions of emplacement rates and thermal history.

Intraplate Volcanism

Intraplate volcanism is the second most common type of volcanic activity in ocean basins. Why and how intraplate volcanism is initiated are important unresolved questions. Oceanic plateaus are the thickest crustal emplacements of basaltic material on Earth, and the temporal variability of their emplacement can be addressed solely by drilling. Volcanism is believed to be preceded by thermal uplift of oceanic lithosphere which forms swells and superswells. The evolution of a mantle plume through time can be examined only through drilling, which in turn can provide constraints on lithospheric deformation and behavior associated with that plume as well as the composition and chemical evolution of the mantle. Much intraplate volcanism has been attributed to mantle plumes, and various plume models have been developed recently.

Dynamics, Kinematics, and Deformation of the Lithosphere

Tectonic processes operate on many scales in the oceanic lithosphere, and development and testing of dynamic and kinematic models are necessary to better understand these processes. Definition of plate driving forces, plate boundary dynamics and deformation, and overall mantle/crust structure (through seismic tomography) is fundamental to geoscience.

Dynamics of the Oceanic Crust and Upper Mantle

The relative importance of the diverse forces—ridge-push, trench-pull, and plate-drag—which act on lithospheric plates and make them move is unresolved. Furthermore, stresses that act upon the lithosphere at and near plate boundaries are poorly understood. The initiation and construction of volcanic margins and oceanic plateaus are complex interactions between pre-existing lithosphere and new material being added to the mantle

and crust during the emplacement phase. Global sampling and petrologic/geochemical analyses of LIPs material can constrain temporal and spatial geochemical variability of the mantle. Furthermore, drill holes provide an opportunity for higher-resolution tomographic experiments which are vital to our understanding of mantle structure, which may or may not be anomalous beneath LIPs.

Plate Kinematics

Knowledge of past plate configurations is necessary to a full understanding of long-term global change, including paleoclimatology and paleoceanography. The trails of mantle plumes are important recorders of past plate motions, and dating of these plumes allows construction of global reference frames. Paleomagnetic determinations from LIPs rocks contribute significantly to knowledge of past plate configurations.

Deformation Processes at Divergent Margins

Divergent margins are among the most prominent physiographic features on Earth. As higher quality seismic reflection data are acquired along divergent margins, more and more of these margins are observed to have major volcanic components. Pure shear and simple shear models predict different patterns of subsidence, sedimentation, and volcanism, and the most straightforward way to test them is to sample sediment and volcanic rock which accumulated during rift and early post-rift phases. The cause of continental breakup, whether passive rifting, hotspot weakening, or some other mechanism, has not been determined for most margins; although some LIPs are clearly associated with continental breakup and plate separation, others are demonstrably not, and thus their precise role in plate separation is not known.

Intraplate Deformation

Those LIPs which are emplaced in mid-plate settings offer the opportunity to study lithospheric behavior away from the complexities of plate boundaries. The thermal anomaly associated with LIPs appears to form swells and superswells before significant emplacement of extrusive or intrusive material in the crust. During and after

LIPs emplacement, the thermal regime of the lithosphere continues to be perturbed, and through time the composition of the magma and its extrusive products that form LIPs reflect the thermal/melting history of the underlying mantle. Ultimately the constructional phase ends and subsidence of the lithosphere begins. The geometry and timing of the deformation affecting plate interiors is best studied by ocean drilling because no other technique can reliably recover relatively unaltered samples required for geochemical and geochronologic analyses.

Cause and Effect of Oceanic and Climatic Variability

The consequences of future oceanic and climatic changes can be dealt with better by understanding the complex interactions in the earth climate system. The physical, chemical, biological, and dynamic changes in the Earth's oceans and atmosphere, along with changing plate configurations and crustal morphology, have all left a spatial and temporal submarine record which is critical in testing models and in developing new ones.

Short Period Climate Change

Evidence is growing that LIPs are emplaced over a very short time span, in some cases roughly a million years. Fluxes of rock, fluid, heat, and gases resulting from these massive constructions have had the potential to significantly affect the Earth's hydrosphere, atmosphere, and cryosphere. Knowledge of the timing and composition of LIP emplacements, obtainable primarily by drilling, must precede detailed analysis of the environmental effects of LIP construction. Furthermore, many oceanic plateaus contain sedimentary sections isolated from continental influences yet above the CCD, and potentially preserve an uncontaminated record.

Longer Period Changes

Distinct volcanic episodes in the Cretaceous have been documented, and other intervals of geologic time are equally characterized by major episodes of volcanism. As with shorter period climate changes, the role of LIP emplacements in planetary climate and ocean circulation can only be examined once knowledge of their timing and

composition is obtained. As noted above oceanic plateaus again offer the opportunity to study purely oceanic consequences of LIPs emplacement.

History of Sea Level

The record of sea level obtained from geologic evidence results from a complex interaction of sediment supply, tectonic history, sediment and water loading, and eustatic adjustments. Oceanic plateaus, and especially their surmounting seamounts, are vital targets for examining the history of sea level, and drilling a range of plateaus with vastly differing geologic histories is necessary to constrain the eustatic curve.

The Carbon Cycle and Paleoproductivity

Volcanic margins and oceanic plateaus contain complementary records of the carbon cycle and productivity. Reduced and oxidized reservoirs vary through time and depth, and represent major variations in ocean chemistry and hence global change. Drilling transects across divergent volcanic margins and on oceanic plateaus containing high-productivity sedimentary records are prime foci for addressing these global environmental changes.

Evolutionary Biology

Continuous sediment records from oceanic plateaus offer an unparalleled opportunity to study the speciation and evolution of organisms when tied to detailed oxygen isotopic and magnetic stratigraphy.

Origin and Evolution of LIPs

Volcanic passive margins, oceanic plateaus, and CFB provinces share elements of the fundamental processes which govern their emplacement and evolution. Any model must account for the transient nature of many provinces, for the persistence of others along hotspot trails, and for the huge volumes of igneous material.

Geodynamic Models

Intense interest in LIPs has been generated in recent years by the introduction of the “mega-plume” and “tail” concept (Figs. 2, 3) (*Gordon and Henderson, 1985; Mahoney, 1987; Richards et al., 1989; White and McKenzie, 1989; Campbell and Griffiths, 1990*), following the original mantle plume concept (*Wilson, 1963; Morgan, 1971*). Although models of the structure and temporal evolution of plumes vary considerably, a common factor is the capacity of a plume to generate large quantities of melt by decompression of upwelling, thermally anomalous mantle. For example, an instability postulated to originate at the core-mantle boundary rises as a “blob” and begins to melt in the upper mantle near the base of the lithosphere (*Richards et al., 1989; Campbell and Griffiths, 1990*). If the blob impinges on continental lithosphere, the melt may give rise to a CFB sequence (*Morgan, 1972, 1981*). If the plume is sufficiently intense, the hot, narrow “tail” of the plume may produce a trail of volcanoes which record the motion of the plate with respect to the plume through time (e.g., New England hotspot track: *de Boer et al., 1988*).

Where the thermal anomaly is associated with continental breakup, the cause-and-effect of which is hotly debated (e.g., *Duncan and Richards, 1991;*

Hill, 1991), it may create a volcanic margin distinguished by its transience, and the hot, narrow focus of the blob (hotspot or plume)—its “tail”—may be manifested as a submarine ridge or seamount chain on the oceanic lithosphere. If the plume initially reaches the hydrosphere or atmosphere in an existing oceanic region, an oceanic plateau may form, and as the plate migrates over the plume a trail of a ridge and/or seamounts may be constructed. *Gordon and Henderson (1985)* and *Mahoney (1987)*, for example, argue for a near-ridge plume origin for oceanic plateaus.

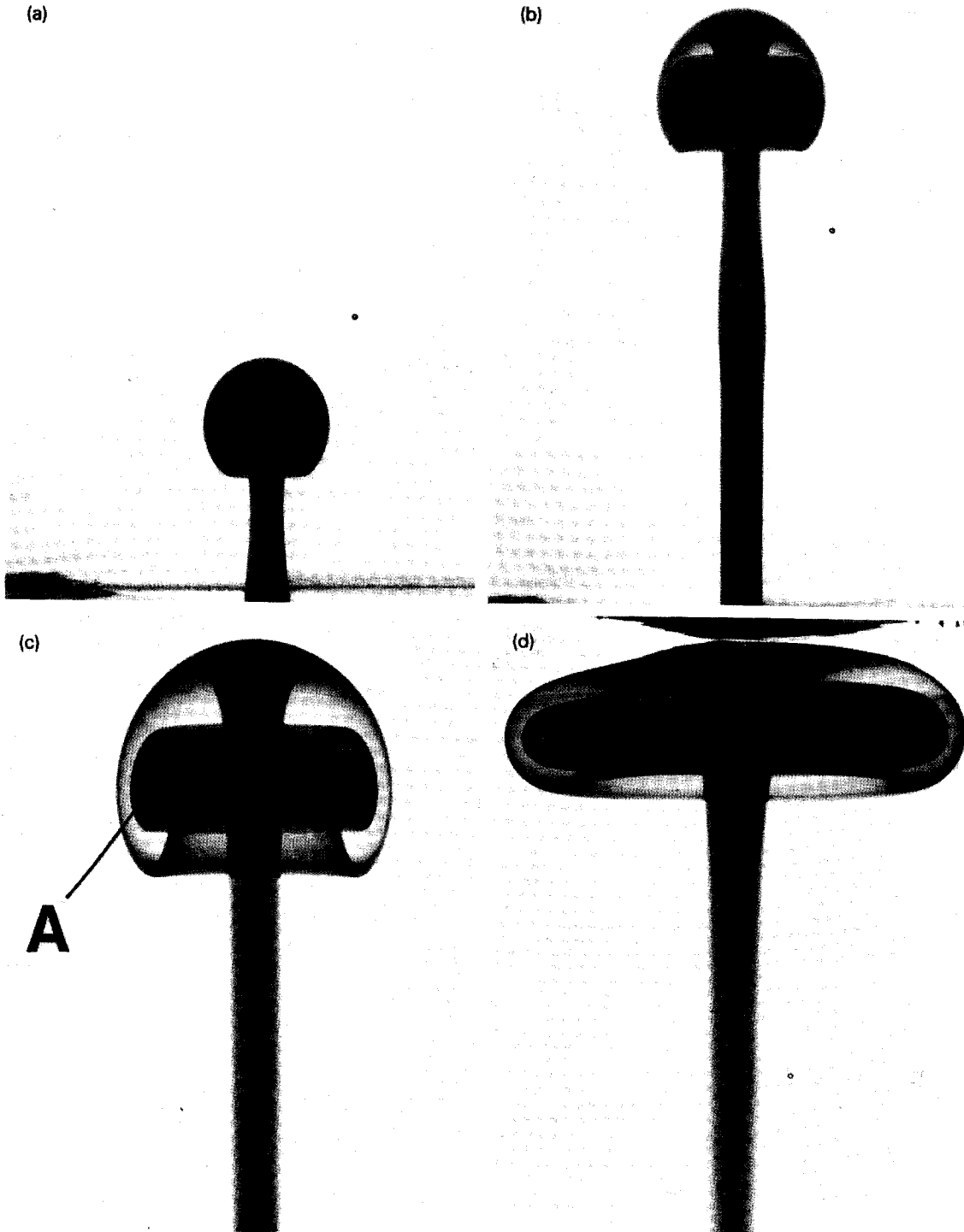
Other possible purely oceanic examples include features such as the “superswell” of French Polynesia (*McNutt and Fisher, 1987*) and its proposed predecessor, the Darwin Rise (*McNutt et al., 1990*); the Cape Verde Rise (*Courtney and White, 1986*); and such massive, apparently purely oceanic plateaus as Ontong Java and Manihiki.

As a working hypothesis, the plume model for the generation of LIPs, as outlined above or in some related form, is widely accepted because it represents the most plausible mechanism for explaining the large amounts of thermal energy required by the massive melting anomalies. However, much of the mid-plate igneous activity and none of the topographic swells in the western North Atlantic and the eastern North American region are easily reconciled with a simple hotspot or plume (*Vogt, 1991*). One possibility is that these features are caused by shallow mantle convection controlled by vertical thermal boundaries possibly related to episodic midplate stress intensification. Another model (*Mutter et al., 1988*) suggests that the conjugate volcanic margins, extending

over large distances along an incipient plate boundary and characterized by transient volcanism, originate by convective circulation within a narrow conduit of hot upwelling asthenosphere bounded by cold, old lithosphere (Fig. 4). None-

theless, some igneous provinces, albeit small ones, are almost certainly generated by lithospheric stretching above asthenosphere of normal potential temperature (1280°C). Furthermore, Pedersen and Skogseid (1989) have suggested that the tran-

Figure 2. Plume model of LIP emplacement (after Griffiths and Campbell, 1990). Photographs show starting plume in glucose syrup at several stages in its ascent. Times elapsed after the source is turned on are (a) 60 s; (b) 130 s; (c) 397 s; and (d) 540 s. Scale is identical in all frames and the head is 6.9 cm across in (c). The distribution of the dye is axisymmetric.



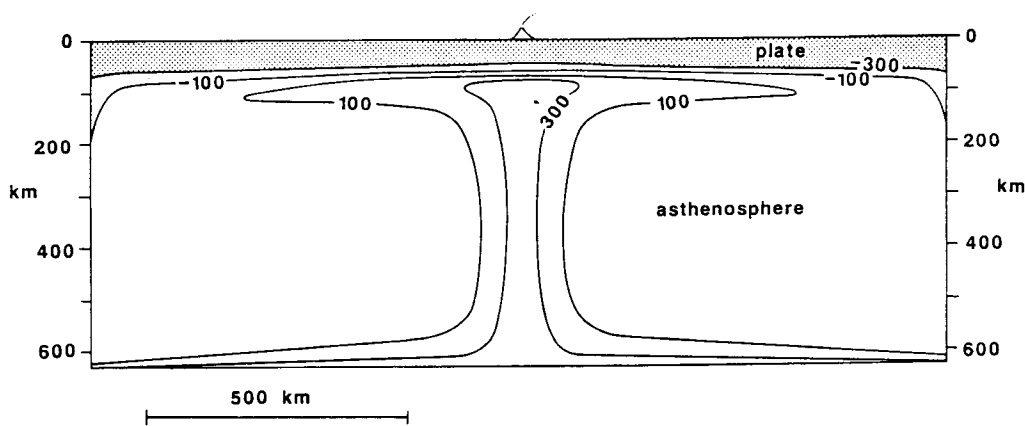


Figure 3. Diffuse thermal anomaly model of LIP emplacement (after White, 1988). The plume model of Courtney and White (1986) is based on an unusually hot deep mantle plume that affects the region far outside the hotspot marking the plume axis. The isotherms show deviations in degrees Celsius from the mean asthenospheric value for the Cape Verde hotspot showing that the plume is deflected laterally as it meets the lithosphere causing elevated mantle temperature in a region more than 1000 km across. White (1988) infers an even wider, about 2000 km, region of elevated temperatures surrounding the Iceland hotspot.

sient part of the NAVP may be produced by a much smaller increase in asthenospheric temperature ($\sim 50^{\circ}\text{C}$) than the $150\text{--}200^{\circ}\text{C}$ suggested for the Cape Verde and Iceland hotspots (Courtney and White, 1986; White, 1988). However the general capacity for smaller scale or lower temperature mantle upwelling to dynamically maintain elevation of large seafloor areas is questionable. It is also conceivable that some plumes are rather "wet" spots (Schilling *et al.*, 1980), in which case melting is a consequence of the reduction of solidus temperatures by the introduction of volatiles, although the generally tholeiitic nature of flood basalts and the strongly depleted dipping reflector basalts (Viereck *et al.*, 1989) is not readily reconciled with the wet spot model (J. Hertogen and M. Storey, pers. comm.).

A further feature of many plume models is that plumes and plate kinematics are unconnected phenomena. There are strong arguments in favor of this view (e.g., the Hawaiian Chain), but some LIPs (e.g., Ontong Java Plateau and the mid-Cretaceous volcanic events in the Pacific in general) are so large that they may reflect first-order modifications of earth dynamics. For example, there may be a connection between these igneous events and changes of spreading rates in the mid-Cretaceous Pacific Ocean (W.J. Morgan, pers. comm.). Recently Larson (1991) has suggested that Cretaceous deep mantle plume activity, as manifested by the formation of oceanic plateaus, bears

a genetic relationship to large-scale variations in magnetic reversal frequency, increased global temperatures, and eustatic sea level changes.

Volumes and Emplacement Rates

Volume estimates for extrusive material in CFB provinces range from $1.75 \times 10^5 \text{ km}^3$ for the Columbia River (Tolan *et al.*, 1989) to $1\text{--}2 \times 10^6 \text{ km}^3$ for the Karoo, Paraná, Deccan Traps, and NAVP (Macdougall, 1988; Rampino and Stothers, 1988; White, 1988). In contrast, the two giant, off-ridge igneous provinces—the Kerguelen and Ontong Java plateaus—have volumes of $\sim 2 \times 10^7$ and $\sim 6 \times 10^7 \text{ km}^3$, respectively (Coffin, 1991). Thus, the volume of magma emplaced in the largest oceanic plateaus, and in the largest volcanic passive margins, appears to be much greater than those in the largest CFB provinces. This inference depends partly on estimated volumes of lower crustal and possibly underplated rock beneath LIPs, but even conservative estimates of the dipping reflection thickness and areal extent support it. Except for selected margin segments in the North Atlantic (Hinz *et al.*, 1987; White *et al.*, 1987; Mutter and Zehnder, 1988; Fowler *et al.*, 1989; Tréhu *et al.*, 1989; Planke *et al.*, 1991; Olafsson *et al.*, in press) and for some plateaus (Furumoto *et al.*, 1976; Hussong *et al.*, 1979; Recq and Charvis, 1986; Recq *et al.*, 1990), few data exist with which to make such estimates beneath most margins and oceanic plateaus, and lower crustal volumes are completely unknown

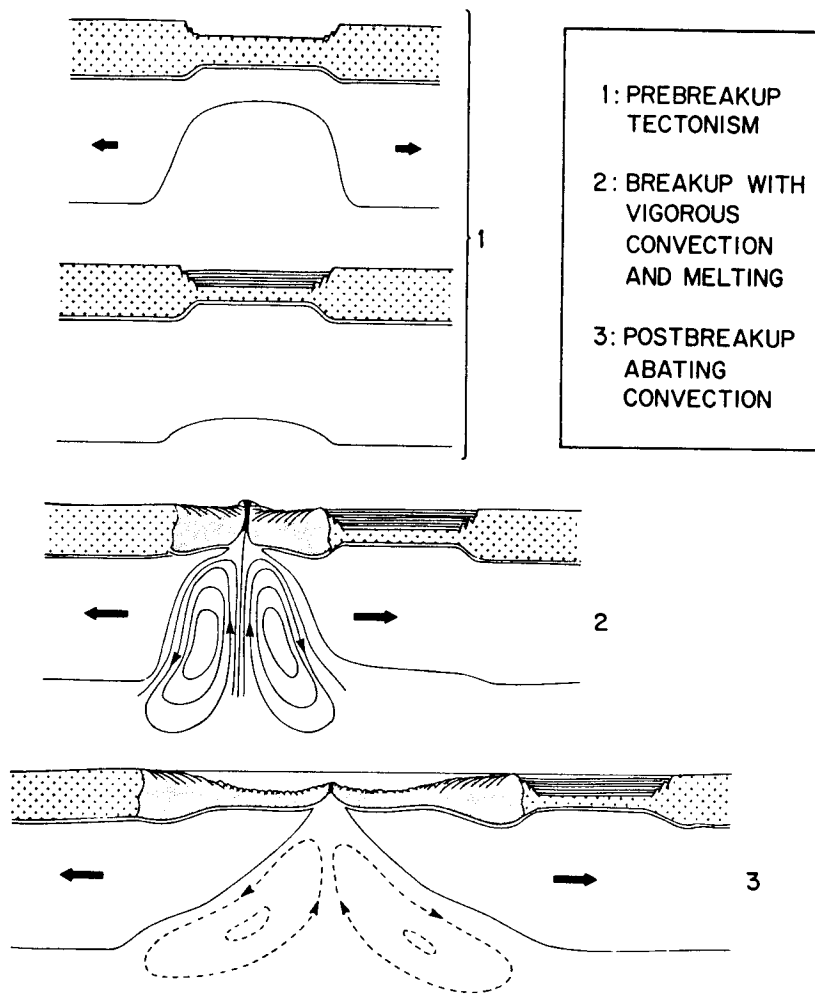


Figure 4. Evolution of a passive volcanic margin according to Mutter et al. (1988). 1) Development of a low strength region providing a locus for later breakup. 2) The horizontal stresses have cut the lithosphere in a weakened zone juxtaposing hot, upwelling lithosphere and old, cold continental asthenosphere initiating small-scale convective circulation resulting in emplacement of thick oceanic crust during the earliest seafloor spreading. 3) Convective circulation abates as seafloor spreading continues.

Swanson et al., 1975) and $1.5 \text{ km}^3\text{yr}^{-1}$ for the Deccan Traps (Richards et al., 1989). Currently, however, little information exists for oceanic plateaus and volcanic margins. The rate of crustal accretion on Iceland may be calculated from its area ($\sim 1 \times 10^5 \text{ km}^2$), average crustal thickness (10-15 km: Flóvenz and Gunnarsson, 1991), and age ($\sim 15 \text{ m.y.}$: McDougall et al., 1984). The values obtained are $0.07\text{-}0.10 \text{ km}^3\text{yr}^{-1}$. In contrast, if the Ontong Java Plateau ($\sim 6 \times 10^7$

for CFB provinces. Very large amounts of intruded and possibly underplated rock would have to underlie CFBs if the two provinces were to be volumetrically comparable.

The emplacement of LIPs occurs very rapidly, with perhaps 90% of a province's volume being erupted in less than 2 m.y., possibly in as little as 0.5 m.y. (Roberts, Schnitker, et al., 1984; Baksi, 1988; Courtillot et al., 1988; Duncan and Pyle, 1988, Rampino and Stothers, 1988). Similar inferences have been made for the North Atlantic volcanic margins (Larsen and Jakobsdottir, 1988; Eldholm et al., 1989), the Kerguelen Plateau (Whitechurch et al., in press) and the Ontong Java Plateau (Mahoney and Tarduno, 1990, Tarduno et al., submitted).

Eruptive rate, especially with regard to global change, is among the most significant questions concerning LIPs, and one for which few data are available. In the case of CFBs, the most reliable estimates appear to be 0.1 km^3 per year for the Columbia River Province (Shaw and Swanson, 1970;

km^3 : Coffin, 1991) had been emplaced in three million years or less, the annual magma production rate of would equaled or exceeded that of today's entire 50,000 km long mid-ocean ridge system, including Iceland ($\sim 20 \text{ km}^3\text{yr}^{-1}$; Ocean Studies Board, 1988). Total volumes of igneous crust emplaced at most volcanic passive margins have yet to be calculated, but if the NAVP, with a minimum extrusive volume of $1.8 \times 10^6 \text{ km}^3$ and a total crustal volume of $6.6 \times 10^6 \text{ km}^3$ (Eldholm and Grue, submitted), was emplaced over three million years, the minimum crustal production rate would have been $2.2 \times 10^6 \text{ km}^3\text{yr}^{-1}$, or about 11% of the present annual global crustal production rate at mid-ocean ridges. Once eruptive rates are better known, questions such as whether higher eruptive rates indicate anomalous rates of mantle convection, higher temperature and degree of melting, or a fluctuation in partitioning of total melt volume between extrusive and lower crustal material may be addressed.

Petrology, Geochemistry, and Dating of Large Igneous Provinces

Disciplinary Working Group Report

Keith Cox, Chair

Members:

Dick, Donnelly, Fram, Frey, Geist, Gillis, Hertogen, Humphris, Jakes, Kelemen, Kroenke, Martin, McNutt, Morgan, Mutter, O'Connor, O'Hara, Pringle, Rhodes, Richards, Storey

FOCI

Lithospheric and Asthenospheric Circulation

Plate Setting of LIP Emplacement and
Relationship to Continental Breakup

Temporal and Spatial Distribution

Source Compositions, Partial Melting, Fractionation
History, and Lithospheric Contamination

LIPs in the ocean and on the continents are distributed in space and time, and emplacement of the provinces is associated with anomalous heating of the upper mantle and crust. Both the igneous crust and the interbedded, overlying, and adjacent sedimentary sections contain important information which can constrain models of asthenospheric and lithospheric behavior.

- ◆ What are the spatial and temporal distributions of LIPs, and what do these distributions reveal about mantle circulation and plate driving forces?
- ◆ What do the geochemical signatures of LIPs tell us about the nature of the underlying lithosphere and asthenosphere?
- ◆ What is the relationship between source composition and geodynamic models (e.g., hotspot vs. non-hotspot)?
- ◆ How is heating of the lithosphere achieved, how does it develop through time, and how does it affect lithospheric stress?
- ◆ By what physical mechanisms are LIPs emplaced?
- ◆ What is the stratigraphy of LIPs, and how does it relate to the seismic structure of “normal” oceanic crust?
- ◆ What is the role of mantle plumes vis-à-vis LIPs?
- ◆ What are the source composition, the degree of partial melting, the fractionation history, and the lithospheric contamination of LIP magmas?
- ◆ What variations in physical properties account for dipping reflector sequences?
- ◆ What plate tectonic settings are most favorable for the emplacement of LIPs?
- ◆ How do LIPs subside through time?
- ◆ How do ophiolites compare with LIPs?

Introduction

Studies of continental LIPs have revealed much about the petrology and geochemistry of the extrusive rocks, but thick continental crust between the exposed igneous sequences and their source regions makes the study of many of the geophysical and geochemical characteristics of LIPs difficult, particularly the volumes of intrusive rock and of possible underplated or serpentized rock. The LIPs Workshop, therefore, concentrated on oceanic plateaus and volcanic passive continental margins, studies of which may constrain the evolution of LIPs in general, thereby adding to our understanding of processes governing both continental and oceanic igneous activity. In the following, important LIP problems will be discussed from the perspective of general igneous geology, petrology, geochemistry, and geochronology. However, points of interaction with other geoscientific disciplines will be noted.

Similarities and Differences Between Continental and Oceanic LIPs

Major LIPs include CFBs, oceanic plateaus, and volcanic passive margins, a primarily "generic" grouping (Fig. 1). More fundamental questions pertain to "genetic" relationships among the various provinces. Most CFBs are associated in both space and time with oceanic hotspots and ocean ridges, and probably have a genetic relationship with their oceanic counterparts (e.g., NAVP vs. Iceland, Greenland-Scotland Ridge; Paraná-Etendeka vs. Rio Grande Rise and Walvis Ridge; Deccan vs. Chagos-Laccadive-Maldives Ridge and Mascarene Plateau; Rajmahal vs. Kerguelen Plateau and Ninetyeast Ridge). This connection, however, can not be made for transient volcanic passive margins worldwide nor for fully oceanic plateaus, particularly in the Pacific, although it is unlikely that they originate via dissimilar processes.

Styles of emplacement of igneous bodies in CFBs are well-known compared with oceanic plateaus and volcanic passive margins. The most abundant rock types are typically sub-horizontal, subaerial tholeiite flows, some of which are known to extend for several hundred kilometers and may have volumes as great as 3000 km³ (Tolan *et al.*, 1989). Intermediate and basic sills are well developed in CFB provinces that overlie sedimentary sequences, and along the Norwegian/UK volcanic margin, and may contribute a significant fraction of the total

volume. Significant volumes of volcanoclastic deposits which comprise the basal portions of the volcanic pile in some provinces (e.g., NAVP; Nielsen *et al.*, 1981) have major implications for volcanic plumbing systems developed during early stages of rifting and may have environmental impact as well. In addition, dacite, presumably produced by shallow crustal melting, directly underlies the basalt flows forming the dipping reflection wedge drilled on the Vøring Margin (Eldholm, Thiede, Taylor, *et al.*, 1987). It is also notable that some provinces contain significant amounts of rhyolite, probably also erupted as high temperature (~1100°C) lavas. The rhyolite is particularly intriguing in terms of possible global effects, because of its potential to produce highly volatile fluxes. Rhyolite has also been drilled on one plateau of continental origin (Lord Howe Rise; Burns, Andrews *et al.*, 1973), and in the Orange Basin off southwest Africa (Gerrard and Smith, 1988), although in the latter case, its presence is not clearly related to the dipping reflection sequence farther offshore. Whether rhyolite is present in purely mafic oceanic plateaus is an interesting question, as is the more general question of emplacement styles of lavas and the role of intrusives.

Tectonic Settings of LIPs and their Relationship to Continental Breakup

The relative timing of volcanism on land, rifting, the emplacement of seaward-dipping and other sub-basement reflection sequences, and the creation of oceanic crust is relatively poorly known. The connection between breakup and volcanism is well-established in the general sense but most important details are unclear, in particular the identification of cause and effect. The influence of pre-existing lithospheric structure on the location of initial rifts has been established only in the very broadest sense (Dunbar and Sawyer, 1989; Sawyer and Harry, *in press*).

In the oceans, hotspot volcanism generates submarine ridges and seamount chains, some of which are clearly built on older oceanic crust (i.e., intraplate) as the plate moves relative to the hotspot. However, important questions regarding the coincidence of the ridge and the hotspot and its long-term maintenance still have to be resolved. For example, the conjugate Walvis Ridge-Rio Grande Rise LIPs began forming on-axis and evolved eventually to an intraplate setting (O'Connor and Duncan, 1990). Relationships between oceanic plateaus and triple junctions have been proposed for some Pacific LIPs

(e.g., Kroenke, 1974, for the Ontong Java Plateau), but data with which to test these ideas are scarce.

Implications for Lithospheric and Asthenospheric Mantle

The physics and chemistry of the mantle underlying LIPs are major unknowns, and a key question is the temperature structure. Models involving passive adiabatic mantle upwelling in localized convection cells (Fig. 4: Mutter *et al.*, 1988) and mantle plumes (Morgan, 1981), either “passive” continental rifting over a continuous mantle plume (Fig. 3: White and McKenzie, 1989) or plume initiation, sometimes accompanied by “active” rifting (Fig. 2: Richards *et al.*, 1989; Campbell *et al.*, 1989; Campbell and Griffiths, 1990), may be tested by determining melting rates and degrees of melting of LIP rock, which in turn constrain the temperature structure. The presence of high-magnesium lavas (picrites, ankaramites) in some LIPs (e.g., Karoo, Deccan, NAVP—see Macdougall, 1988) has been interpreted as evidence of a thermal anomaly, but this is not universally agreed. Identification and separation of dynamic and thermal effects in uplift and subsidence histories are also problematic.

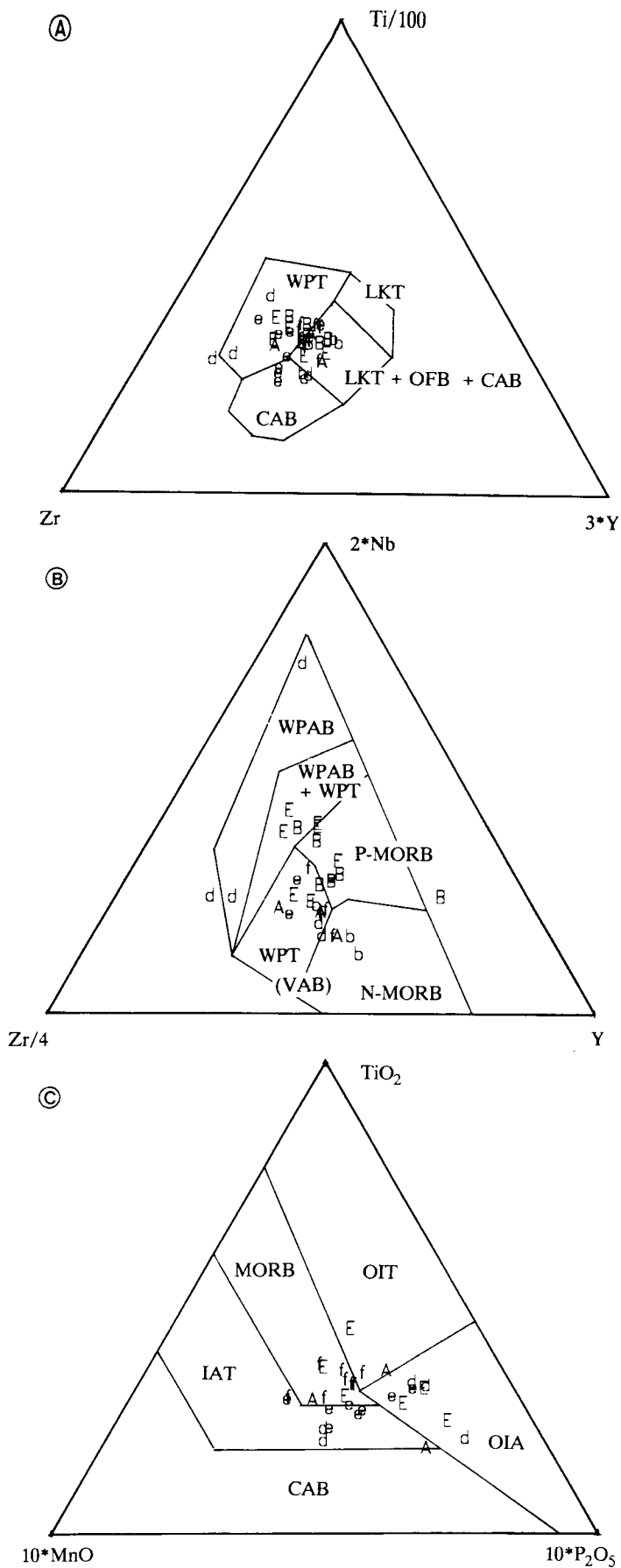
The major geochemical problem lies in identifying the numerous compositional reservoirs that might have contributed to the magmatism. Systematic study of ocean plateaus and volcanic margins may eventually contribute to the interpretation of isotopically distinct components (Zindler and Hart, 1986; Hart, 1988; Weaver, 1991), and to understanding the role of the crust and old lithospheric mantle in the generation of CFB provinces (e.g., Menzies, 1991). Similarly whole rock analyses can be useful in examining source heterogeneity. For example, broad scatter in these data from CFBs and oceanic plateaus suggest complex petrogenetic processes in their formation (Fig. 5). In the simplest case of oceanic plateaus far from continental influences (e.g., Central Pacific, Iceland), asthenospheric and deep mantle lithospheric reservoirs are expressed. Volcanic margin sequences record the transition from continental to oceanic setting and may hold the key to distinguishing asthenospheric from lithospheric mantle reservoirs. Continental lithosphere may strongly influence and create complex relationships in LIPs emplaced in its vicinity. For example, the formation of a new ocean basin associated with a CFB province may involve production of new asthenospheric material from former continental

lithospheric mantle (e.g., Hawkesworth *et al.*, 1986; Mahoney *et al.*, 1983, 1989; Storey *et al.*, 1989; Hawkesworth *et al.*, 1990). Such material might be recycled to near-by spreading axes, and might remain identifiable, as has been demonstrated along the Mid-Atlantic Ridge at 35°N (Shirey *et al.*, 1987). Conceivably, with sufficient data on the distribution of such materials, a test against continental reconstructions and former hotspot positions might be possible.

The temporal geochemical evolution of an individual LIP has the potential to reveal details in the evolution of the mantle process which initiated and sustained it, especially with regard to entrapment of material by a plume, and to potentially time-varying volcanic products. Similarly, the overall geochemical evolution of LIPs through geologic time could provide insight into changing mantle chemistry. Exotic terrains which contain thick sequences of mafic lavas (e.g., Triassic portion of Wrangellia: Howell *et al.*, 1984; Richards *et al.*, in press; Gorgona: Storey *et al.*, 1991; Mahoney, 1987; Millward *et al.*, 1984), if conclusively demonstrated to represent oceanic plateaus or other LIPs, may offer an excellent opportunity to study pre-Jurassic LIPs in terms of mantle evolution as well as detailed petrology, geochemistry, and geochronology. In addition, large oceanic plateaus, and possibly volcanic margins, are unlikely to subduct, and therefore may have added significantly to continental lithospheric volume over geologic time (Kroenke, 1974; Schubert and Sandwell, 1989).

Global Effects of LIPs

Evidence suggests that emplacement of LIPs can double or more the Earth's ordinary production of heat, magma, and volatiles over periods of a million years or more. Therefore it is highly probable that LIPs produce significant global effects, which range from the purely geological to those affecting the biosphere. Some speculations about possibilities in the geologic category have been made above. Geochemically it is important to characterize volatile emissions in terms of species (e.g. CO₂, SO₂) and quantities, because of their potential environmental impact. Rhyolites and other evolved rock types, even if present in relatively small volumes, may greatly enhance volatile emissions. Determining whether volcanism is submarine or subaerial is also crucial in assessing whether, at least initially, effects are confined primarily to the atmosphere and/or to



the oceans. Quenched, submarine flows in oceanic plateaus and volcanic passive margins could make major contributions of some elements (e.g., Cl, F, S) to the oceans.

Techniques Available and their Application

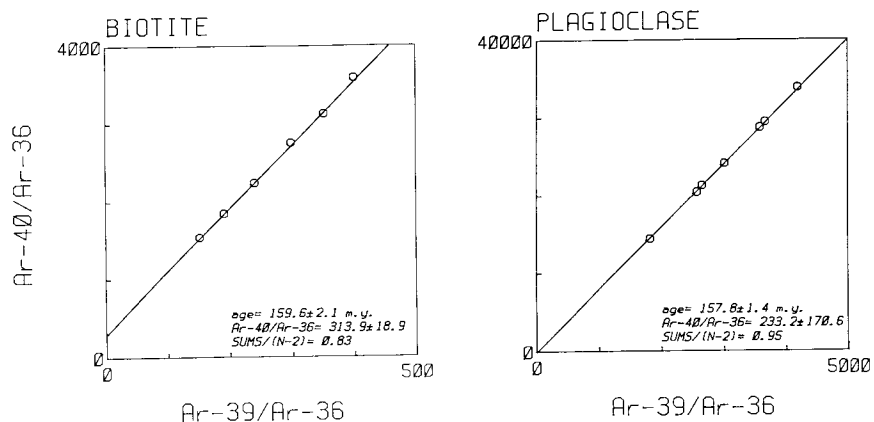
Precise geochronology techniques are essential to the study of LIPs since dating documents stratigraphic history and the determination of key parameters such as magma production and emplacement rates. ⁴⁰Ar/³⁹Ar laser dating can now provide high precision dates for oceanic rocks (Fig. 6). Drill holes penetrating ~150 m into basement would probably encounter 10-15 cooling units and thereby obviate the risk of sampling only superficial, and possibly anomalously young flows (see Chapter 5). Tectonically disturbed zones and transect drilling might pro-

Figure 5. Whole-rock analyses from several CFB provinces plotted in "tectonomagmatic discrimination" diagrams. Broad scatter on these diagrams has been attributed to complex petrogenetic histories including mantle metasomatism, source heterogeneity, multi-stage fractionation, and/or contamination by continental tholeiites (Holm, 1982; Mullen, 1983; Prestvik and Goles, 1985; Duncan, 1987; Wright et al., 1989). The diagrams show that oceanic plateaus, at least those in the South Atlantic and Indian Ocean, record similar degrees of scatter. This suggests that the petrogenetic processes involved in production of oceanic plateau lavas may be nearly as complex as those involved in the generation of continental tholeiites (B.S. Martin, pers. comm.).

a) ⁷³Ze-Y-Ti plot of Pearce and Cann (1973). b) ⁷³Zr-Y-Nb plot of Meschede (1986). c) ⁷³MnO-P₂O₅-TiO₂ plot of Mullen (1983).

WPT: Within Plate Tholeiite, LKT: Low K₂O Tholeiite, OFB: Ocean Floor Basalt, CAB: Calc-Alkaline Basalt, WPAB: Within Plate Alkali Basalt, VAB: Volcanic Arc Basalt, N-MORB, "Normal" Mid-Ocean Ridge Basalt, P-MORB: "Plume-type" Mid-Ocean Ridge Basalt, OIT: Ocean Island Tholeiite, IAT: Island Arc Tholeiite, OIA: Ocean Island Andesite, CAB: Island Arc Calc-Alkaline.

Figure 6. Example of high precision dating of oceanic rocks recovered during ODP Leg 129 at Site 801 in the Pigafetta Basin (Lancelot, Larson et al., 1990) based on $^{40}\text{Ar}/^{39}\text{Ar}$ laser fusion isochrons for co-existing plagioclase and biotite from an upper sequence alkalic microdiorite. Each plagioclase datum represents an individual laser fusion analysis of about 1 mg (~40 125–250 μ grains); each biotite datum represents about



0.1 mg (~15 75–125 μ flakes). Both isochrons are concordant, with error estimates based on analytical errors alone ($\text{sums}/n-2 < 1$) and $^{40}\text{Ar}/^{39}\text{Ar}$ intercepts indistinguishable from the atmospheric ratio. Best age is weighted age of the two isochrons, 158.4 ± 1.2 Ma. After M. Pringle (pers. comm.).

vide the opportunity to study age ranges through more extensive depth sequences. $^{40}\text{Ar}/^{39}\text{Ar}$ laser dating of individual mineral grains (e.g., *Lo Bello et al.*, 1987) can be particularly useful in dating ash layers as well as weathered dikes and sills in marginal sedimentary basins. This may better constrain the time interval between the start of continental extension and onset of seafloor spreading. Magnetostratigraphy, which has provided the most accurate estimate for the duration of Deccan Trap volcanism, is also a key tool, especially in conjunction with precise radiometric dating. Although many oceanic plateaus were emplaced during the Cretaceous Long Normal Polarity Superchron, short polarity events or subchrons may exist within the superchron (*Tarduno et al.*, 1989; *Tarduno*, 1990).

Isotopes and relatively immobile minor and trace elements can be used to identify components from different reservoirs, and may constrain plume involvement (e.g., *Mahoney*, 1987; *Hart*, 1988; *Weaver*, 1991; *Mahoney and Spencer*, 1991), since many suspected plume-related occurrences have characteristic signatures (Fig. 7). Sr, Nd, Pb, Re-Os, and possibly Hf radiogenic isotopes are particularly important, especially when used in conjunction with rare earth and alteration-resistant, incompatible trace elements. Rare gases may also provide important information. Similarly, these tools have the potential to identify which plume a LIP might be related to, as well as the compositional continuity of plumes through time and the nature of the plume source region. Most information is expected from comparative studies (e.g., sites on oceanic plateaus, submarine ridges, and volcanic margins compared with adjacent normal seafloor) and from studies along

transects of long-lived or petrologically variable features (e.g., Greenland-Scotland Ridge). Petrological studies in combination with trace element and isotope geochemistry and $^{40}\text{Ar}/^{39}\text{Ar}$ laser dating will permit determination of the origin of the rhyolite/dacite in CFBs (e.g., Karoo: *Cox*, 1988), volcanic margins (e.g., Vøring Margin: *Parson et al.*, 1989), and plateaus (e.g., Lord Howe Rise: *Burns, Andrews, et al.*, 1973). These rocks may derive from melting of old continental crust, from igneous differentiation of basalts, or from possible melting of underplated basic rocks and fractionation. Insights into their origin have considerable bearing on modeling of thermal aspects of mantle-crust interaction, residence time in shallow magma chambers, and integrated amounts and emission rate of volcanic gases. In isotopic studies, the severe, multi-step acid leaching technique has been effective in removing secondary alteration (*Mahoney*, 1987; *Cheng et al.*, 1987; *Weis and Frey*, in press).

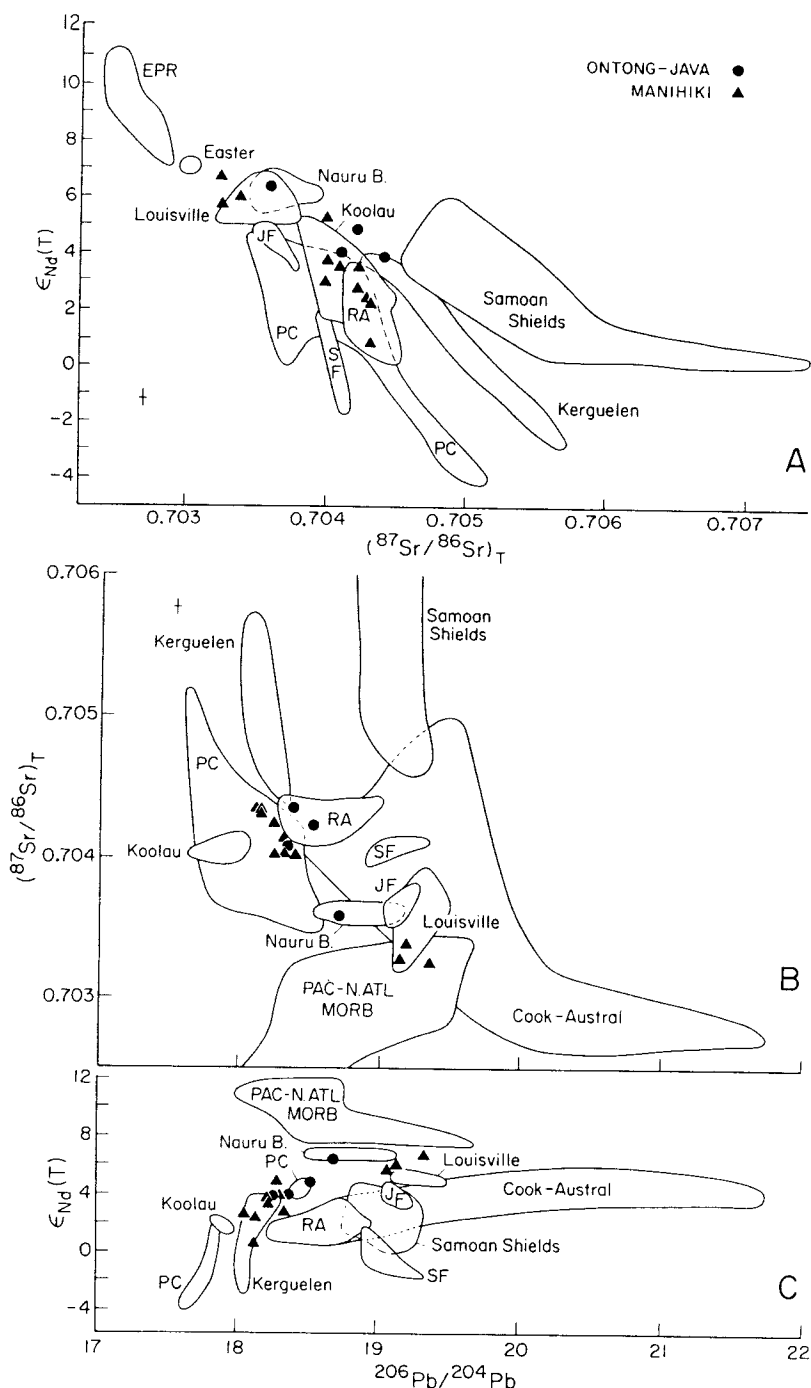
Several techniques are now available for estimating depths and temperatures of magma generation, and degrees of melting. The most familiar of these are based on major elements (e.g., *Klein and Langmuir*, 1987), but a trace element inversion method has also recently been developed (K. O'Nions and D. McKenzie, pers. comm.). In major element methods freshness of samples is important, but it may be possible to work with altered samples by calibrating the technique against plagioclase and pyroxene phenocryst compositions. Possible limitations are that major element methods are restricted to relatively primitive basaltic rock types, and that calculations for extent of melting critically de-

Figure 7. Isotopic ratios from Manihiki and Ontong Java plateau lavas. Nd and Sr isotopes are age-adjusted to 110 Ma, Pb isotopes are present-day values. For comparison, fields are shown for East Pacific Rise (EPR) and/or North Atlantic MORB, Easter Island (EA), Louisville Seamount Chain (LSC), Nauru Basin (NB), Kerguelen Plateau (K), Pitcairn (PC), Samoan shields (SS), Rarotonga (RA), San Felix and San Fernandez (SF, JF), the Cook-Austral Islands (C-A), and the Koolau shield of Hawaii (HI). The plateau data, unlike most modern South Pacific islands, provide evidence for an important low $^{206}\text{Pb}/^{204}\text{Pb}$ "DUPAL" component in their sources. From Mahoney and Spencer (1991).

pend on Na and Ti abundances, which are distinct in various mantle sources. Another approach in identifying the physical and chemical character of the mantle source is to examine rare earth element patterns, which can, for example, reveal the presence or absence of garnets in that source.

Hydrothermal alteration strongly controls ocean chemistry. The emplacement of giant LIPs, e.g., Ontong Java and Kerguelen, may be recorded in chemical sediments off LIPs by Sr and Nd isotopic anomalies. More localized alteration studies include fluid-rock interaction, metamorphism, and mineralization. In addition to conventional petrographic, electron microprobe, scanning electron microscope, and ion microprobe studies, multivariate statistics is a useful tool to analyze routine major and trace element geochemical data and other continuous variables to quickly separate altered from fresh samples. The fresh samples can then be analyzed by the above techniques to infer magmatic processes. These techniques can also be used to quickly generate and test hypotheses concerning rock-fluid reactions.

Lithostratigraphic analysis of igneous rock and interbedded sediment can be used to determine whether



emplacement was subaerial or submarine. Vertical seismic profiling and downhole logging may be used to identify flow units and their physical and chemical properties. Plate models using a hotspot reference frame can be used to determine which hotspots are associated with a common mantle source region, and also can be used to address the temporal continuity or discontinuity of individual hotspots.

Conjugate Volcanic Passive Margin and Oceanic Plateau Development

Disciplinary Working Group Report

Dave Roberts, Chair

Members:

Coffin, Crane, Eldholm, Harry, Larsen, McNutt, Okay, Pedersen, Skogseid, Tucholke

FOCI

Heating of the Lithosphere and Magma Production
Igneous Emplacement Mechanisms, Location, and Timing
Pre-, Syn-, and Post-Rift Horizontal and Vertical Movements
Structure of the Margins and the Continent-Ocean Transition

The mechanisms of continental margin formation are neither agreed upon nor well understood, and it is generally accepted that conjugate pairs must be investigated. LIPs appear to be common along passive margins.

- ◆ Does volcanism on margins occur primarily during late rifting (on continental crust), at the time of breakup, or during the initial phase of seafloor spreading?
- ◆ What is the petrological and geochemical nature of the upper mantle beneath an embryonic oceanic rift?
- ◆ What is the relationship between source composition and geodynamic models (e.g., hotspot vs. non-hotspot)?
- ◆ What is the nature of the earliest “oceanic” crust emplaced in a continental rift?
- ◆ How does the composition of ocean crust evolve in space and time during the initial few million years of seafloor spreading?

- ◆ How do pure shear and simple shear rifting mechanisms relate to volcanism?
- ◆ What is the vertical tectonic history of volcanic margins?
- ◆ What is the distribution of strain in the crust and mantle across the margin and its conjugate?
- ◆ Why are some passive margins volcanic, and others non-volcanic?
- ◆ What is the distribution of volcanics and intrusives across conjugate margins?
- ◆ Why do continents break up where they do?
- ◆ What is the geometry of incipient seafloor spreading?
- ◆ What are the nature and structure of the COT?
- ◆ What is the distribution of flexural strength across a margin, and how does it vary with time?

VOLCANIC PASSIVE MARGINS

Introduction

Study of passive margins has reached a stage where a number of opposing ideas and hypotheses have emerged, e.g., volcanic vs. non-volcanic margins, passive vs. plume-induced rifting, transient vs. persistent magmatism, pure shear vs. simple shear deformation, and symmetric vs. asymmetric conjugate margin structure. Scientific inquiry and debate of these characterizations and their accompanying theories have not yet eliminated any of them from consideration nor resolved their underlying processes, and it is clear that more data are necessary to test the ideas properly.

With regard to volcanic vs. non-volcanic margins, it was only ten years ago that increasingly sophisticated seismic images began to be employed in documenting structures within igneous basement along many passive continental margins (Hinz, 1981) (Fig. 1). Prominent wedges of intra-basement, seaward dipping reflections (Fig. 8) are observed in many areas (Hinz and Weber, 1976; Hinz and Krause, 1982; Mutter et al., 1982; Roberts et al., 1984; Eittrem et al., 1985; Hinz et al., 1987; Skogseid and Eldholm, 1987; Larsen and Jakobsdottir, 1988; Austin et al., 1990; Hinz, 1990). DSDP Leg 81 and ODP Leg 104 drilled into the seaward dipping wedges and demonstrated that they consist of basalt flows and thin interbedded sediment layers (Roberts, Schnitker et al., 1984; Eldholm, Thiede, Taylor et al., 1987). The drilling results, combined with extensive geophysical and geological studies, particularly in the North Atlantic (e.g., Morton and Parson, 1988), have shown that the seaward dipping reflections (Fig. 9) are part of much larger

extrusive and intrusive complexes at the margin and that in many cases the complexes are underlain by characteristic high-velocity, perhaps "underplated" or serpentinized peridotite bodies in the lower crust which are not typical components of either continental or oceanic crust.

Recognition that the initiation of passive continental margin formation is associated in places with large-scale magmatism has led to a classification of rifted continental margins into non-volcanic and volcanic types. The non-volcanic type is characterized by rapid initial subsidence, prominent blockfaulting, and little or no volcanism during continental breakup. The volcanic margin is characterized by rapid voluminous extrusive/intrusive magmatism during breakup of the continental lithosphere. Crustal uplift or little initial subsidence are also characteristic phenomena. The Bay of Biscay and the Vøring margins are generally considered respective end-members of the two margin types (COSOD II, 1987), although most margins may be intermediate types.

Volcanic Margin Styles and Settings

Seismic reflection data show considerable variation in magmatic-tectonic style and setting, both parallel and perpendicular to the strike of the conjugate volcanic margins. For example, intra-basement reflections representing extrusive constructions along the North Atlantic margins vary greatly in continuity, dip, amplitude and reflection pattern (Fig. 10). The observed seismic pattern, of course, reflects the combined effects of constructional mode, lava composition and production rate, and syn- and post-constructional subsidence and deformation. Understanding the variability in character is essential to reconstruct

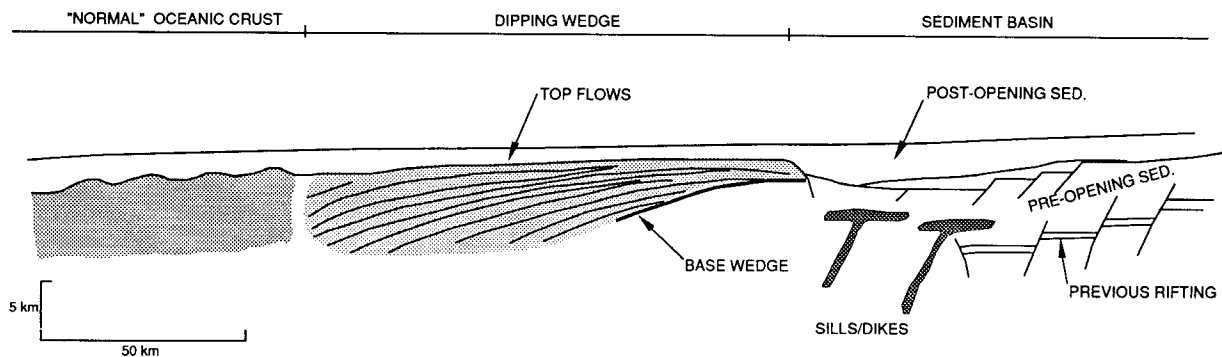


Figure 8. Generalized cross-section of a volcanic margin in an area of previous rifting and basin formation episodes.

the margins' histories and also to formulate an effective drilling strategy.

The character and volume of igneous complexes along the Atlantic (e.g., *Morton and Parson, 1988*) and northwest Australian (e.g., *Falvey and Mutter, 1981; Mutter et al., 1988*) margins are characterized by different geometries as indicated sche-

matically in Figure 11. Regionally, three geometries of magmatic activity are apparent along the COT. The uniform margin is relatively regular and symmetric, whereas the point source configuration is characterized by a hotspot, and the maximum width reflects the initial plume position. This geometry is commonly located near

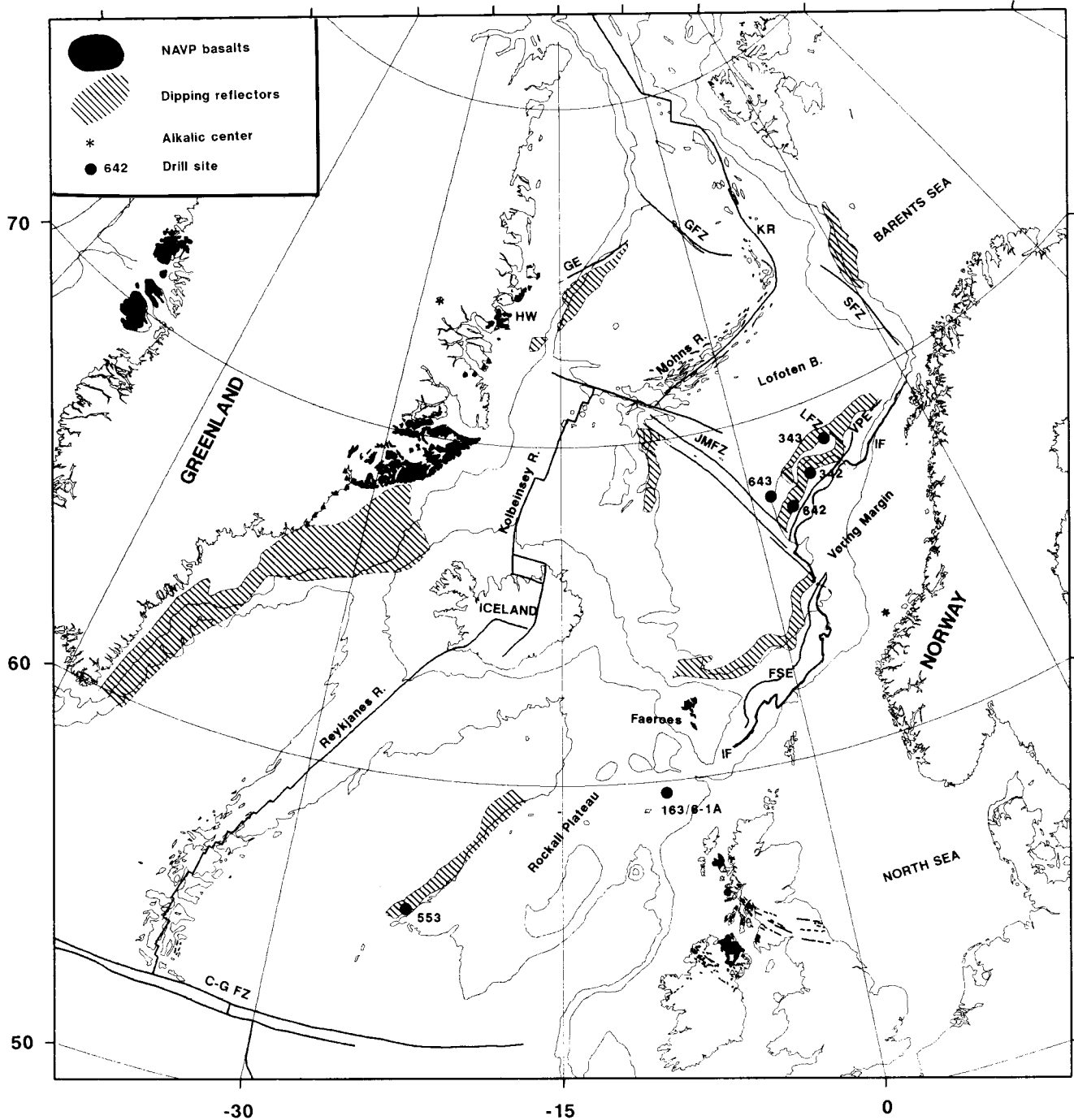


Figure 9. North Atlantic Volcanic Province. The onshore part comprises plateau basalts, intrusion centers (dots), alkaline volcanic centers and dikes (solid lines). The volcanic margins are indicated by the main seaward dipping wedges. Note that early Tertiary extrusive complexes at the margins cover areas much larger than dipping wedges. Locations of selected DSDP/ODP/industry drill sites are shown. From Eldholm (in press).

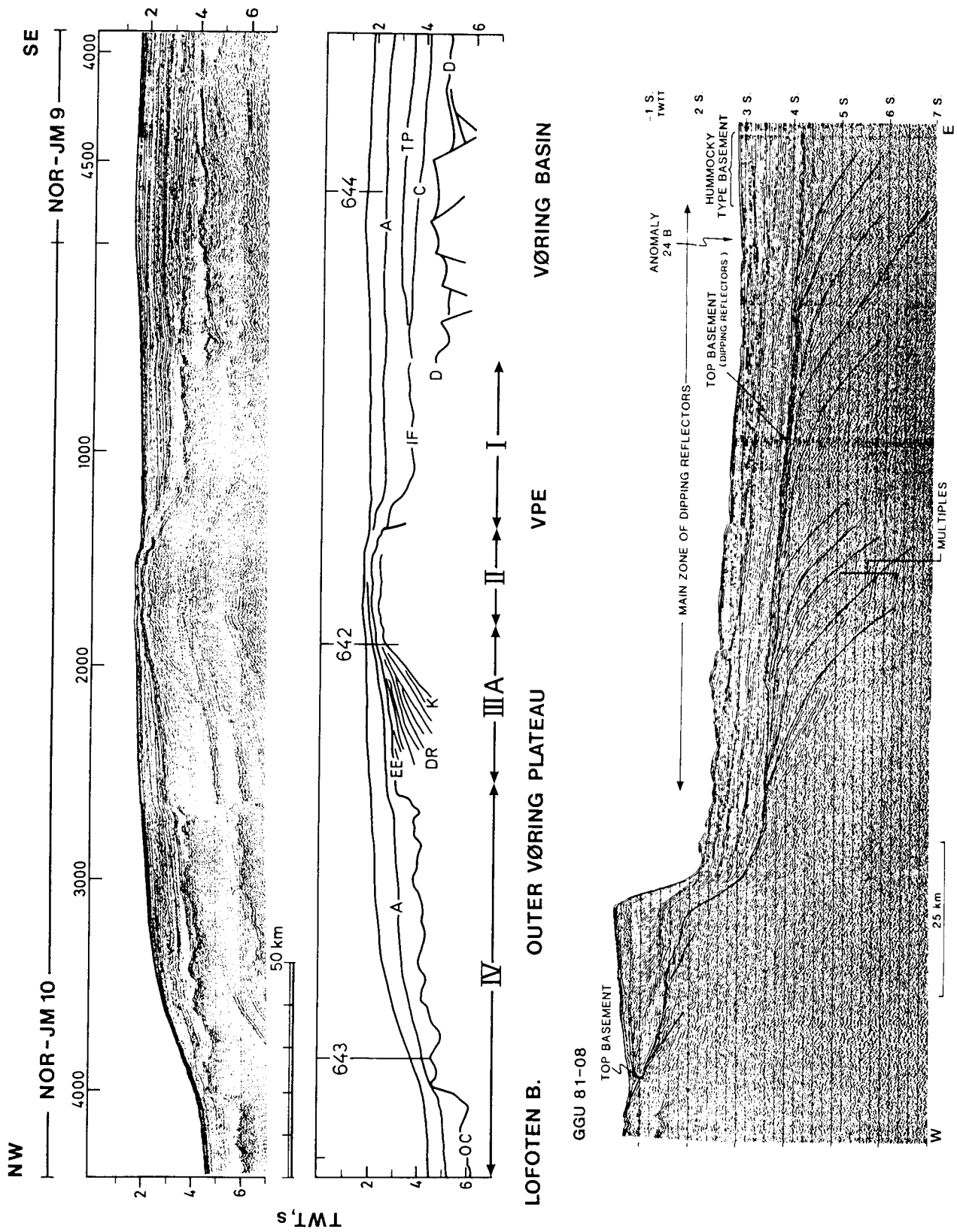


Figure 10. Seismic examples of seaward dipping reflector sequences at the Vøring Margin off Norway (Eldholm et al., 1989) and off Southeast Greenland (Larsen, 1990).

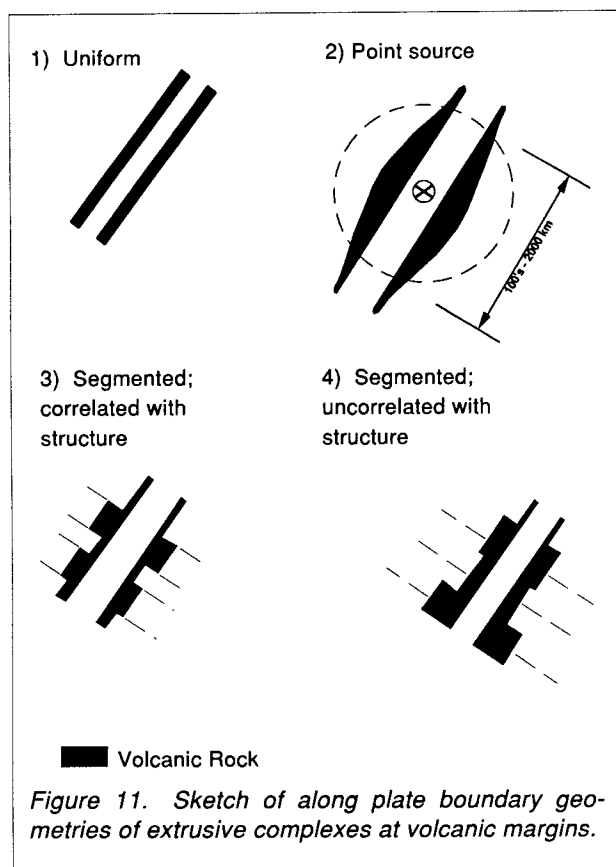


Figure 11. Sketch of along plate boundary geometries of extrusive complexes at volcanic margins.

large CFB provinces (e.g., NAVP, Etendeka-Paraná, Deccan Traps). The segmented margin records variable volcanism which is either governed by pre-existing structures or independent of the structural segmentation of the crust. These first-order regional patterns may be complicated by rift propagation, shifts in location of the rift and initial spreading axes, large sheared margin segments, and neighboring triple junctions.

A margin's variability perpendicular to strike is most easily evaluated by reconstructing the plates to the time when the igneous pulse had abated and normal oceanic crustal was being generated. Asymmetric conjugate margin magmatic sequences may originate during the rift stage if crustal extension is asymmetric, i.e. achieved by simple shear. Asymmetry, however, may also occur in a pure shear setting depending on pre-rift structures and changes in position of the rift zone or the initial spreading axis.

Composition and mode of magmatism controls the position of magmas in the region of continental breakup. Magmatism focused in a narrow zone of injection enhances symmetry, whereas a broad feeder system produces a more irregular imprint. When continents finally separate, i.e.,

when a growing block of entirely oceanic crustal material is being produced, symmetric development is normally expected. In Iceland, however, basaltic wedges appear to accrete along active listric faults which act as feeders for the melts (Gibson and Gibb, 1987). This concept of syn-constructional tectonism has been applied to the Vøring Margin (Gibson and Love, 1989; Eldholm et al., 1989), and it may explain the asymmetric location of some extrusives.

The Major Problems

High priority scientific themes associated with volcanic margins involve the thermal and mechanical states of the lithospheric/asthenospheric mantle during breakup, the associated response of the crust to asthenospheric upwelling and plate driving forces, and the processes of melt generation, migration, and emplacement. The outstanding end-member models of tectonic and magmatic processes include passive vs. plume-induced rifting, transient vs. persistent magmatism, pure shear vs. simple shear extension, and symmetric vs. asymmetric structural development.

Knowledge of initial lithospheric parameters, e.g., thickness and thermal properties, and crustal thickness, is necessary in order to devise experiments which will constrain volcanic margin development. These conditions can best be established by regional geological/geophysical work and xenolith studies outside of the region influenced by rift-drift related deformation, and by modeling of extension and post-rift subsidence, which is constrained by geophysical data and calibrated by drilling. Modeling is particularly useful in constraining thermal perturbations which occur during rifting.

We aim to devise techniques and diagnostic criteria in order to evaluate processes which cause the breakup of continents and the formation of passive margins, and those which are responsible for large-scale magmatism at volcanic margins, especially the transient nature of the igneous pulse. Drilling, of course, can only sample parts of rock units at the margin. Even limited drilling, however, may provide constraints and allow further development of models for a magmatic-tectonic evolutionary cycle that are compatible with geodynamic processes initiating and maintaining volcanic margin evolution.

In the following we summarize and discuss major problems remaining to be solved.

Active Thermal Process vs. Passive Asthenospheric Upwelling

The question of whether an active thermal process, e.g., a plume, or passive upwelling of the asthenosphere initiates the formation of volcanic margins remains unanswered (see Chapter 4). Geochemical analyses of magmas and comparison of observational data with models of passive asthenospheric upwelling vs. an ascending deep mantle thermal anomaly could resolve the initial cause of rifting and eventual breakup. Studies of this kind may also tell if a plume is necessary to form volcanic margins, or if it only provides a convenient source for the additional needed heat (*Pedersen and Skogseid, 1989*). Such basic constraining information as the dimensions of plumes, asthenospheric upwellings, and hotspots is lacking for nearly all oceanic LIPs, and requires further study.

Thermal Anomaly Variation

Spatial and temporal variation of the thermal anomaly is reflected in the composition and alteration of sediments adjacent to the incipient plate boundary, and in the nature of igneous suites produced by asthenospheric upwelling and the subsequent initial accretion of oceanic crust. Nature and behavior of the thermal anomaly may be inferred from geodynamic modeling using the two- or three dimensional tectono-stratigraphic setting and crustal configuration as boundary conditions. However, one should also look for more direct, or indirect, evidence of mantle and magmatic temperatures in the composition of igneous rocks and in the metamorphism of interflow sediments (see Chapter 4). This includes studies of lava composition, and of reworked continental material within igneous rock underlying the basalt. An example is the dacitic lava at ODP Site 642 (Figs. 12, 13), which is presumed to have originated by shallow crustal melting. Furthermore, xenoliths within intrabasement flows and thermal metamorphism in underlying, interbedded, and overlying sediment should be examined. For maximum benefit these studies should be augmented by fission-track analyses of sediment on the continental side of extrusive complexes.

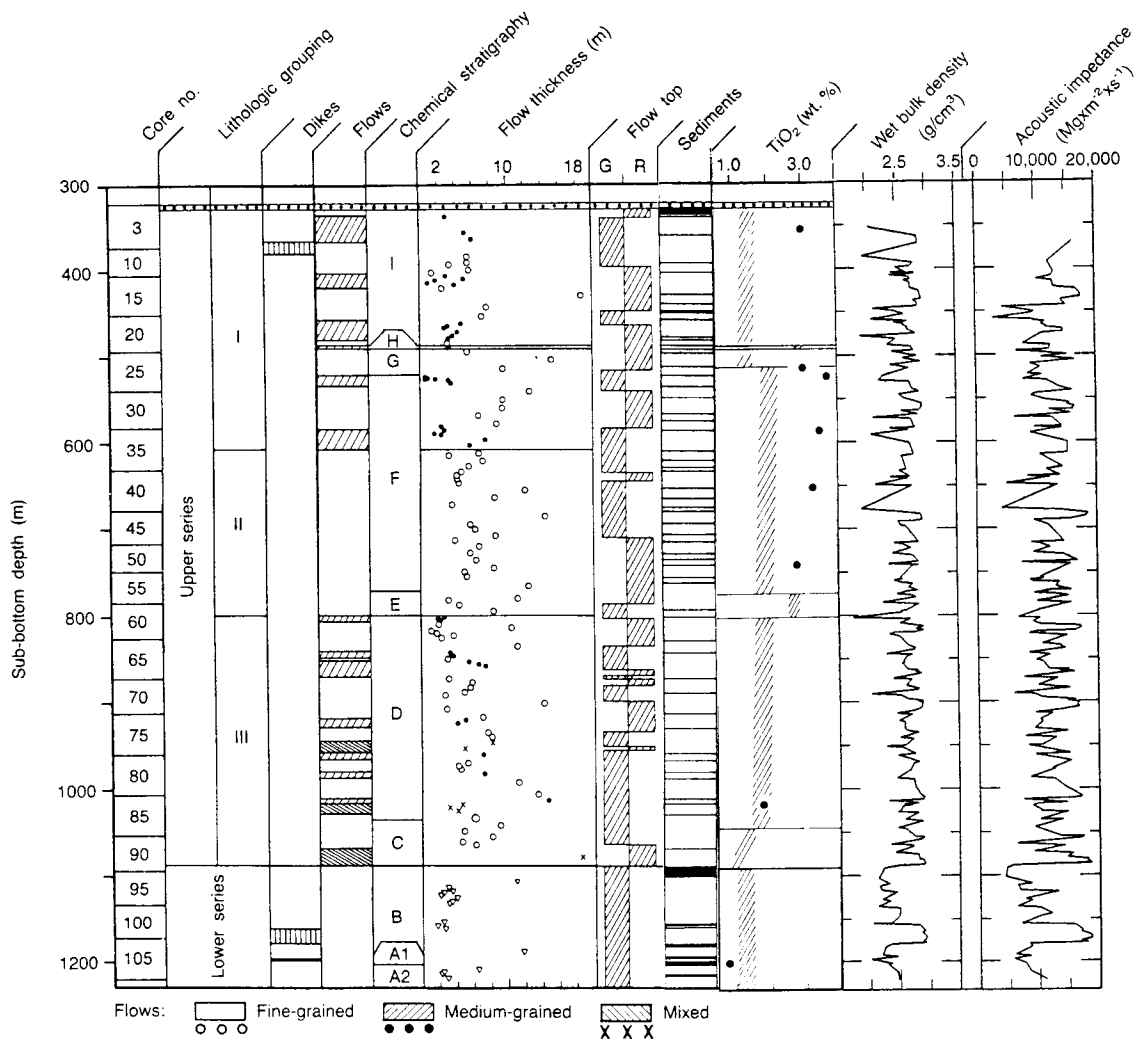
Transient vs. Persistent Magmatism

In the North Atlantic there is no evidence of large-scale emplacement of extrusives after transient magmatism associated with breakup and initial seafloor spreading abated, except along the hotspot trail (Greenland-Scotland Ridge) where seaward dipping reflections (*Larsen and Jakobsdottir, 1988; Larsen, 1990*) suggest that oceanic crust has accreted subaerially over nearly 60 m.y. To address the fundamental question of transient vs. persistent magmatism associated with breakup, even within the same LIP, samples must be obtained from conjugate igneous sequences both parallel and perpendicular to the axis of breakup. The petrology and geochemistry of the rocks may be compared with those of samples from normal oceanic crust, hotspots, and CFBs. To date only two scientific drill holes (DSDP Site 553, ODP Site 642) have penetrated into the seaward dipping wedges and only Site 642 (Fig. 12) has penetrated an entire wedge, albeit at its feather edge. Diagnostic indicators of transient and persistent magmatism may develop as the petrological and geochemical nature and variability of igneous margin provinces, and their substratum, become better sampled.

Relationships between transient or persistent magmatism and the transition to normal seafloor spreading must be examined, especially with regards to geochemical changes. Furthermore post-breakup magmatism not clearly related to hotspot activity should be evaluated.

Melt Generation, Migration, and Emplacement

All melts related to breakup must be considered in devising experiments to determine and constrain melt generation, migration and emplacement. These melts form at least two, and possibly three types of igneous complex: 1) extrusive complexes; 2) intrusives, primarily sills and dikes emplaced during the rift stage; and 3) high-velocity lower crustal bodies. Basalts dominate the extrusives, although other lavas may be produced, such as dacite flows (Fig. 12) below the seaward dipping wedge at Site 642 (*Parson et al., 1989*) and rhyolite in the Orange Basin off southwest Africa (*Gerrard and Smith, 1982*), although in the latter case the spatial relationship of the rhyolite to the wedge may preclude a clear genetic association between the two. Sills and low-angle



dikes are well known within Cretaceous and Paleocene sediment on the UK and Norwegian margins (Gatliff *et al.*, 1984; Gibb *et al.*, 1986; Hitchen and Ritchie, 1987; Myhre *et al.*, in press). Commercial drilling in the Rockall Trough and Faeroe-Shetland Channel has sampled olivine tholeiite sills of oceanic affinity (Gibb *et al.*, 1986) similar to the upper lava series at the Faeroes, and the upper sills geochemically resemble transitional MORB (Gibb and Kanaris-Sotiriou, 1988). Isotopic systematics of lava from the COT can be used to determine if contamination by continental material has occurred (e.g., Taylor and Morton, 1989).

Composition and emplacement of high-velocity bodies near the base of the crust are poorly understood. Only a few margins have enough deep crustal data to determine accurately the geometry of these bodies, and results from two of the better surveyed margins are shown in Figure 14. Whether the high-velocity lower crust is underplated or not cannot be directly resolved by

Figure 12. Selected litho- and chemical stratigraphy, petrography and physical properties of lavas and interbedded sediments at ODP Site 642 (Figs. 9, 10) the only site that has yet penetrated an entire seaward dipping reflection sequence (upper series). G and R indicate grey and red flow tops, respectively. From Eldholm (in press) based on Viereck *et al.* (1989), Parson *et al.* (1989) and Eldholm, Thiede, Taylor *et al.* (1987).

drilling. However, indirect geochemical inferences in terms of composition and volume, e.g. lower pressure fractionation, may be drawn from the geochemical signature of the extrusives.

Generation of melt, its migration, and its emplacement may be studied by examining volumes of igneous rock units, their geochemical stratigraphy, and their geochronology parallel and perpendicular to conjugate volcanic margins. Additional aspects requiring examination are their spatial variations along the COT in hotspot and non-hotspot regions (Fig. 15). The results, if

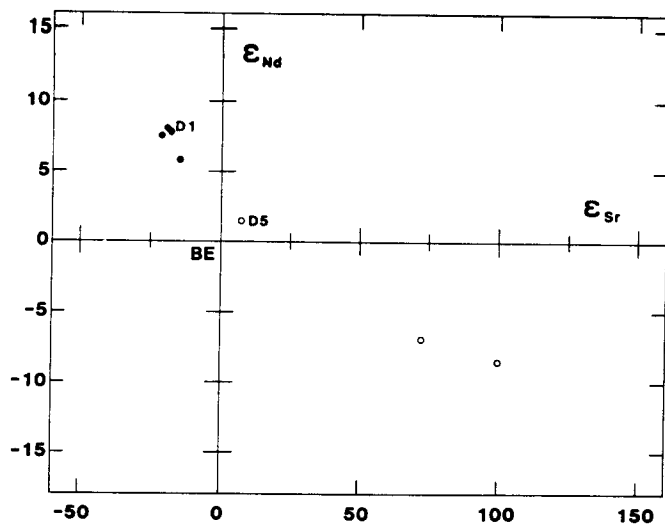


Figure 13. ϵ_{Nd} - ϵ_{Sr} diagram illustrating the fundamental difference between ODP Site 642 (Figs. 9, 12) upper series (open circles) and lower series (filled circles). The upper series is similar to North Atlantic MORB, while the lower series has characteristics of continental crustal rocks. D5 is a dike in the lower series which is strongly contaminated by crustal melt. From Larsen et al. (1990).

employed in geochemical and petrological models, could constrain the composition and volume of deeper rocks. It is particularly important to use and/or develop relations between compositional pressure and temperature of magma formation, and geochemical stratigraphy to study melt pressure, temperature, and fluid regime in the astheno- and lithosphere, including source temperature, degree of partial melting and melt fractions, and size and spatial distribution of magma chambers.

Melt production, migration, and emplacement rates can be calculated from age and volume information, both of which are extremely sparse along volcanic margins, and oceanic LIPs in general, as documented elsewhere in this report (see Chapter 3). Very little is known about volumes of igneous rock along volcanic margins other than of extrusive basalt. Ideally the total volume of igneous material emplaced during breakup should be determined, thus constraining emplacement mechanisms. Furthermore, little is understood about partitioning of melt material, i.e., extrusive vs. intrusive vs. underplated (if not expanded oceanic crust, serpentinized peridotite, or other *in situ* mantle) bodies, and about the vertical and lateral extent of magma movement.

Important constraints on volcanic stratigraphy and LIP construction rates may be gained by detailed paleomagnetic measurements, including paleo-secular variations, of oriented cores. Complementary studies of coeval CFBs and adjacent "normal" oceanic crust, however, must be undertaken.

Rift Mechanism and Tectonic Evolution

Mechanical evolution of the lithosphere and asthenosphere is reflected by structural movements and/or deformation along plate boundaries as well as in plate interiors.

Structural geology and stratigraphy reveal the amount of lithospheric extension that accompanied rifting, the extent of crust affected by the rift episode, and the mode of crustal deformation, e.g., faulting or flexure. Initially, an apparent absence of faulting and of a clearly identified rift unconformity had been interpreted to result from rapid crustal breakup without appreciable structural deformation and extension (Mutter et al., 1988). Consequently some volcanic margins were described as non-extensional. However, recent seismic data off Norway (Skogseid et al., in press; pers. comm.), southwest Africa (Austin and Uchupi, 1982; D. Roberts, pers. comm.), western India (Biswas and Singh, 1988), and in the Carolina Trough (Austin et al., 1990), together with field studies of the Late Triassic-Early Jurassic basins of the US Atlantic coast (Manspeizer and Cousminer, 1988) document extensional faulting during the rift stage. Thus many margins with a strong volcanic signature have experienced crustal extension expressed as block and/or listric faulting. On the other hand, similar extensional features appear absent off Southeast Greenland (H.C. Larsen, pers. comm.) where flexural deformation is apparent (Nielsen and Brooks, 1981). Lack of evidence for extension may result from poor resolution in available MCS data. If, however, the lack of extension is real, the nature of the extension process must be explained in view of normal faults and rift unconformities at some volcanic margins while similar extensional features are absent at other margins.

This leads to fundamental questions about the "driving force" for rifting and subsequent continental breakup at volcanic margins. Is rifting of "pas-

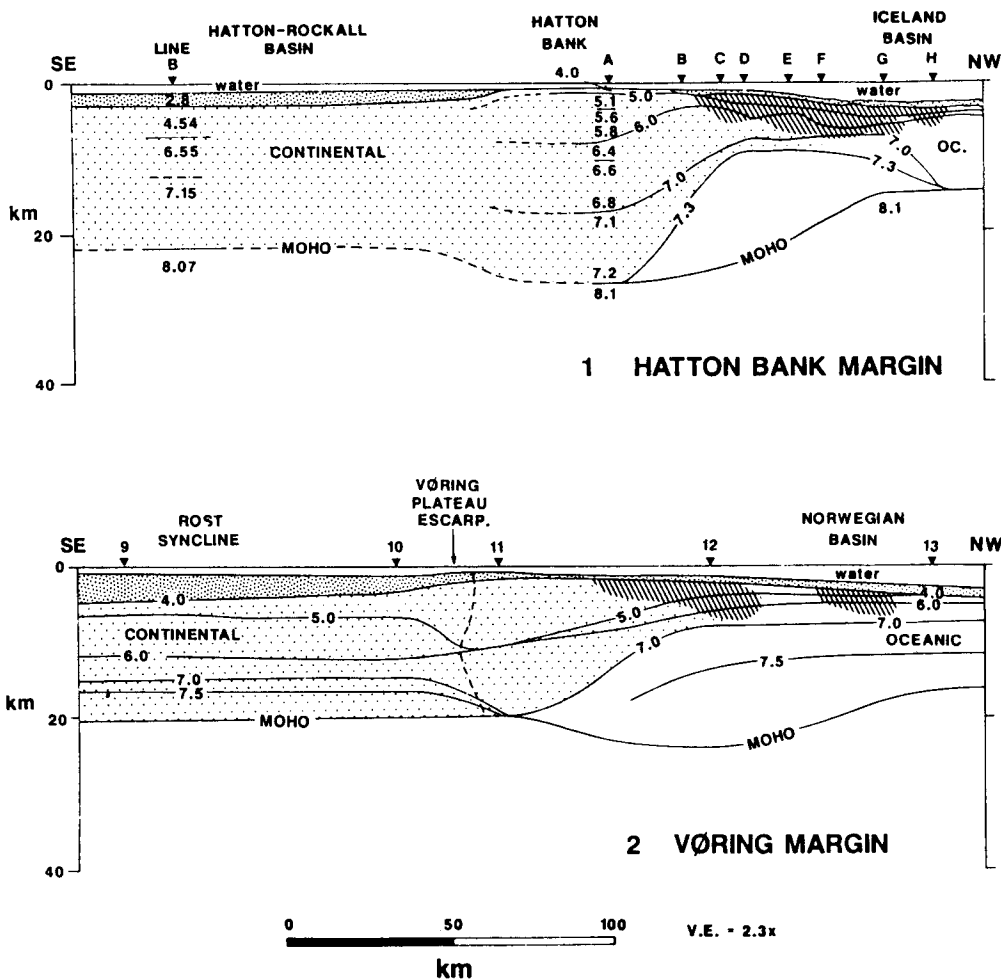


Figure 14. Cross-sections showing the crustal structure and possible underplated bodies for two North Atlantic margins. From White and McKenzie (1989) based on Hatton Bank data of Scrutton (1972) and White et al. (1987), and Vøring Margin data of Mutter et al. (1988). Oblique shading shows seaward dipping wedges, dense stipple sediments, and light stipple continental crust.

sive" lithosphere a response to a continuous mantle plume (White and McKenzie, 1989), or is it an "active" response to plume initiation (Campbell et al., 1989; Richards et al., 1989; Campbell and Griffiths, 1990; Hill, 1991). In the passive model considerable lithospheric extension precedes volcanism, whereas the active model does not require rifting. In fact many CFBs appear to have been emplaced without appreciable extension (Hooper, 1990; Duncan and Richards, 1991), although others have been related to rifting (e.g., Paraná-Etendeka, Peate et al., 1990).

Reconciliation of these apparently contrasting observations can only be achieved through deriving an accurate tectono-stratigraphic relationship between igneous and sedimentary sequences, precise dating, and study of the compositional "fingerprint" of igneous rocks. Such studies (Fig. 10) will also

shed light on whether response to crustal extension is pure shear, simple shear, or some combination involving change in style with depth or time (Buck et al., 1988; Sawyer and Harry, in press). They will also reveal how symmetric and asymmetric tectonic and magmatic features along conjugate volcanic margins reflect and relate to mode of rifting, as well as how pre-existing structural setting influences the new rift episode and associated magmatism leading to initiation of seafloor spreading. Better understanding of the nature of the COT, i.e., a gradual change in basement vs. a sharp tectonically defined boundary, would be expected. The magmatic-tectonic setting along the line of breakup may also provide clues to possible tectonic and magmatic rift propagation and propagation rate, and to the influence of "lock points" on rifting.

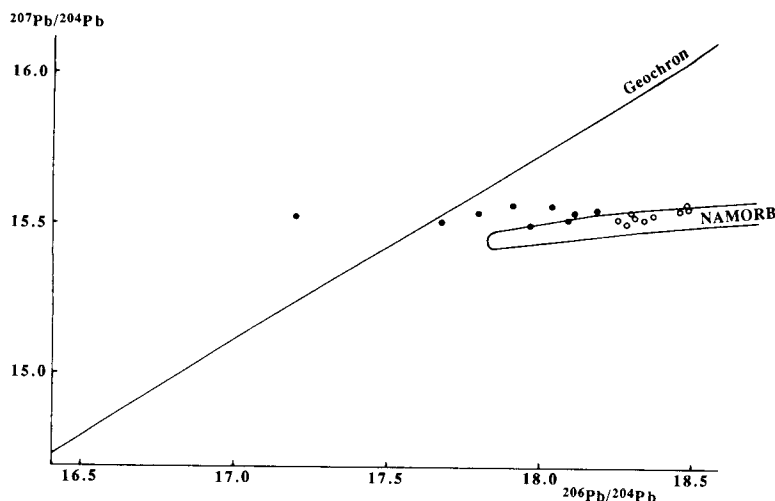


Figure 15. Pb-isotopic characteristics of lavas constituting the dipping reflections at DSDP Site 553 (Fig. 9) (filled circles) revealing a linear trend from North Atlantic MORB composition toward that of ancient U-depleted crust or sub-continental lithosphere. Site 642 tholeiites (upper series, Fig. 12) are included for comparison (open circles). From Larsen et al. (1990).

The post-rift evolution of volcanic margins poses important questions, many of which have environmental implications (see Chapter 6). For example, the process which governs temporal and spatial changes in the mode of oceanic crustal accretion from subaerial and submarine flow emplacement to normal seafloor spreading is unknown. This relates to the mode, i.e., fault- vs. flexure-dominated, and the rate of margin subsidence. At many margins, extrusive complexes are elevated with respect to adjacent oceanic crust, raising the issue of whether the extrusive edifice has subsided with the growing ocean crust or the elevation difference is tectonically controlled. Nonetheless, we do not yet know if thermal subsidence of extrusives underlain by lower crustal high-velocity bodies follows the standard depth-age function generally applicable to oceanic crust (Parsons and Sclater, 1977) and ocean ridges (Detrick et al., 1977).

OCEANIC PLATEAUS

Study of oceanic plateaus is at a nascent stage. The ages of most plateaus are not well known, their crustal structures and petrological/geochemical characteristics are poorly-understood, and the effects of their emplacement on the hydrosphere and atmosphere are virtually unknown. Only a single ocean drilling hole, Site 807 on the Ontong Java Plateau, has penetrated deeper than 100 m into the igneous basement of a plateau (Kroenke, Berger, et al., 1991). Of the two giant plateaus, Ontong Java, the size of Alaska, has yielded basement rock from 3 sites, and Kerguelen, four times the size of the United Kingdom, has had its basement penetrated at 4

sites (Kroenke, Berger, et al., 1991; Schlich, Wise, et al., 1989). Although it is relatively easy to determine the area of oceanic plateaus and the volume of plateau material lying above the level of adjacent ocean basins, the volumes of extrusive, intrusive, and total crustal material are not constrained by data. Few modern deep refraction experiments have been conducted on oceanic plateaus, and little deep reflection data have been acquired. Plateaus rarely have reliable igneous rock dates, and thus rates of igneous rock emplacement are impossible to determine accurately.

In the following we summarize the major scientific themes and outstanding questions associated with oceanic plateaus. The presentation will be temporal, covering pre-, syn-, and post-emplacement aspects of plateau evolution, and potential global effects. We emphasize that even though ocean drilling is a key tool in studying plateaus, it must be integrated with other geoscientific tools and techniques in order to further our understanding of the origin and evolution of these features and of the regional and global effects of their emplacement.

Mantle Behavior in Space and Time

Most oceanic plateaus, and indeed LIPs in general probably result from some sort of "hotspot"-type volcanism, regardless of whether they form intraplate or at plate boundaries. The flux of mass and heat from this volcanism is liberated in an extremely non-uniform manner in both space and time. For example, although volcanism is distributed independently of plate age (except for a local effect near the mid-ocean ridge), that occurring in French Polynesia and Hawaii accounts for nearly half of the current total flux from oceanic

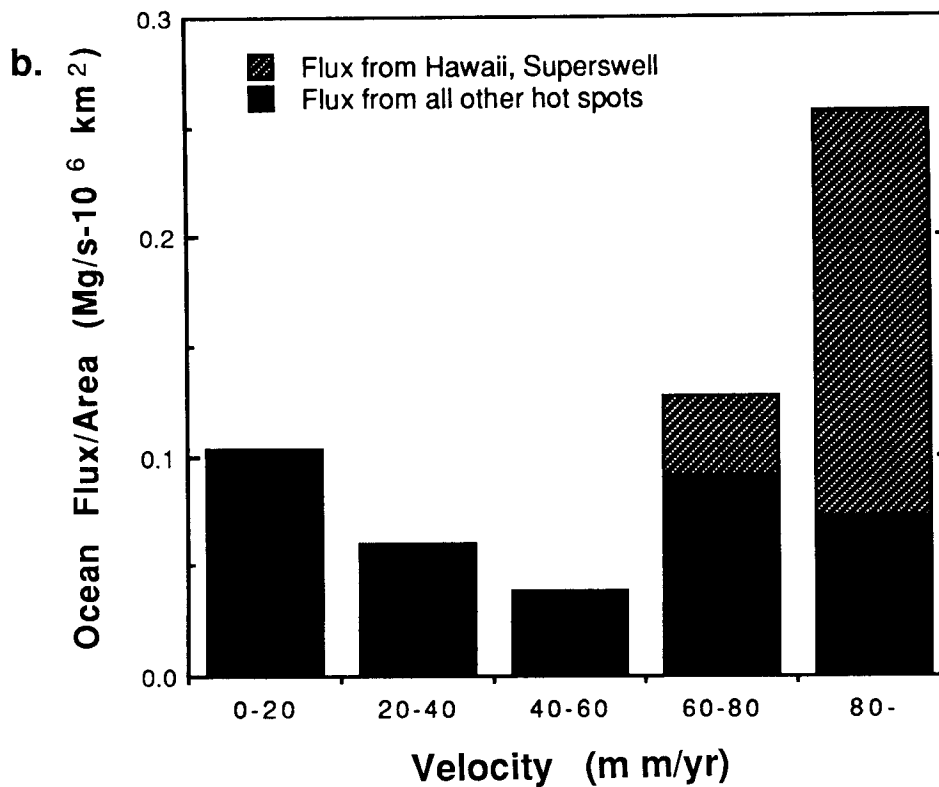
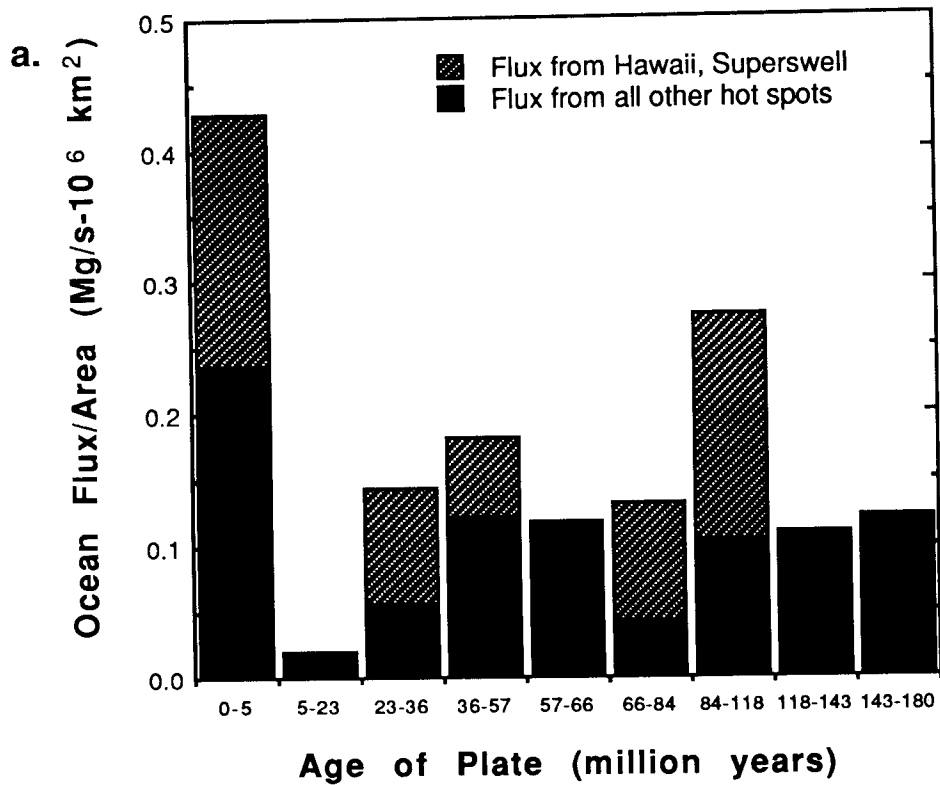


Figure 16. (a) Distribution of flux from oceanic hotspots as a function of age of the overlying plate. Flux is normalized by the total area of oceanic lithosphere in each bin. (b) same as a, except that flux is plotted as a function of the absolute velocity of the overlying plate with respect to the hotspot frame of reference. After McNutt (1990).

hotspots (Fig. 16a, b). The Early to mid-Cretaceous was marked by unusually high flux compared to later time intervals (Fig. 17). The two giant plateaus, Ontong Java and Kerguelen, were apparently emplaced within a ~10 m.y. span in the Early Cretaceous.

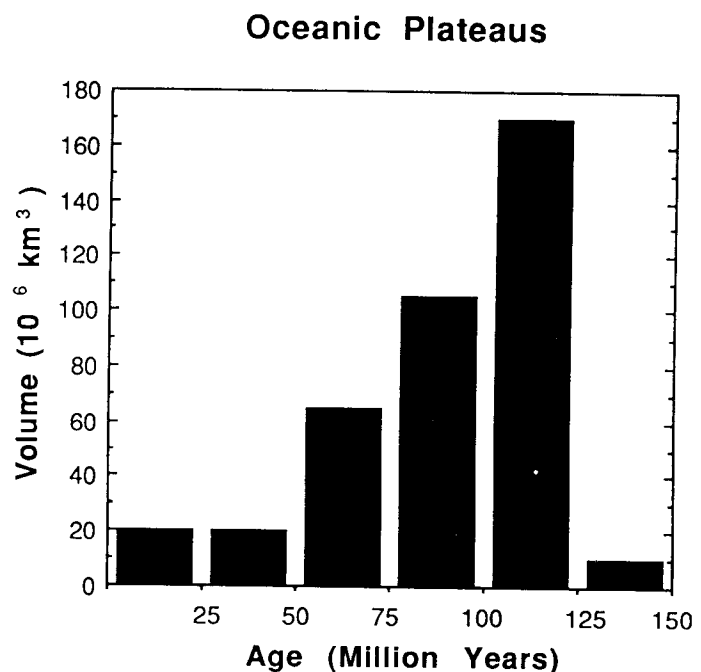
Longevity of mantle upwellings has been demonstrated or speculated upon in several instances. For example, the Deccan Traps were extruded at ~65 Ma, and the same hotspot subsequently created the Chagos-Laccadive Ridge and most of the Mascarene Plateau (Morgan, 1981). Emplacement of the Bunbury Basalt at ~135 Ma was followed by the Naturaliste Plateau, Rajmahal Traps, Kerguelen Plateau/Broken Ridge, Ninetyeast Ridge, and Kerguelen/Heard islands (Davies *et al.*, 1989; Storey *et al.*, 1989, 1991). The oldest seamount in the Hawaiian-Emperor chain is dated at ~70 Ma (Clague *et al.*, 1975).

Geophysical evidence from two large Pacific volcanic provinces, the present-day "Superswell" in French Polynesia and the mid-Cretaceous Darwin Rise presently located in the northwest Pacific (Fig. 18), suggests that focusing of volcanism in time and space may be related to unusual mantle dynamics. The two volcanic provinces were probably formed over the same region of the mantle, but separated in time by approximately 100 m.y. (McNutt and Fischer, 1987). A proposed sequence of events begins with formation of a near-ridge oceanic plateau, followed within the next 10 to 20 million years by initiation of several nearby, off-ridge, age-progressive hotspot chains. There is good evidence in both cases for broad (over several 1000s of km) regional thinning of the lithosphere and dynamic uplift (~150 m) of the crust by hot mantle material rising within a low viscosity zone (LVZ) beneath the plate. Furthermore, circumstantial evidence suggests that formation of these large Pacific volcanic provinces is related to very rapid plate velocity, perhaps because plate motion is facilitated by the lubricating effect of the sub-lithospheric low viscosity zone. Assuming that the low viscosity zone is itself the direct consequence of heat and/or volatile content of upwelling mantle, this model suggests that mantle upwellings responsible for the formation of plateaus and

swells, and LIPs in general, may also influence motion of the overlying plates.

Contrary to the usual belief that hotspot volcanism occurs quite independently from the general drift of plates, the scenario described above, if correct, would imply a direct connection between mantle circulation, the formation of LIPs, rates of plate motion, and their combined effect on sea level and global paleoenvironment. Unfortunately, insufficient information on timing of volcanic events and associated horizontal and vertical plate motions exists to truly test this hypothesis for the Darwin Rise and the Superswell. Moreover, it is not clear to what extent this model, or parts of it, may apply to other plateaus. As previously mentioned, plate reconstructions for the mid-Cretaceous are not well documented. By determining paleolatitude as a function of time for cores from pelagic and reefal caps of volcanoes and plateau basement, the north-south component of plate motion can be recovered. This information could be used to examine if different plateaus backtrack to the same region of the mantle, which could constrain the longevity and periodicity of major mantle upwellings. It could also be determined if rates of plate motion increase during and immediately after emplacement of plateaus. If so, it would imply a previously

Figure 17. Estimates of igneous crustal volumes emplaced as oceanic plateaus for 25 m.y. intervals over the past 150 m.y. (E.L. Winterer, pers. comm.).



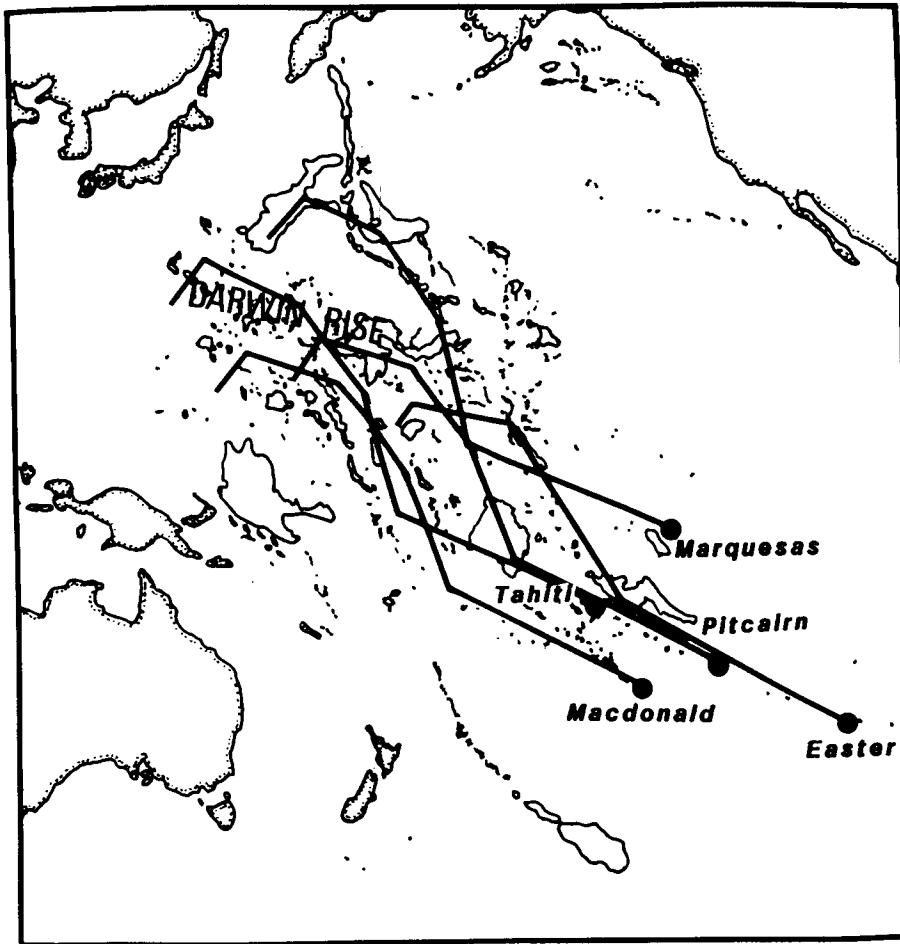


Figure 18. Location of the proposed Darwin Rise (Menard, 1964, 1984) and tracks of superswell hotspots from Gordon and Henderson (1985). After McNutt and Fisher, (1987).

unsuspected connection between plateaus (and LIPs in general) and plate tectonics, perhaps related to the associated lowering of asthenospheric viscosity. For example, at present the bulk of the flux from oceanic hotspot volcanism occurs in regions of maximum plate velocity with respect to the mantle (Fig. 16b). Analyses of drill samples could also be used to compare mean rates of reversals and magnitudes of secular variation with timing of emplacement of plateaus. Outpouring of many oceanic plateaus in the Early to mid-Cretaceous interval correlates with the Cretaceous Long Normal Polarity Superchron, and the anomalous region of very low rates of secular variation in the central Pacific corresponds to the location of the Superswell. There may be additional evidence, therefore, that plateaus, and LIPs in general, influence the geomagnetic field. One possible mechanism would be to “anchor” convection columns in the core by the thermal influence and the dynamic topography imposed on the core/mantle boundary by the upwelling mantle (Larson, 1991).

Plate Setting

The plate setting of emplacement of the two primary classes of oceanic plateaus, those exhibiting persistent and those characterized by transient volcanism, is not defined in many instances. This is the case for the two giant plateaus, Ontong Java and Kerguelen. Possible settings, with examples, are:

- 1) mid-ocean ridge (e.g., Iceland)
- 2) passive margin as a transverse ridge, commencing on-axis and progressing off-axis (e.g., Etendeka/northeast Walvis Ridge—Rio Grande Rise/Paraná)
- 3) leaky fracture zone/zone of weakness (e.g., Ninetyeast Ridge)
- 4) intraplate (e.g., Tuamotu Ridge)

Identification of magnetic anomalies on adjacent oceanic crust and of fracture zone traces, commonly interpreted from satellite altimeter data, are required to determine the plate setting of a plateau. Combining the plate setting with accurate dates of plateau construction may help to determine if oceanic plateaus (and LIPs in gen-

eral) are preferentially emplaced in certain plate settings, and to examine whether a genetic relationship exists between plate setting and oceanic plateau emplacement.

Underlying Crust

Many plateaus appear to be constructed entirely of some combination of MORB and OIB source magmas, but some are composed at least partially of continental crust, e.g., Mascarene Plateau (*Baker, 1963*). Seismic tomography, and deep reflection/refraction experiments have the potential to reveal continental lithosphere beneath plateaus, but few data exist. Recovery of plateau basement material by dredging and drilling may determine which plateaus are composed, at least in part, of continental material, or were contaminated by continental lithosphere.

Emplacement

Surface igneous emplacement may occur either at a point source, such as a shield volcano (e.g., Hawaii), or at fissures (e.g., Iceland). Furthermore, basalt emplacement may be predominantly subaerial (e.g., Kerguelen) or submarine (e.g., Ontong Java). High-resolution, 3-dimensional seismic reflection images of the upper igneous crust of oceanic plateaus offer one opportunity to discriminate between the two modes of extrusion. On the Kerguelen Plateau, MCS data document the presence of dipping reflection sequences similar to those observed on volcanic margins (*Colwell et al., 1988; Coffin et al., 1990; Schaming et al., 1990*). MCS data may also show strong angular unconformities between plateau basement and the overlying sediment (e.g., Kerguelen Plateau), which may be interpreted as resulting from subaerial erosion (Fig. 19). Samples of basement and overlying sediment obtained by drilling, however, provide the only conclusive data on environment of deposition. Few oceanic plateaus have had MCS surveys, and no 3-D data have been collected. Basement and deep sediment samples from plateaus are similarly sparse. Future drilling and MCS data acquisition have the potential to determine the dominant mode of extrusion on oceanic plateaus, and the relative proportions of subaerial and submarine volcanism.

The process of deeper crustal accretion is even more poorly-constrained. The sole oceanic LIP

away from passive margins which has been studied in both deep MCS and refraction experiments is Hawaii (Fig. 20). Normal mantle velocities are observed beneath Hawaii. Several other oceanic LIPs (e.g., Iceland, Kerguelen, Ontong Java) have limited deep refraction data. Flat-lying and dipping reflections (Fig. 19) interpreted as sequences of lava flows with a minimum thickness of 7 km have been documented on the Kerguelen Plateau (*C.E. Chudyk, pers. comm.*). A low-velocity layer exists beneath Kerguelen Island and Iceland, and mantle velocities of 7.5 km/s or greater are impossible to discern. In general the sparse results from oceanic plateaus show a velocity structure similar to that of oceanic crust; however, the layers are thicker (*Coffin, 1991*).

Estimates of volcanic flux as a function of time are uncertain due to lack of reliable basement dates from plateaus. In the few cases of plateaus from which igneous rocks are available, rocks are from the top of the volcanic pile and are assumed to represent the end of plateau construction. Volcanic-rich sedimentary sections in basins adjacent to oceanic plateaus may preserve a time record of major eruptive phases of the plateau. Some plateaus are deeply rifted, thereby exposing an igneous stratigraphy. A rift on the Manihiki Plateau, for example, exposes about 2 km of igneous rock. Suspected obducted plateau fragments (e.g., Curacao and Gorgona of the Caribbean flood basalt province: *Klaver, 1987, and Storey et al., 1991, respectively; Wrangellia: Richards et al., in press*) may yield information on construction rates. Major questions awaiting resolution are the duration, rate, and episodicity of volcanism and intrusion on oceanic plateaus.

Many reef-capped volcanoes are superimposed on large plateaus (e.g., Chagos-Laccadive Ridge, Mid-Pacific Mountains, Tuamotu Archipelago, Ontong Java Plateau, Ninetyeast Ridge, Manihiki Plateau), but the temporal relationship of the volcanoes to the plateaus is uncertain. An important question is whether or not formation of the surmounting volcanoes is a separate volcanic event.

Petrological and geochemical evolution of plateau-forming magmas has only recently been addressed (*Storey et al., 1991; Mahoney and Spencer, 1991*). Studies of CFB provinces and rifted plateaus such as Kerguelen/Broken Ridge (*Wise, Schlich, et al., 1991*) and Manihiki (*Winterer et al., 1974*) may provide the best opportunity for gain-

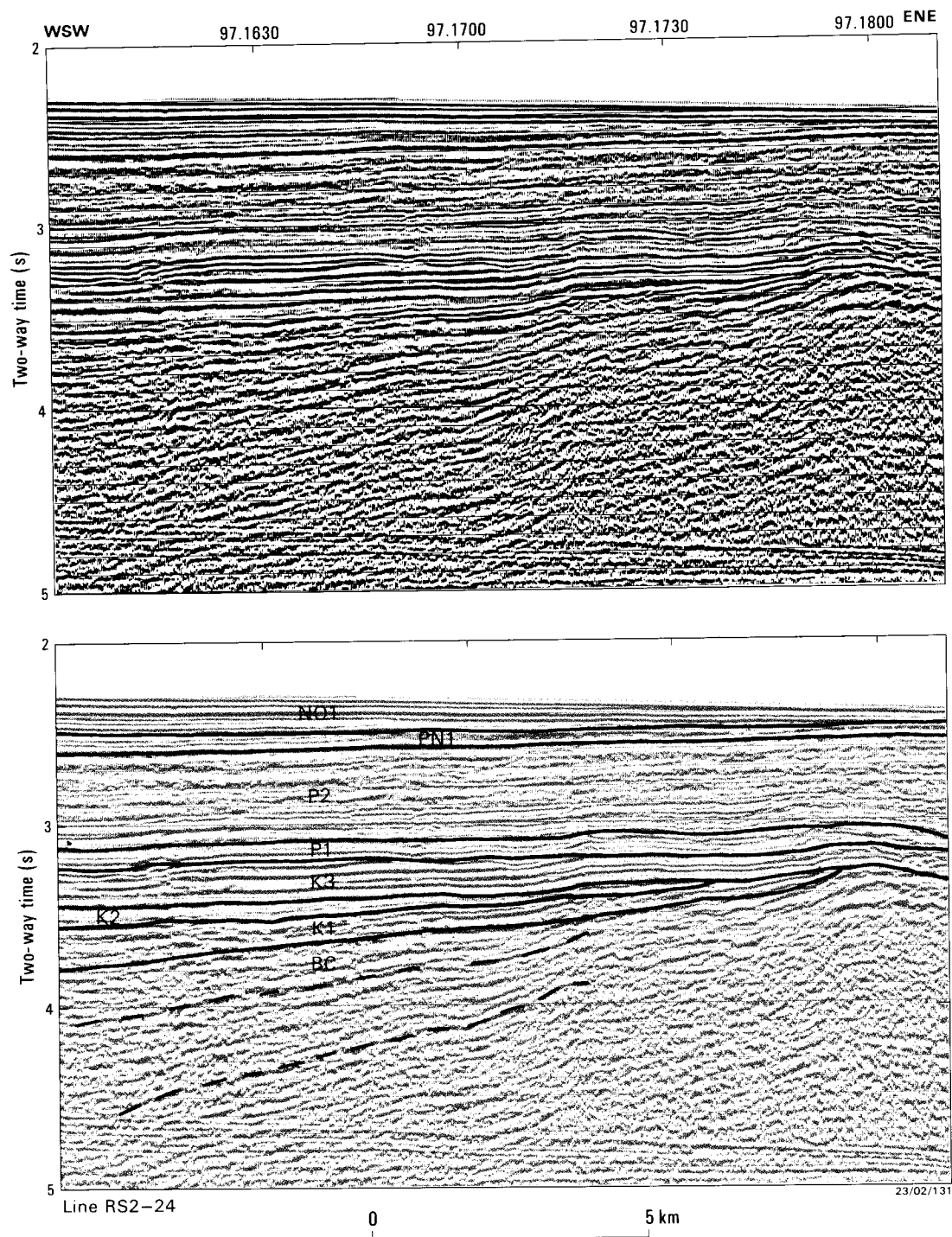


Figure 19. MCS data showing sedimentary sequences K1 and K2 overlapping igneous basement complex (BC) which contains dipping reflections. After Coffin et al. (1990).

ing understanding of magma evolution. The absence of samples from depth precludes understanding the petrology and geochemistry of the initial material which ascends from the mantle and commences plateau construction. Island samples from the Pacific Superswell and limited dredge rocks from guyots of the Darwin Rise

indicate that both provinces lie on an isotopic mixing line between HIMU and EMII (e.g., Hart, 1988; Weaver, 1991). Kerguelen Plateau basalts are transitional between MORB and OIB sources and characterized by a DUPAL signature (Davies et al., 1989; Storey et al., 1989; Weis et al., 1989), and distinctive isotopic fingerprints are also typical of

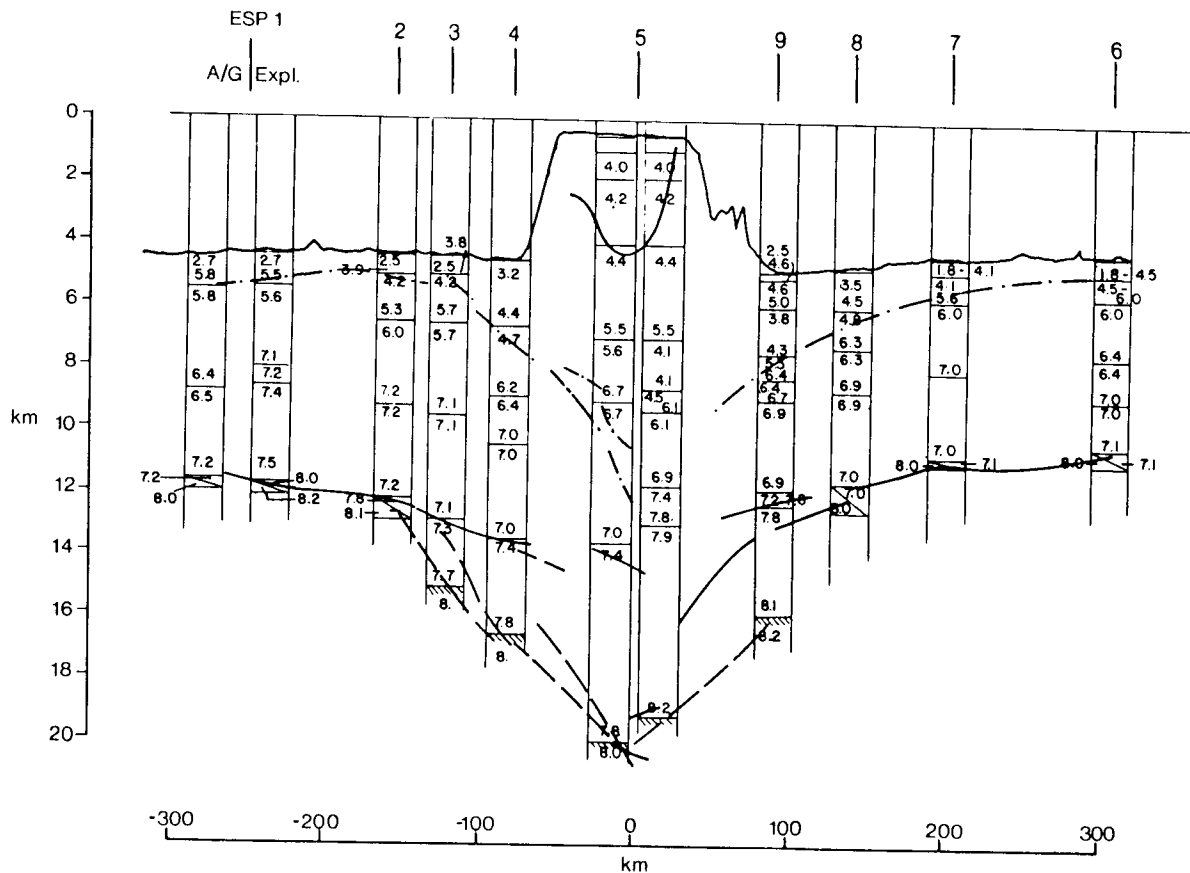


Figure 20. Summary of the velocity and crustal structure of Hawaii and adjacent oceanic crust obtained by ESPs. Horizontal lines in each column represent depth to a prominent change in velocity with depth. The numbers refer to velocities (km/s) immediately above and below velocity changes. The dashed-dot, continuous, and dashed lines represent prominent seismic reflections which have been converted to depth using ESP velocities. These three reflections are interpreted as corresponding to the top of oceanic crust, the base of pre-flexed oceanic crust, and the M-discontinuity, respectively. Note that two possible solutions are shown for ESP1 and ESP5. After Watts et al. (1985).

other hotspot provinces in the Atlantic and Indian oceans. Because it is nearly impossible to dredge oceanic plateaus, however, it is not known whether many share the same unusual mantle geochemistry as nearby hotspots, or whether they are closer to MORB in composition. Geochemical analyses from drill cores which recover basalt from oceanic plateaus and less altered samples from volcanoes could be used to relate oceanic plateau geochemistry to the temporal and spatial distribution of mantle heterogeneity, and to determine the longevity of distinctive mantle signatures such as DUPAL (Dupré and Allègre, 1983; Hart, 1984) and SOPITA (Staudigel et al., 1991). They could also help to determine if radiogenic enrichment seen for many plateaus (especially in the Southern Ocean) is merely a geochemical tracer, or if the volume of enriched mantle is sufficient to supply the extra heat required to form plateaus.

Post-emplacment

Following emplacement, oceanic plateaus appear to subside along a thermal subsidence curve or some variation thereof (Fig. 21; Detrick et al., 1977). The starting point for this subsidence may be high above sea level, e.g., Kerguelen (Fig. 22; Coffin, in press). Dynamic flow in the mantle and resulting lithospheric thinning associated with the formation of plateaus, however, may lead to departures in the vertical motion history of the seafloor with respect to predictions of the standard thermal plate model (e.g., Parsons and Sclater, 1977).

Oceanic plateaus and swells can be distinguished on the basis of geoid height and topography (Sandwell and MacKenzie, 1989). Swells may or may not develop into oceanic plateaus, depending on whether magma penetrates the crust to form extrusives characteristic of a plateau. The vertical motion history of a swell which does not

develop into a plateau may represent the least complicated end member of lithospheric behavior associated with a LIP emplacement. Figure 23 shows one proposed vertical motion history for a swell. Thinning of the lithosphere resulting from the heat flux supplied by hot upwelling mantle would be seen as a substantial (~10 m.y.) hiatus in sedimentation on guyot summits and reduced subsidence rates compared to those predicted by plate age and the standard thermal plate model. Ultimately, the lithosphere drifts away from the locus of mantle upwelling, and it subsides more rapidly as it gradually rethickens to normal values. This phase would be apparent as an enhanced subsidence rate of the volcano compared to that predicted by its magnetic age.

Drilling the summit of a reef-capped volcano on a plateau would allow testing and calibration of this end-member model. It could be determined if the plateau initially subsides along the *Parsons and Sclater* (1977) curve. Perhaps improved constraints on the age of the volcano, its paleodepth at the time of volcanism (as determined from the height of the original volcanic basement above that of the surrounding seafloor), and the rate of accumulation of the earliest reef facies will point to important thermal and dynamic vertical motions even during the initial, near-ridge phase of volcanism. Drill samples could also be used to estimate timing of dynamic uplift of the seafloor, and whether it is simultaneous over the entire region of a swell or superswell (5000 km maximum dimension in the case of the Darwin Rise and the Pacific Superswell). The time interval between development of a dissolution surface on the summit of the reef and formation of low-stand terraces on the flank might constrain how rapidly the uplift occurs, and yield, in turn, a value for mantle viscosity or rate of metamorphic phase change. The duration of the hiatus between uplift and resubmergence of the volcanic platform would provide information on the amount of lithospheric thin-

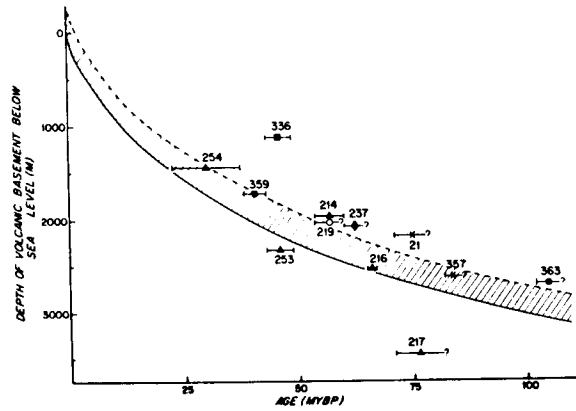


Figure 21. Isostatically adjusted basement depth plotted against age for those aseismic ridges that are known to have been formed at or near sea level and that have not experienced subsequent uplift. Predicted subsidence curve (solid line) determined by assuming these ridges formed at sea level and then subsided along the empirical depth vs age curve of Sclater et al. (1971). Dashed line is this same curve displaced upward by 300 m. Numbers refer to DSDP sites. Horizontal bars indicate estimates of possible age error; question mark is used where basement was not reached. Key: triangle: Ninetyeast Ridge; X: Rio Grande Rise; closed circle: Walvis Ridge; square: Iceland-Faeroe Ridge; open circle: Chagos-Laccadive Ridge; diamond: southeast Mascarene Plateau. After Detrick et al. (1977).

Figure 22. Age-depth curves for igneous basement at Kerguelen Plateau ODP sites 738, 747, 748, 749, and 750. Calculated basement depths for all sites are given for 0 and 110 Ma; for sites 738, 748, and 750 calculated basement depths at the end of shelf deposition are indicated. These correspond approximately with core-determined depths to seafloor at the end of shelf deposition. From Coffin (in press).

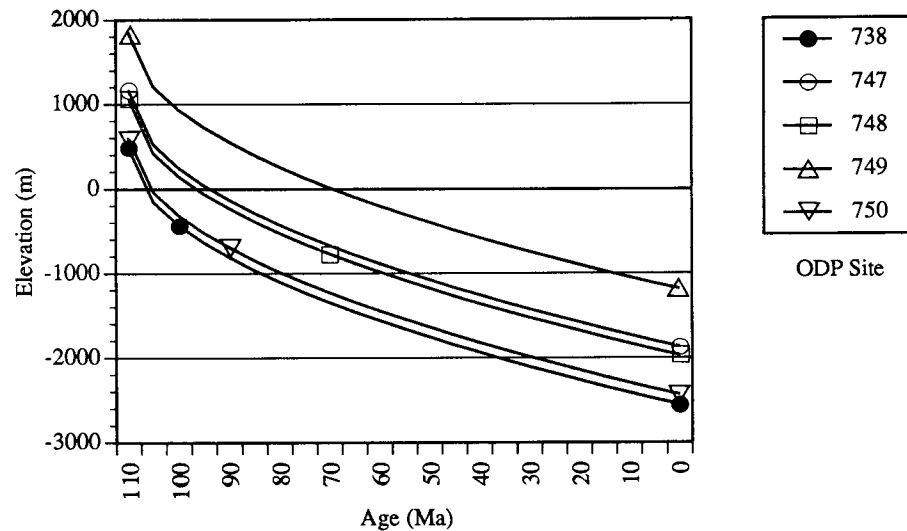
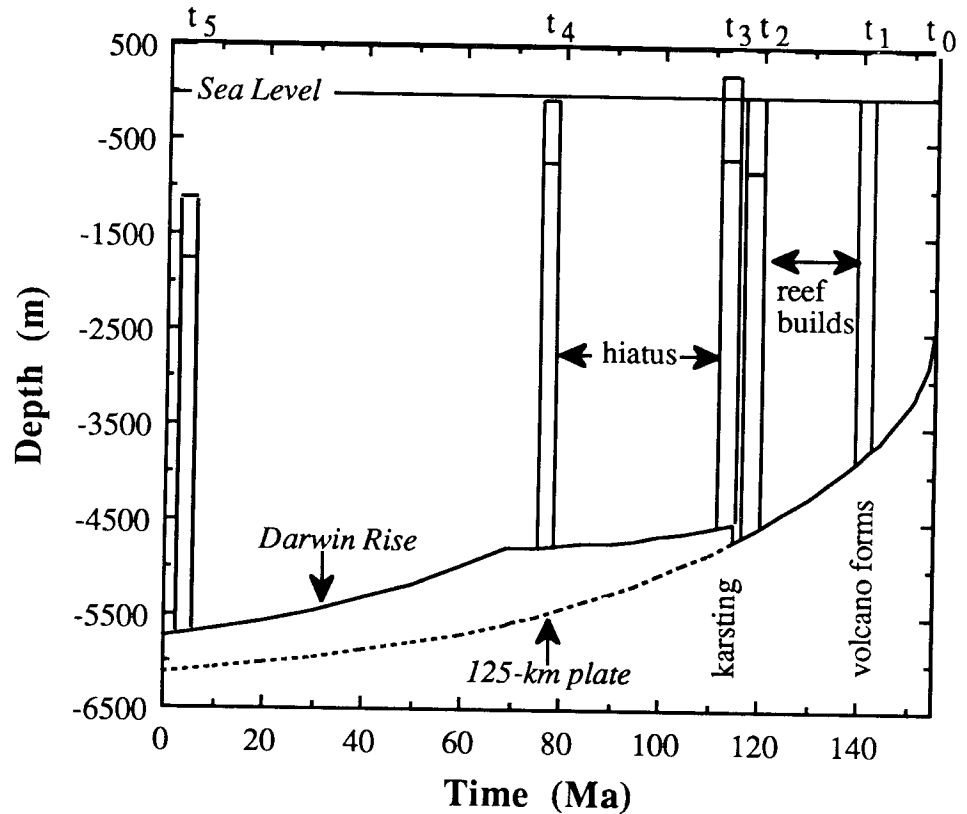


Figure 23. Schematic model for vertical motions on the Darwin Rise for the specific case of a 140 Ma volcano on 155 Ma lithosphere. The lithosphere forms at time t_0 , and a near-ridge volcano is constructed at time t_1 on lithosphere of otherwise normal depth, since there can be no thermal swell formation for lithosphere that is already thin by virtue of its youth. The reef cap that develops on the subsiding volcanic platform then becomes the sea level reference that can be used to chart the vertical motion of the seafloor at all later times. Between times t_0 when the lithosphere forms and t_2 , the lithosphere subsides as a 125 km-thick thermal plate. At time t_2 , the seafloor is uplifted to form a superswell. At time t_3 , hot mantle upwelling

dynamically uplifts the seafloor by approximately 150 m and depresses the geoid by approximately 40 m. Both factors lead to a fall in sea level of approximately 200 m which would be apparent as dissolution surfaces and sink holes simultaneous in age over the entire volcanic province. In fact, such surfaces have been seen in Seabeam images from drowned guyots of the Darwin Rise with sink holes extending to 180 m



depth, but the assumption that the karstic surfaces are concordant is difficult to test with limited dredge samples, mostly taken from deeper reef flanks. Between t_3 and t_4 the lithosphere subsides at the rate of a 75 km-thick thermal plate with effective thermal age at t_3 given by its depth at time t_3 . Between times t_4 and t_5 (the present), the plate resumes the subsidence rate of a 125 km thick plate, with effective age at t_4 given by its depth at t_4 . After McNutt et al. (1990).

ning. Finally, drill samples could constrain when the lithosphere begins to return to normal thickness. Thickening of the lithosphere associated with cessation of hotspot volcanism would indicate that thick lithosphere can be a barrier to magma penetration.

Post-emplacment extension, compression, and/or shear bearing little or no relationship to thermal subsidence models may also affect the vertical tectonic history of an oceanic plateau. For example, on the Kerguelen Plateau, sag basins developed, widespread normal faults were active, and strike-slip motion occurred (Houtz et al., 1977; Coffin et al., 1986, 1990; Schaming and Rotstein, 1990). Large-scale rift structures formed on the Manihiki Plateau (Winterer et al., 1974). On the

two giant oceanic plateaus, Kerguelen and Ontong Java, and possibly others, different portions of the features appear to have experienced different tectonic histories, and thus diverge widely from the subsidence history predicted by thermal plate models. Furthermore, many oceanic plateaus have steep, faulted flanks which are difficult to explain isostatically. More information is needed to determine the temporal and spatial development of post-emplacment deformation on oceanic plateaus, which could provide information about the post-emplacment stress regime of the plateau. The state of lithospheric stress in the vicinity of oceanic plateaus could be estimated by examining if deformation preferentially occurs on plateaus as opposed to adjacent oceanic crust.

Global Paleoceanography, Paleoclimate, and Paleoenvironment

Disciplinary Working Group Report

Jerry Winterer, Chair

Members:

McLean, Officer, Rampino, Sliter, Wise

FOCI

Paleoclimate, Ocean Warming, and Sea Level

Paleoceanography—Circulation, Gateways, Chemistry, Productivity, and Evolution

Terminal Cretaceous Event and other Mass Extinctions

The highest-resolution stratigraphic records are found on passive margins and oceanic plateaus. The bathymetry and paleobathymetry of the LIPs have allowed deposition of sediments influenced by a full range of physical, biological, chemical, and geological oceanographic factors.

- ◆ How are climate, sea level, ocean circulation, ocean chemistry, the oceanic heat budget, and biological evolution and production related to orbital variations, extra-terrestrial encounters, emplacement of LIPs, and plate movements?
- ◆ How rapid was the terminal Cretaceous event?
- ◆ How did the geochemistry of the ocean at various depths vary through the event and recovery?
- ◆ How rapid was the Tertiary recovery?
- ◆ Do the K–T and other boundary events correlate with the emplacement of any LIPs?

Introduction

Oceanic plateaus and submarine ridges, as well as certain microcontinents and marginal plateaus, are of special interest to paleoceanography and paleoclimatology because they are:

- ◆ isolated from continental detritus, and thus preserve a fairly pure pelagic sediment that is generally rich in biogenous components with datable fossils.
- ◆ perched above the surrounding deep seafloor, usually lying well above the CCD. Therefore, a calcareous biogenous section, commonly without major hiatuses, is preserved.

Scientific problems associated with LIPs involving global paleoceanography, paleoclimate, and paleoenvironment fall naturally into two categories, "passive" and "active". Oceanic LIPs are passive repositories of sediment deposited at differing paleodepths with varying inputs of continental detritus, and thus they may preserve unique sedimentary records. Some plateaus, ridges, and volcanic margins have gentle side slopes or structural benches on their flanks which have preserved sediment deposited over a large depth range. Thus, they provide not merely a glimpse into ancient mid-water oceanographic conditions, but also a suite of paleodepths along transects. As oceanic LIPs subside, each transect

site records conditions at gradually increasing depths yielding information on changing conditions at all paleodepths.

On the other hand, plateaus, ridges, and volcanic margins play an active role in the oceans and atmosphere. The igneous constructions act as oceanographic gatekeepers, and have the potential to have affected sea level, oceanic and atmospheric chemistry, and biotic evolution and extinction.

In the following we first describe the significance of the sediment accumulations on oceanic LIPs in relation to past changes in oceanography, climate, and environment, focusing on times of particularly significant change. Then we consider the feature's active role in modifying global conditions, concentrating on potential major effects.

Oceanic LIPs as Passive Sediment Repositories

Mesozoic Paleooceanography

Oceanic plateaus provide an exciting opportunity to interpret the paleoceanography of the Pacific superocean during the Cretaceous. Plate motion and crustal subsidence have preserved records of both horizontal and vertical variability in the water column. In fact, the thickness and character of sedimentary caps on topographic

highs have been used to identify the passage of plates beneath the highly productive equatorial divergence (Lancelot, 1978; Lancelot and Larson, 1975). Important information, however, is still lacking about the oceanographic and

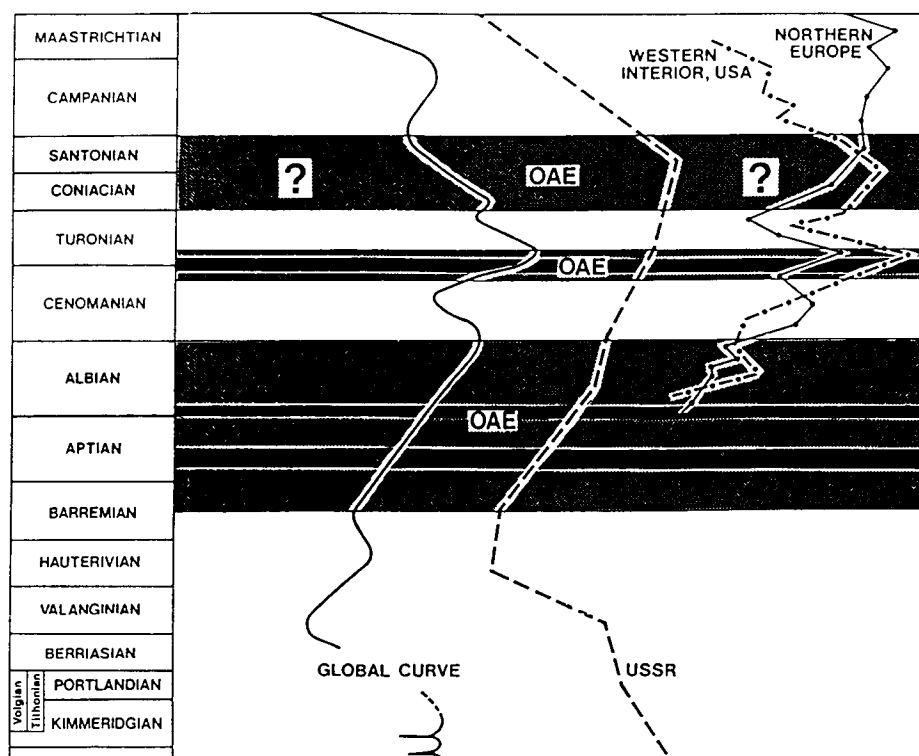


Figure 24. Stratigraphic intervals characterized by deposition of C_{org} -rich strata plotted against various sea level curves. Intervals of intense carbon burial shown by darker bands in the broader oceanic anoxic event (OAE). Modified from Jenkyns (1980).

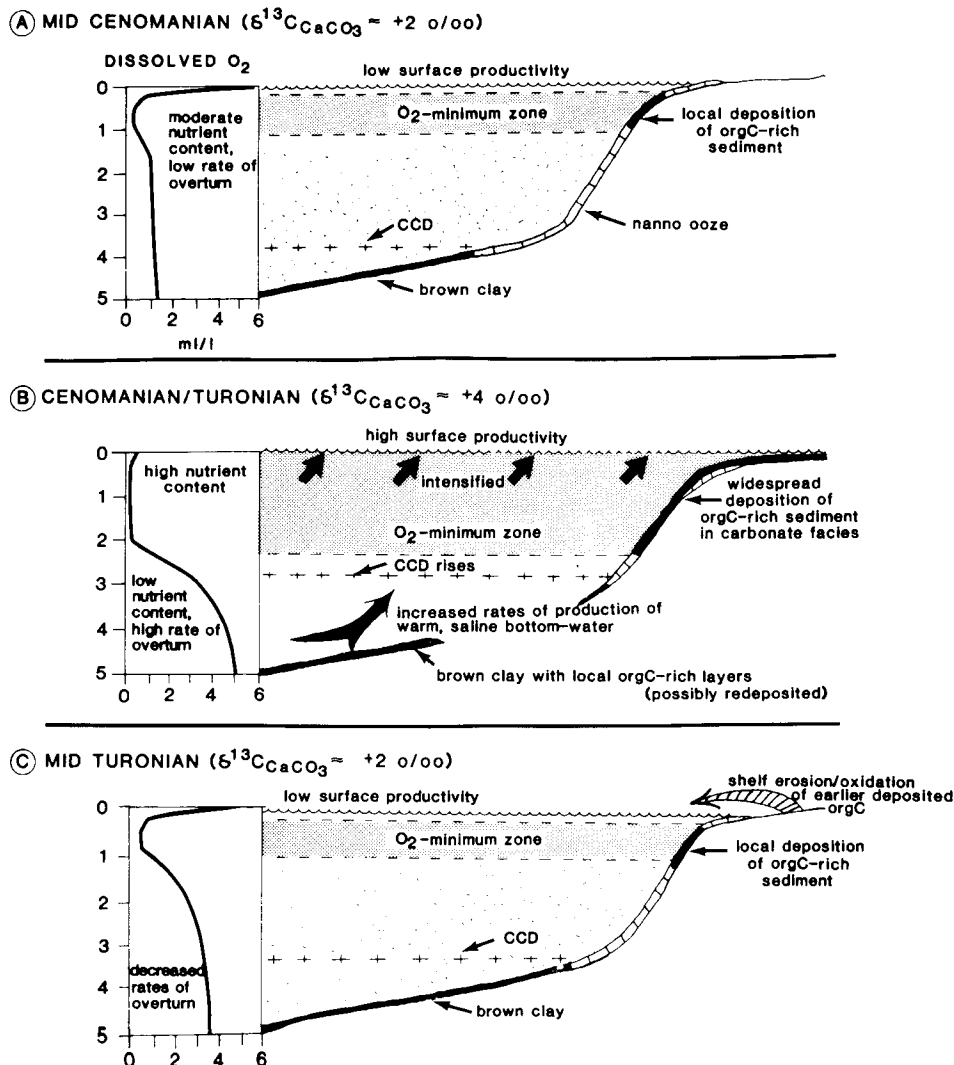
the upper water column for specific intervals during the Cretaceous. Important questions include: How did the width and intensity of the equatorial divergence vary? What was the vertical extent and intensity of stratification in the upper water column and how did it vary? What was the intensity of current flow of intermediate-depth water? What was the variation in organic productivity between low and intermediate latitudes for specific time slices? What were the chemical characteristics of the water masses? Of particular importance is to document the characteristics of the mid-Cretaceous warm ocean as well as the cooler, more latitudinally gradational Late Cretaceous ocean. Information from ocean drilling could be used to test and constrain advanced paleoceanographic circulation models (e.g., *Barron and Peterson, 1989*).

Anoxia and the History of Oceanic Oxygen Profiles

Controversy over the nature of anoxic "events" continues: are they due to intensification and expansion of the mid-water oxygen minimum, or is there stagnation completely to the bottom? Oceanic plateaus with gently sloping flanks are ideal sites for obtaining paleo-oxygen profiles.

Cretaceous marine sediment records several episodes during which sediments rich in organic carbon (C_{org}) were deposited (Fig. 24). *Schlanger and Jenkyns (1976)* hypothesized that widespread and broadly synchronous deposition of C_{org} -rich strata (black shales) during these intervals, termed oceanic anoxic events (OAE), resulted from widespread and expanded oxygen minimum zones (Fig. 25). Although anoxia in restricted basins in the smaller Cretaceous oceans, such as the Angola

Figure 25. Expanded oxygen-minimum model for the Cenomanian-Turonian boundary OAE. From Arthur et al. (1987).



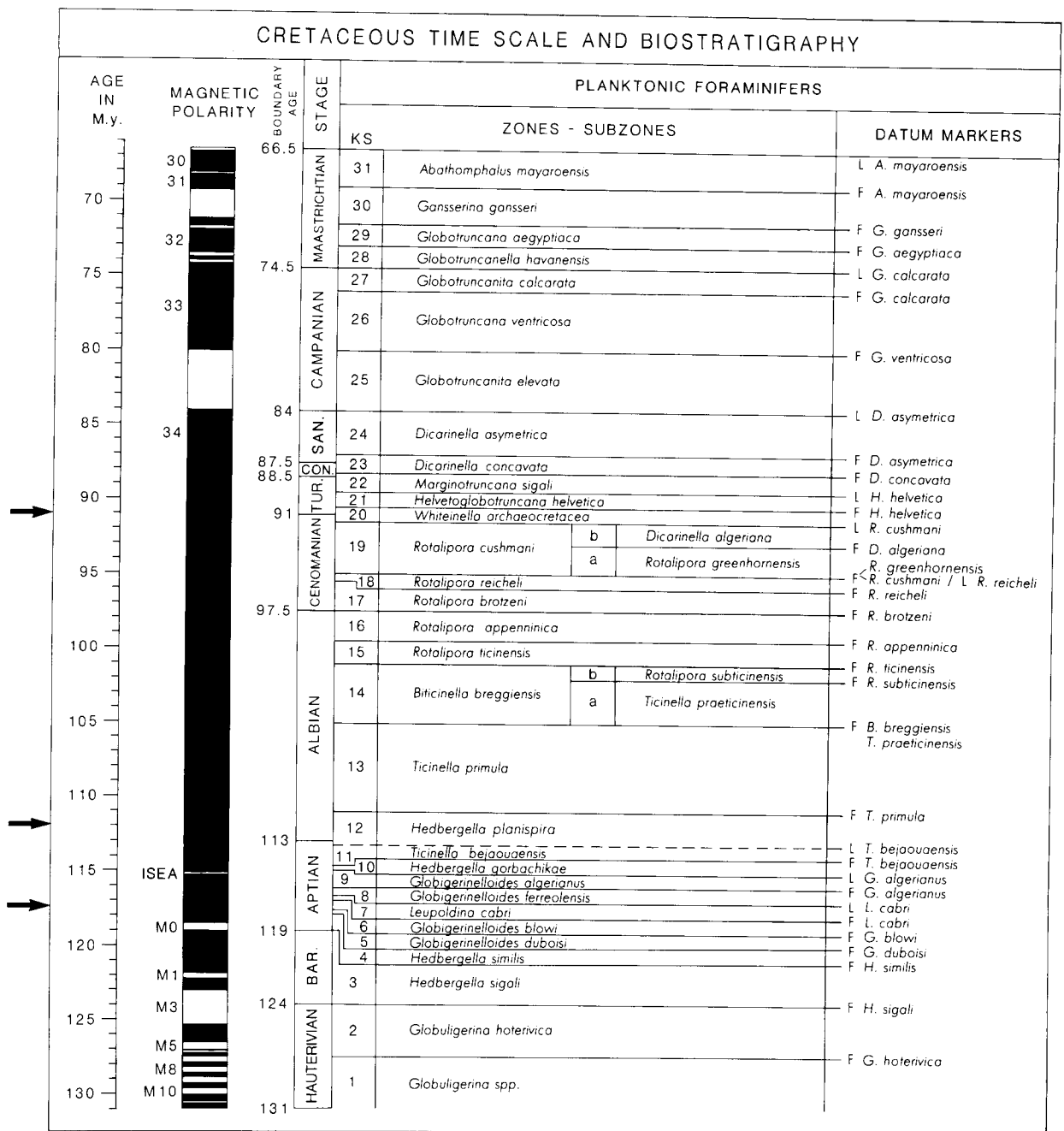


Figure 26. Intervals of intense carbon burial at 91, 112 and 117.5 Ma (arrows) plotted against biochronology based on planktonic foraminifers from Sliter (in press).

Basin in the South Atlantic, may extend to the seafloor; anoxia in the Cretaceous Pacific Ocean is restricted mostly to topographic highs (Schlanger et al., 1987). Pacific sediment records at least several anoxic episodes during a 35 m.y. period from the Aptian to the Santonian (Fig. 26). Two of these episodes, in the early Aptian and at the Cenomanian-Turonian boundary, were of short duration, less than 1 m.y., and have been correlated over a wide geographic extent (Sliter, 1989). A third, at the Aptian-Albian boundary, although

also widespread in extent, was of longer duration, more complex, and less well defined (Sliter, in press).

Lending support to the OAE hypothesis is the occasional occurrence of characteristic planktonic foraminiferal assemblages in contemporaneous intervals devoid of black shales. In other words, although the precise interval is dated and characterized by microfaunal assemblages, the sediment does not show visual evidence of C_{org} deposition. Although the record is incomplete, these occur-

rences, primarily from the Pacific basin (Sliter and Premoli-Silva, 1990; Sliter, in press), suggest that the depositional site could have been located below the depth of black shale deposition. This hypothesis, however, requires much further testing.

Patterns of Cretaceous Evolution

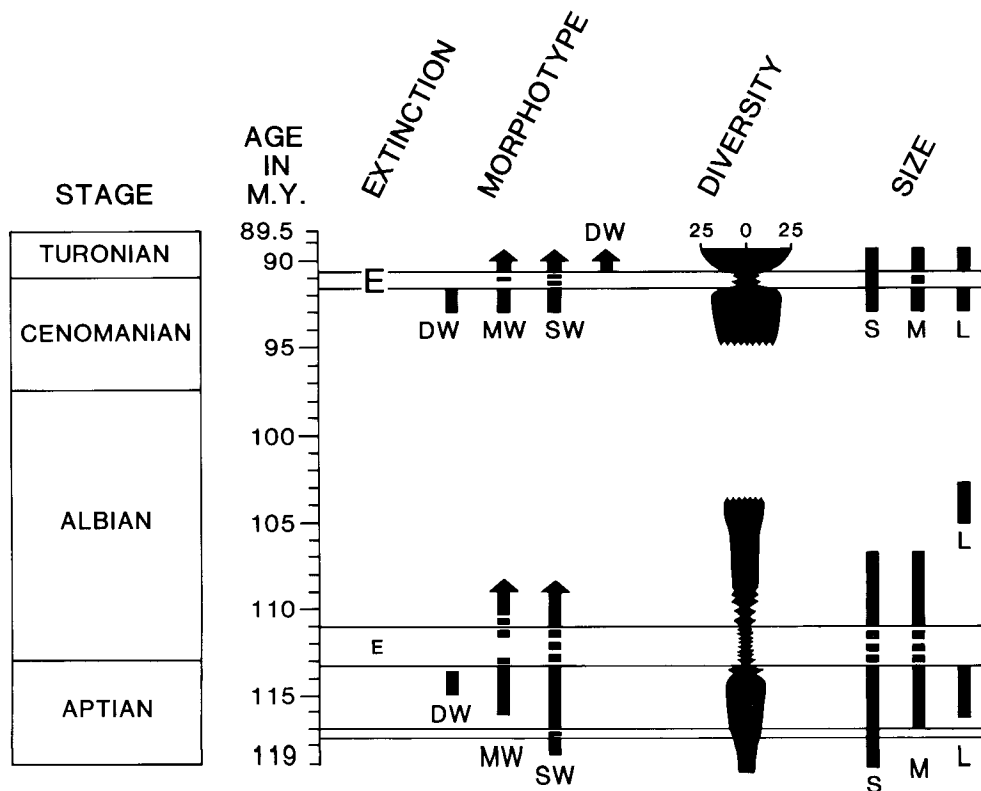
Biotic evolution during the mid- to Late Cretaceous shows several periods of extinction and adaptive radiation. These include the dramatic appearance of several genera of benthic foraminifera characteristic of intermediate water depths in the Barremian (~122 Ma), and the extinction and radiation of planktonic foraminifera at the Aptian-Albian boundary (~113 Ma), the Cenomanian-Turonian boundary (91 Ma), and during the late Santonian to early Campanian (~84 Ma). Each of these biotic events is associated either with intervals characterized by intense organic carbon burial, i.e. OAEs or, in the Barremian, with the onset of increased organic-rich deposition (Fig. 27).

Extinction patterns associated with OAEs are similar in some respects, but each has its own character. Each event, and the K-T boundary as well, is characterized by a reduction of planktonic faunas to a low-diversity assemblage of small globular forms devoid of larger, more ornamented species. In fact, the lack of a noticeable extinction event during the early Aptian OAE could be attributed to the sole faunas of the time, small globular species. Foraminiferal morphology reflects the environmental response of the various "types" of foraminifers. The small globular forms resemble modern species which live above the thermocline in the warmer mixed surface layer, whereas the more morphologically complex forms resemble modern species which live in deeper waters within and below the thermocline. Changes in the Cretaceous assemblages across the OAEs thus strongly suggest changes in the chemical or physical stratification of the world ocean.

Improved analysis of the biotic and geochemical signals associated with each extinction pre-

Figure 27. Patterns of extinction and adaptive radiation for various morphotypes of planktonic foraminifera at intervals of intense carbon burial shown by arrows in Fig. 26. Distributions and patterns are not continuously shown from Albian to Cenomanian.

Chronostratigraphy from Sliter (1990). Presence and relative impact of extinction shown by letter E. Morphotype distribution: DW = deep water, MW = mid-water, SW = shallow water. Diversity shows number of species and pattern of reduction and recovery across the organic-rich intervals. Distribution by specimen size: S = small, M = medium, L = large. Pre-early Aptian forms consist only of small, shallow-water types.



sents the opportunity to better interpret Cretaceous paleoceanography and the possible contribution of volcanism to chemical changes in the world ocean. Documenting population changes offers a means of assessing the rate and continuity of paleoceanographic change.

K-T Boundary Stratigraphy

A principal aim is to document patterns of extinctions and replacements across the boundary, especially as a function of the life habitats of the biota, e.g., their position in the water column, latitude, and relation to fertility patterns.

The K-T extinctions debate results from differing interpretations of a common data base and involves: 1) asteroid/comet impact vs. terrestrial volcanism as causative factors, 2) sudden impact-induced catastrophe spanning a few months to a few years vs. gradual volcanism-induced bio-evolutionary turnover spanning several hundreds of thousands of years, and 3) "impact winter" blackout and cooling via impact dust vs. possible "greenhouse" warming/pH changes via release of mantle CO₂ onto the Earth's surface.

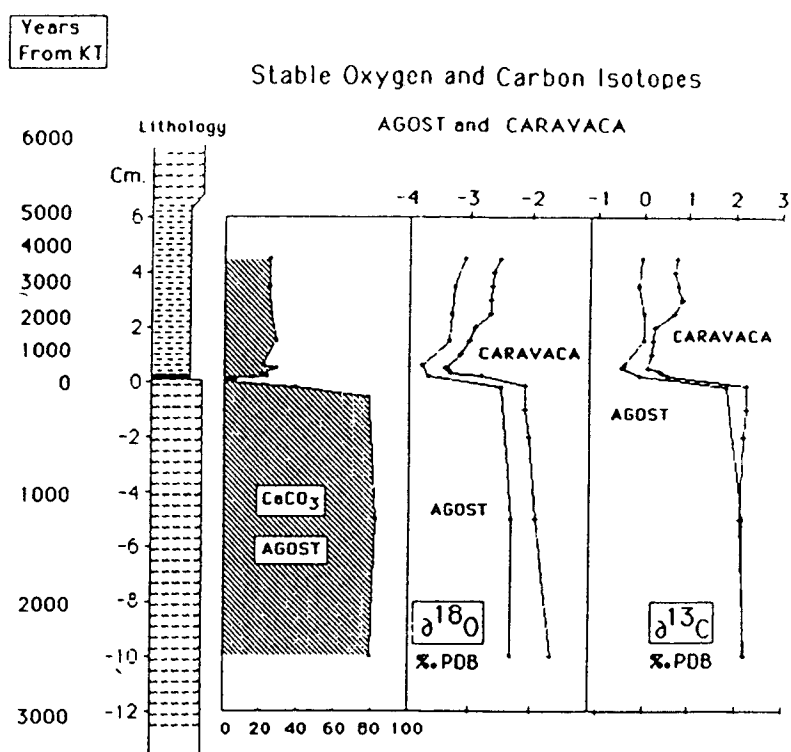
Resolution of the debate requires complete K-T transition sections. At some of the best sections such as Caravaca (Fig. 28), where the K-T boundary is a sudden short-lived event (Smit, 1990), the extinctions appear to be catastrophic.

At other locations, hiatuses may obscure the critical record. Some localities, such as Seymour Island, Antarctica, show an apparently gradual faunal transition, and little evidence of a marked extinction horizon at the K-T boundary. For example, disappearance of Cretaceous dino flagellates and foraminifera occur at different stratigraphic levels, neither of which coincides with an iridium layer at the K-T boundary. Biotic changes from latest Cretaceous into earliest Tertiary seem to occur over an extended interval with no single extinction horizon and may relate to global climate change and/or changes in marine chemistry. The K-T biotic turnover, and other changes (see subsequent

"Ocean/atmosphere geochemical effects" and "Biotic extinction/evolution" sections), may have been coeval with long duration (several hundreds of thousands of years) mantle CO₂ degassing associated with Deccan Traps volcanism. Complete sections across the K-T boundary, preferably in regions of high sedimentation rates, would help to resolve ambiguities related to events at this critical time.

Keys to understanding the nature of the K-T chemical/climate changes exist in calcareous microplankton. Extinction of coccolithophorids would have exacerbated the climatic consequences of an impact- or volcanically-induced carbon cycle perturbation (Caldeira and Rampino, 1990a, 1991). Their organic and CaCO₃ particulates remove much CO₂ from the atmosphere and mixed layer, storing it in marine sediment. Lowering the pH of the top 10 m of the mixed layer to about 7.3 to 7.0 via injection of volcanic CO₂ into the mixed layer might reduce productivity of the coccolithophorids, contributing to chemical/climate

Figure 28. Comparison of stable isotope values from bulk carbonate of the Agost and Caravaca sections in Spain. The vertical axis is linear with time. The consistent 0.5 per mil shift in δ¹⁸O between Caravaca and Agost may reflect the different paleoceanographic positions of the two sections (after Smit, 1990).



changes. Plateaus with high productivity and depths conducive to preservation of calcareous microplankton are therefore critical to understanding the K-T "event".

Iridium enrichment in K-T boundary clays is also important in understanding the global extinctions, and both extra-terrestrial (Alvarez *et al.*, 1990) and earthly (Officer *et al.*, 1987; Courtillot *et al.*, 1988) causes have been proposed. The proposed endogenous origin is related to the emplacement of the Deccan Traps during the initiation of the Réunion hotspot, and the fact that the Piton de la Fournaise volcano on Réunion is still producing iridium gases which may have been related to the K-T iridium anomaly (Touain and Meyer, 1989). However, resolution of this question is dependent on complete K-T sections to evaluate the magnitude, episodicity, and duration of the iridium enrichment.

Mesozoic and Cenozoic Sea Level

Records of sea level change are preserved on volcanic margins and on shallow or once-shallow portions of oceanic plateaus, submarine ridges, and their surmounting guyots. Although the topic of eustatic sea level change has been addressed in a previous JOI/USSAC-sponsored workshop (Watkins and Mountain, 1988), a special focus at this workshop was the potential role of plateau-surmounting guyots in sea level studies. Their effective use will depend critically on the ability to distinguish the thermal/dynamic signal from truly global, eustatic changes in sea level. Therefore, the sea level record from reefs on LIPs will have to be carefully cross-referenced to those on isolated reefs elsewhere far removed from mantle thermal effects in order to remove the eustatic component. Table 1, which compares the sign, magnitude, duration, rate, and pattern of sea level changes resulting from various eustatic and tectonic effects, shows that spatial patterns of the signal are clearly the most distinguishing features, thus underlining the conclusion of the previous workshop that global sampling of sediment in many tectonic regimes is necessary to resolve important sea level questions.

Table 1.
Causes of Sea Level Changes (M. McNutt, pers. comm.)

	Eustatic	Conductive Cooling	Dynamic Uplift	Geoid Warping
Sign	+ or -	+	-	-
Time Scale (yr)	10 ⁵ -10 ⁷	10 ⁸	10 ⁴ -10 ⁸	10 ⁴ -10 ⁸
Magnitude (m)	50-100	4000	200	30
Rate (m/m.y.)	10-500	≤170/(t) ^{1/2}	?	?
Pattern	Global	(f) of Plate Age	Radial	Radial

Paleocene Shift from "Modern" to "Mesozoic" Deep Circulation

Isotopic evidence from Maud Rise at ~65°S documents a change from warm, saline, "Mesozoic" bottom water which extended as shallow as 2000 m, to cool, "modern" bottom water. This transition requires global substantiation. The ODP sites 689-690 depth transect on Maud Rise yielded excellent Cenozoic stable isotope records which show an unexpected inversion of δ¹⁸O values for certain intervals during the Eocene and Oligocene (Kennett and Stott, 1990). The proposed circulation model (Fig. 29) envisions a low-latitude source of warm, saline deep water, overlain by less dense, less saline (and cooler?) upper water (Kennett and Stott, 1990).

Understanding global circulation systems is a key goal for paleoceanographic and paleoclimatic reconstructions, and additional sites on plateaus are needed to test the new model. Eocene-Oligocene oceans need to be examined globally in order to establish the geographic extent and duration of the episode, which part of the water column was affected, the sources of isotopically anomalous waters, and the variations in intensity.

Inception of Antarctic Glaciation

Oceanic plateaus off Antarctica are ideal recorders of ice-rafted debris (IRD), an important monitor of Antarctic glacial history. Because the plateaus are elevated well above the adjacent abyssal plains, the IRD record is not complicated by clastics introduced by turbidites, nepheloid layers, and/or wind. In addition, at paleodepths above 3500 m, any pre-Pliocene IRD is likely to be deposited along with pelagic carbonate. Thus,

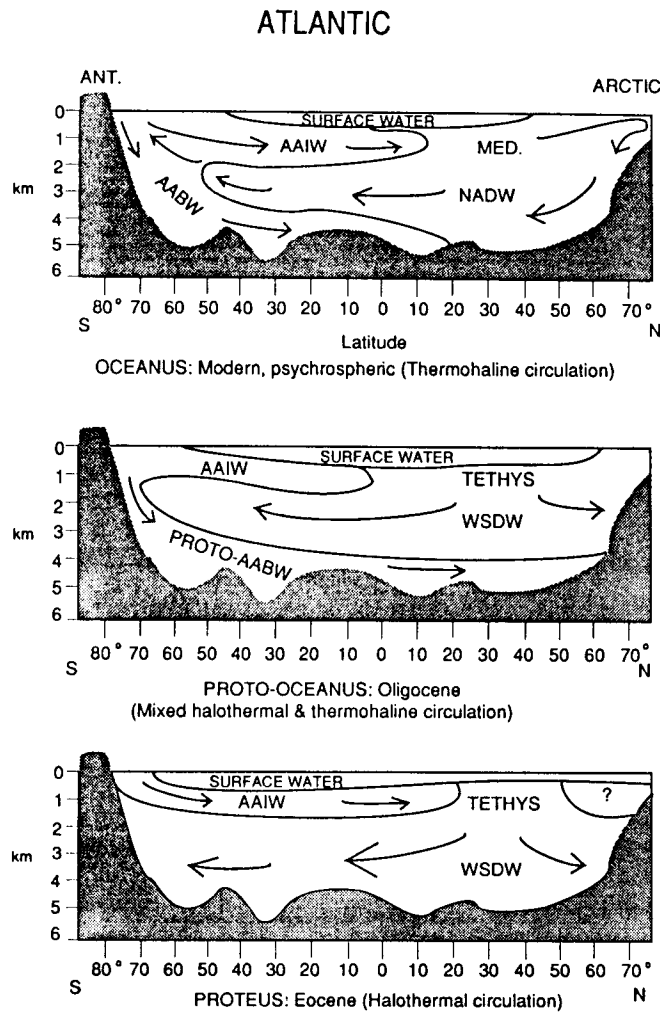


Figure 29. Evolution of deep and intermediate water circulation during the Cenozoic as inferred from isotopic results. Proteus, the Eocene ocean, was dominated by halothermal circulation; Proto-Oceanus, the Oligocene ocean, exhibited mixed halothermal and thermohaline circulation; while the modern ocean, Oceanus, is a psychrospheric ocean dominated by thermohaline circulation. AABW = Antarctic Bottom Water; AAIW = Antarctic Intermediate Water; NADW = North Atlantic Deep Water; WSDW = Warm Saline Deep Water; Med = Mediterranean. After Kennett and Stott (1990).

complementary stable isotope and CaCO_3 records can be obtained on a sample-by-sample basis.

Recent recovery of lower Oligocene IRD at ODP sites 738, 744, and 748 on the Kerguelen Plateau, as much as 1000 km north of the Antarctic continent, have provided unambiguous evidence of extensive glacial activity at 35–36 Ma, suggesting the presence of a major continental ice sheet on Antarctica at that time (Barron, Larsen, et al., 1989; Schlich, Wise, et al., 1989). Other occurrences of middle to late Eocene clastics at sites 738 and 744

are less well established or accepted, but serve to highlight the lack of knowledge about the timing of the earliest Cenozoic glaciation in Antarctica, and the extent and character (e.g., mountain/valley vs. continental) of glacial activity in Antarctica.

Oceanic LIPS as Active Instruments in Global Change

Sea-level Effects

Emplacement of oceanic plateaus, submarine ridges, and marginal volcanic plateaus displaces water, owing both to build-up of volcanic rock above normal oceanic depths and to transient thermal and dynamic uplift. The result is a eustatic rise of sea level, recorded primarily on continental margins, which may be further enhanced by isostatic loading of the margin by additional water. The rise is modulated by local tectonics. The rate and magnitude of the eustatic rise are functions of the volume, rate and duration of emplacement of igneous rock, and to the isostatic and flexural response of the lithosphere.

The volumes of water-displacing igneous rock in the largest plateaus are about $4 \times 10^6 \text{ km}^3$ (Schubert and Sandwell, 1989). This rock would yield a eustatic rise of about 10 m, far less than the amounts modeled by the EXXON group (Haq et al., 1987), but comparable to those of Pitman and Golovchenko (1991). The rate of lava production determines whether the sea level rise will be seen as an “event”, or smeared out over a long time period, as is the case for fluctuations caused by changes in global seafloor spreading rates. Following emplacement of new igneous mass, thermal and dynamic uplift ceases and the mass subsides, inducing a global eustatic fall, probably at a slow, exponentially-decreasing rate. The net effect of a rapid plateau build-up and slow subsidence would be a rapid flooding event followed by a slower fall.

To test possible connections between oceanic LIPs construction and changes in global sea level, the timing of initiation and duration of emplacement episodes must be constrained in order to determine the volumes of water-displacing rock being added through time. Also, maximum-flooding surfaces on a number of continental

margins must be dated. In addition to the radiometric chronology of igneous emplacement, the inception of plateau lava production may also be dated at adjacent sites by studying increased dissolution of sediment from new CO₂ injected into the ocean; the presence of ash layers; or moat/arch effects, as seen in seismic records and in the vertical trajectories of suitable reef-capped seamounts.

If rates of plateau emplacement and excess (over normal oceanic crust) volumes of oceanic LIPs crust can be determined, the effect of emplacement on eustatic sea level may be calculated. Similarly, if rates and environments of emplacement, and magma types are known, fluxes of gases such as CO₂ and SO₂ into the ocean and atmosphere may be calculated.

Ocean/atmosphere Geochemical Effects

The timing of outpourings of submarine basalts may be detectable through geochemical anomalies recorded in the sedimentary record in older basins, oceanic plateaus, and on continental margins. Submarine eruptions would release volatiles such as CO₂ which might lead to changes in the alkalinity of the ocean and to dissolution anomalies in calcareous sedimentary sequences deposited above the CCD on pre-existing features. Moreover, trace metal-rich plumes originating at undersea vents might leave a record of metal-rich sediment on nearby oceanic LIPs. It is also possible that submarine volcanism could produce spikes in the Sr-isotope ratio in deep-sea sediment through the addition of radiogenic Sr to the oceans. These kinds of anomalies, which could act as signatures for oceanic LIPs volcanism, might be detectable by drilling and careful sampling of sediment on or off pre-existing oceanic LIPs.

When plateau or volcanic margin eruptions were subaerial, ash layers may be found in older basins and plateaus as well as on the adjacent continental margins. An example is tephra in the North Sea which is believed to originate from

the North Atlantic volcanic margins (*Eldholm, 1991*). Plateau sections downwind of major flood basalt provinces, e.g., Broken Ridge relative to the southern end of the Ninetyeast Ridge (*Peirce, Weissel, et al., 1989*), may also provide good places to drill for better age constraints on volcanism.

Biotic Extinction/evolution

Could there be a connection between volcanism that produces oceanic LIPs and biotic extinctions? *Rampino and Stothers (1988)*, for example, suggested a correlation between LIPs on land and the timing of mass extinction events (see Table 2). Large-scale submarine and subaerial volcanism might contribute to mass extinction events in several ways: 1) through addition of trace metals such as As, Sb, and Se, which are poisonous to marine life, to the marine environment; 2) through the release of heat by undersea volcanism which could destabilize the water column, leading to large-scale overturn with effects on surface-dwelling organisms; 3) through release of CO₂ into the ocean and the atmosphere which would redistribute itself through the ocean/atmosphere system, with possible effects on climate and life. The Deccan Traps, for example, could have released

Table 2.
Ages of flood basalt initiations and mass extinctions (after *Rampino and Stothers, 1988*).

Flood Basalts		Mass Extinctions	
Episode	Age	Stage	Age
	(10 ⁶ years)		(10 ⁶ years)
Columbia River	17 ± 1	Early to Middle Miocene	14 ± 3
Ethiopian	35 ± 2	Late Eocene	36 ± 2
Brito-Arctic	62 ± 3	Maastrichtian	65 ± 1
Deccan	66 ± 2	Cenomanian	91 ± 0
Rajmahal	110 ± 5	Aptian	110 ± 3
Serra Geral	130 ± 5	Tithonian	137 ± 7
South-West African	135 ± 5		
Antarctic	170 ± 5	Bajocian	173 ± 3
South African	190 ± 5	Pliensbachian	191 ± 3
Eastern North American	200 ± 5	Rhaetian/Norian	211 ± 8
Siberian	250 ± 10	Dzulfian/Guadalupian	249 ± 4

TOPOGRAPHIC EFFECT

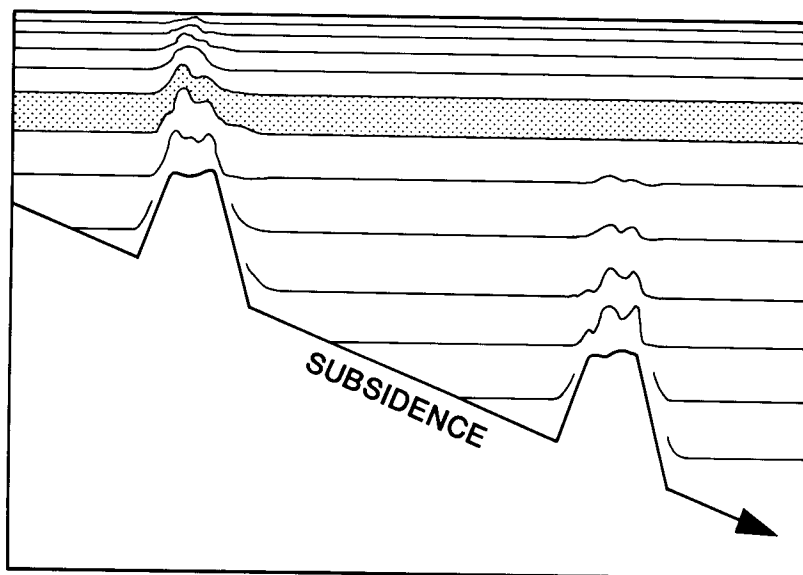


Figure 30. Model of topographic upwelling showing lessened effect in the upper-water column upon subsidence of topographic high (W. Sliter, pers. comm.).

up to 2×10^{17} moles of CO_2 over a period of several hundred thousand years. This is enough to cause a global greenhouse effect of about 2°C (Caldeira and Rampino, 1990b). As another example, the mid-Cretaceous superplume (Larson, 1991) may have produced atmospheric CO_2 levels from 3.7 to 14.7 times the modern pre-industrial value of 285 ppm. This may have resulted in global warming of from 2.8° to 14.7°C over today's global mean temperature (Caldeira and Rampino, 1991). Short-term injection of dust and aerosols into the atmosphere could cause brief but severe cooling spells. A larger release from a more massive oceanic plateau or volcanic margin eruption could have had a greater effect.

It is important to date major phases of volcanism at various oceanic plateaus and volcanic margins for comparison with times of mass extinction events, biotic turnovers, and major evolutionary events (see "Patterns of Cretaceous Evolution" section). Massive volcanic releases of mantle CO_2 that might elevate mantle CO_2 flux rates significantly above steady state rates would imprint a geochemical/biotic "signature" on the oceanic LIPs strata. Components of the "signature" are: 1) pH changes manifested in reduced calcareous microplankton sedimen-

tary CaCO_3 production and preservation rates; 2) shifts in ^{13}C isotopic values recorded in biogenic CaCO_3 via uptake of mantle CO_2 (mantle CO_2 is depleted in ^{13}C); 3) shifts in ^{18}O values in biogenic CaCO_3 reflective of CO_2 -induced climatic warming; 4) pH/warming-induced stresses reflected by reduction and collapse of calcareous microplankton for the duration of volcanic forcing, producing "Strangelove" oceans (Hsü and McKenzie, 1985); and 5) coeval chemical perturbations, perhaps in the form

of siderophile enrichment spikes associated with deep mantle plumes.

Detailed studies over the past 10 years of the K-T extinctions lead to the obvious question of what similarities and differences exist among the various events of the Phanerozoic. Some have tabulated occurrences of CFB emplacements coincident with other extinction events (Courtillot *et al.*, 1988). Others have tabulated occurrences of major sea level changes and anoxic conditions associated with other extinction events (Rampino and Stothers, 1988). Both correlations may be correct and all these effects—intense volcanism, major sea level changes, and anoxia—may be inter-related. The environmental impact of emplacement of oceanic plateaus and volcanic margins may be as important in explaining oceanic biotic crises as that attributed to CFBs. The temporal history of oceanic LIP basalts, however, is poorly known compared with those onshore.

Gate Keepers for Global Deep-water Circulation

Oceanic plateaus, submarine ridges, and outer highs at volcanic passive margins can constitute significant obstacles to oceanic circulation. Thus the history of these barriers, in terms of areal extent and depth profile, is required to understand the history of water interchange between ocean basins. Sediment on highs monitors this history, especially where benches or gentle flank slopes have permitted deposition over a range of

paleodepths. The history of the barrier/gateway is partly encoded as changes in paleodepths recorded by benthic fossils, by changing dissolution levels, and by the record of current activity (e.g., sedimentary structures, transported minerals or fossils, hiatuses, and erosional effects).

Shallow-water Effects, e.g., Taylor Columns

Oceanic plateaus, submarine ridges, volcanic margin outer highs, and surmounting seamounts on all of these features produce instability in the water column and disruption due to upwelling of ocean currents along the features' flanks and disruption of horizontal flow. Where the depth of the feature is such that perturbations reach the upper water column, associated changes are seen in the thermocline, density gradients, and productivity (Fig. 30). In modern cases, enhanced productivity due to upwelling is most apparent above features shallower than 1000 m and in oligotrophic oceans above 500 m (Boehlert and Genin, 1987). Enhanced productivity effects maintain themselves above the feature despite prevailing currents due to small and mesoscale eddies and internal waves. The importance of identifying topographic upwelling is in distinguishing these effects from those produced by other forms of upwelling such as upwelling at the equatorial divergence. This differentiation becomes important when considering the passage of topographic highs beneath the equatorial divergence due to plate motion. Conversely, changes in the flux of pelagic organisms above submerged Cretaceous highs should provide information of the character and intensity of stratification and oceanic productivity.

Rationale and Strategy for Drilling LIPs

Oceanic plateaus and volcanic margins are excellent laboratories for the study of both internal processes and external consequences of large scale igneous events. Igneous rock as well as relatively undisturbed sediment on top and on the flanks of volcanic edifices record the features' genesis and evolution. In addition, many plateaus and volcanic margins are uniquely situated to have passively accumulated sediment which has monitored changes in global and regional paleoenvironment. An improved understanding of the extent, significance and formation of LIPs requires carefully designed geological/geophysical experiments of which drilling is an integrated and essential part. Successful drilling, however, critically depends on high-quality preparatory work. In the following, we first comment on the need for site surveys to provide a framework for drilling, and then outline strategies for volcanic margin and oceanic plateau drilling. The general lack of key geological information about these features necessitates an approach which reconciles the need for both exploratory drill holes and focused, problem-oriented drilling projects.

Recognizing that ODP is a proposal-driven, community-wide research program, we principally make general recommendations relating to regions and oceans with a focus on strategy rather than on local areas, specific transects, and sites. Specific site selections and drilling plans should be based on consideration of the merits of individual drilling proposals.

Site surveys

Understanding velocity structure, lateral heterogeneity, and crustal thickness is necessary to

characterize overall conjugate volcanic margin and oceanic plateau structure. Of particular importance are the structure and configuration of extrusive constructions and deep crustal bodies. In the case of volcanic margins, the pre-rift crustal configuration and rift-related extensional features require description, and for oceanic plateaus, the pre-emplacment crustal structure and emplacement-related deformation. Detailed MCS data providing both shallow and deep resolution, supplemented by wide-angle reflection and refraction experiments, are in fact prerequisites for drilling LIPs. In areas of special interest such as dipping reflection wedges and other intra-basement reflection patterns, local three-dimensional seismic data may be required to gain maximum benefit from drilling. Deep MCS data have yet to be collected over oceanic plateaus, and are needed to constrain crustal and upper mantle structure, and deformational history.

All of the above information can only be obtained by seismic surveying augmented by gravity, magnetic, and heat flow data. Gravity data help to constrain the strength, and hence the thermal state of the lithosphere at the time of LIP emplacement (e.g., *Watts, 1978*). Magnetic data can constrain age of the seafloor and properties of the Earth's magnetic field at the time of volcanism (e.g., field polarity, paleolatitude, temporal uniformity of the field). Dredging, where possible, can also supply useful igneous basement samples for geochronology, petrology, and geochemistry. Table 3 summarizes site survey data standards as devised by the JOIDES Site Survey Panel (SSP, 1986).

Table 3.
Site Survey Data Standards for Passive Margins and Plateaus.

Techniques	Passive Margins	Plateaus
Deep penetration SCS	(X)	(X)*
High resolution SCS	(X)	(X)
MCS & velocity determinations	X	(X)*
Seismic data on cross lines	X	(X)*
Seismic refraction	(X)	(X)*
3.5 kHz (X)*	(X)	
Multi-beam bathymetry	(X)*	(X)* or
Sidescan sonar (shallow)	(X)*	(X)*
Heat flow (X)*	(X)	
Magnetics & gravity	(X)	(X)
Paleoenvironmental cores	(X)	
Geotechnical cores	R	R
Dredges	(X)*	
Photography	(X)	
Current meter - bottom shear	(X)*	

Key: X = Vital; (X) = Desirable; (X)* = Desirable but may be required in some cases; R = Vital for re-entry sites

Site surveys are needed both to locate drill sites and to guarantee that drilling results can be calibrated with seismic data in order to achieve regionally significant interpretations. For example, the deformational, including vertical motion, histories recovered from drilling only two sites into a LIP can be used to interpolate the results across the entire LIP using seismic stratigraphy if reflections in the two drill cores can be correlated. Therefore, seismic surveying should not be solely limited to drill targets. Similar considerations apply to reference holes on normal oceanic crust or the continental margin.

Ocean Drilling

In practical terms drilling of oceanic plateaus and volcanic margins can only sample a limited part of the igneous material emplaced during their formation. The goal of drilling is therefore to determine composition, age and genesis of various rock units (sediment, igneous and metamorphic rock) comprising the upper crust of oceanic LIPs. The results of drilling can constrain and motivate further development of models linking mag-

matism, tectonics, and global change. More specifically, drill samples of volcanic margins and oceanic plateaus can contribute to resolving mechanisms of magma production, differentiation, and eruption during the initial stages of emplacement, and how igneous processes evolve. As another example, if emplacement ages are well-established from dating drill samples, and if crustal volumes are determined from seismic data, the effect of oceanic LIPs emplacement on eustatic sea level can be calculated.

In the following we develop overall drilling strategies for conjugate volcanic margins and oceanic plateaus which address their three major scientific themes—internal mantle and crust processes, external effects of LIPs emplacement, and passive sediment repositories recording global change. We preface

these strategies with the acknowledgment that some of the most fundamental unanswered questions regarding oceanic LIPs involve their age and composition. This information is required before we can attempt to accurately characterize their origin and emplacement, and their involvement in global change. It is therefore essential that all drill holes on untested oceanic LIPs be continued into basement so as to constrain the age and petrology/geochemistry of the rocks. These holes should extend at least ~150 m into volcanic basement (or to bit destruction) in order to obtain relatively fresh samples for dating, magnetostratigraphy, and petrologic/geochemical analyses, as well as to minimize the possibility of sampling an unrepresentative, post-emplacement sill or flow. Given large variations in lava composition and age over kilometers of stratigraphy in land exposures of all types of igneous rock, some oceanic LIP holes must be drilled much deeper than 150 m into basement for geochemistry, petrology, geochronology, and magnetostratigraphy.

Conjugate Volcanic Passive Margin Strategy

The strategy is to drill a transect of relatively closely spaced holes across the volcanic margin

which are tied to reference holes not influenced by transient extrusive activity. Ideally, drill sites should be located on either side of the ocean to form a conjugate transect (COSOD II, 1987). However, if seismic coverage and quality are excellent on both margins it may not be necessary to drill a complete transect across both conjugates, or to drill at all on one side. The transect should be augmented by specific holes to evaluate along-strike margin variability, in particular the potential influence of hotspots. However, design of the transect would be different depending on the focus of study, e.g., transient igneous activity during breakup or persistent activity along the plume trail.

Drilling should address the three-dimensional configuration of the present-day conjugate margins; the lateral and vertical movements of the lithosphere during and after rifting; and the composition and mode of emplacement of igneous rock. Drilling a transect would constrain parameters for modeling of basin subsidence, and together with plate tectonic reconstructions, would also constrain structural development of the margin. This would allow a better understanding of rift processes, in particular the history of vertical and horizontal motion. Furthermore, the transect would address questions concerning rates of magma production, differentiation, and eruption during the initial stage of rifting and the evolution of igneous processes during the transition from rifting to seafloor spreading. Thus, drilling experiments must be designed to allow recovery of as stratigraphically complete extrusive sequences as possible.

The sample material, combined with downhole experiments, would also provide important constraints for quantitative models of the geometries and compositions of rocks beyond the reach of the drill. It is particularly important to combine drilling with VSP experiments, and "walk-away" VSPs should be carried out at strategic sites. This approach, combined with petrological/geochemical analytical techniques and modeling (see Chapters 4, 5, and 6) as well as geophysical modeling, would also indirectly provide improved understanding of the lower crust and mantle and the processes responsible for volcanic margin formation.

On a typical volcanic margin, the transect would sample various tectono-stratigraphic units across the margin. Specific aims would be to de-

termine the igneous stratigraphy of large extrusive edifices including the prominent seaward dipping reflection wedges, and to obtain estimates of compositional variability within these. Figure 31 shows schematically the transect drilling strategy to determine chemical and volumetric stratigraphy of the main phase(s) of igneous activity. It would include studies of lava composition, reworked continental material within pre-basaltic, intra-basement sequences, xenoliths within intra-basement flow sequences, and thermal metamorphism in the sediment below, between, and above the flows. The strategy would include a series of moderately deep holes (500 to 1000 m), achievable by present drilling technology, designed to provide a reasonable sampling of the extrusive stratigraphy. Moreover, a drilling transect would determine the magnitude and timing of uplift and subsidence, and the position of basalt flows in relation to the sedimentary stratigraphy sequence would date the timing and duration of the extrusive event.

The entire volcanic margin transect concept is demonstrated by the two examples in Figure 32. One transect, the "South Atlantic" case, exemplifies breakup within a craton or a region with little or moderate sediment cover; the other, the "Norwegian Sea" case, breakup within a major sedimentary basin. If the lithosphere broke in an existing sedimentary province, reference holes (industry and other) in the basin landward of extrusive edifices may provide valuable information, particularly about initial magmatism (dikes, sills), sedimentary stratigraphy, existence of tephra and ash related to breakup volcanism, and basin subsidence. Parts of the volcanic margins which experienced rift uplift and subaerial lava emplacement are prone to erosion. Consequently, part of the sedimentary record may be missing where extrusives are within easy reach of the drill. Reference holes on the flank or off the rift axis could establish the history of vertical movement.

On some volcanic margins the COT is strongly flexured with no clear evidence for crustal extension. Figure 33 shows an example of a short drilling transect to model flexure and mechanical strength of the crust. Seismic data constrain margin geometry, and drilling data would provide information on timing and thermal evolution by

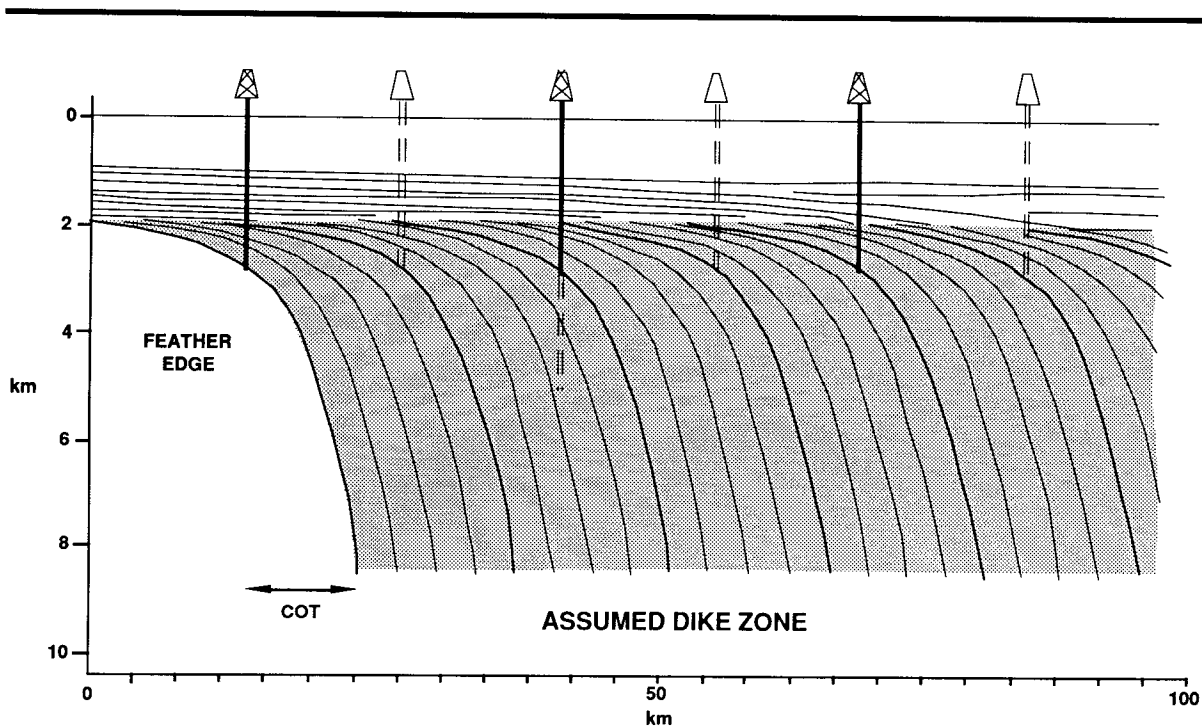


Figure 31. Schematic cross-section of a seaward dipping reflection wedge showing generalized lava stratigraphy and potential stratigraphic coverage achieved by transect drilling (Larsen et al., 1990).

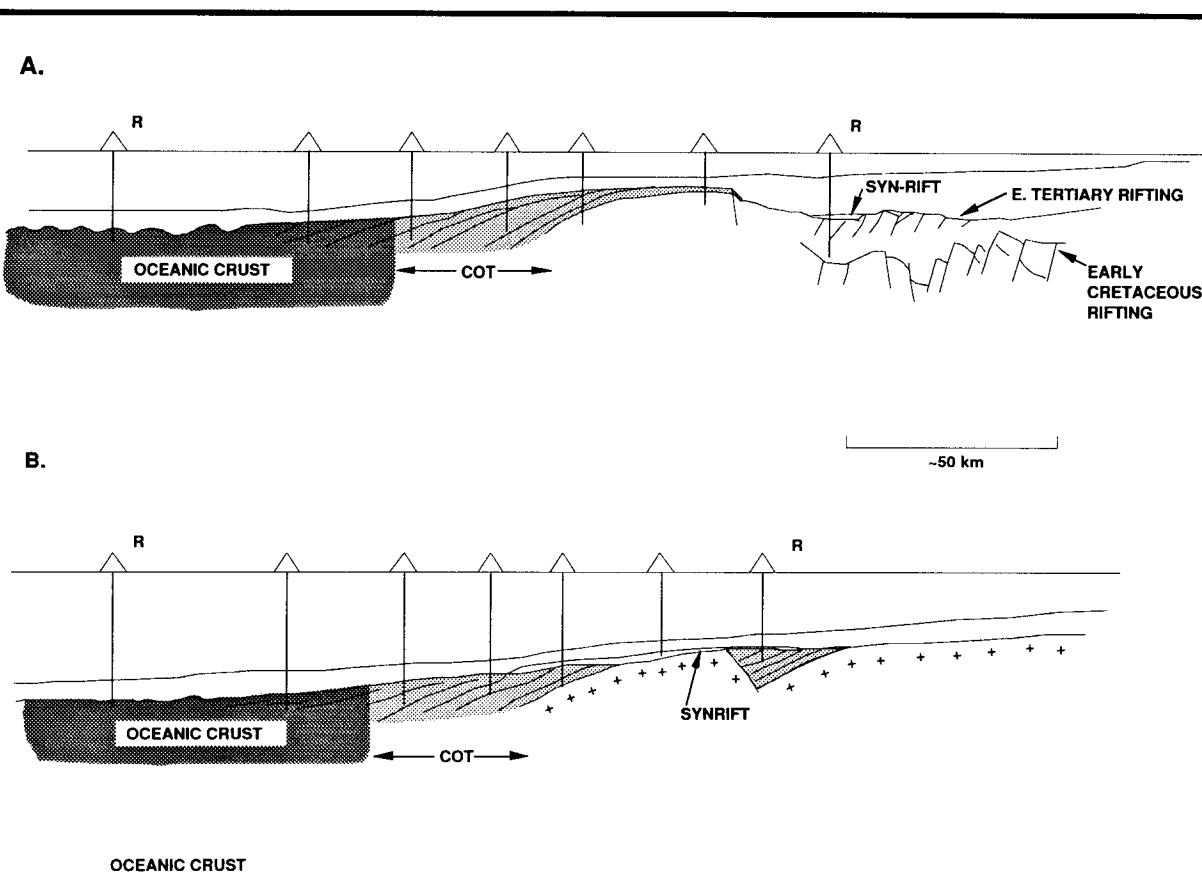


Figure 32. Examples of transect drilling in the vicinity of the COT at volcanic margins developed within a sedimentary basin region (top) and in a cratonic region (bottom). Sites annotated R are reference sites on either side of the transient extrusive complex.

sampling reworked basement (Site A) and the seaward dipping basalt and sediment (Site B).

In view of the present state of knowledge of transient volcanic margins and the availability of existing data, the rifted volcanic margins in the North Atlantic Ocean, north of the Charlie Gibbs Fracture Zone at $\sim 52^\circ\text{N}$, appear to be strong candidates for transect drilling. Realizing limitations of present drilling technology, initial transects should be in areas of minimal sediment cover to ensure considerable penetration into the extrusives.

LIPs across the Continent-Ocean Transition

Where CFB provinces continue into an ocean basin as an oceanic plateau, submarine ridge, or seamount chain, the basalt should contain information on the hotspot and on plume source evolution from a CFB across a rifted volcanic margin to an oceanic plume. In many ways this might be considered as the "Atlantic" or "Indian Ocean" hotspot option (e.g., NAVP/Iceland hotspot; Deccan Traps/Réunion hotspot; Paraná-Etendeka/Tristan hotspot), as opposed to the "Pacific" one. To study this evolution, a strategy of drilling along the strike of the hotspot trail across the COT is proposed. This would maximize the contribution of detailed CFB studies to oceanic LIPs research.

In general, where CFBs are associated with oceanic LIPs, lava sequences on the margins are thick and onshore exposures may provide the only opportunity to reach the earliest lavas which may have recorded processes occurring during

the initial phase of emplacement. Examination of this lava would help to establish a baseline of magma sources, differentiation processes, and possible eruptive styles whose evolving importance could be traced across the margin and into the ocean basin through the geochemistry and petrology of the drilled samples. The transition from continental to oceanic volcanism via conjugate volcanic margins is poorly understood and has not yet been studied by drilling.

The transect would consist of some closely spaced sites near the COT, and extend with more widely spaced sites towards the mid-ocean ridge. These sites would be complemented by reference holes on oceanic crust away from the plume trail. The transect would drill basement concentrating on geochronology and geochemistry, with a view to tracing continental compositional components into the oceanic environment, determining rates of magma production, and identifying plume components. In addition, comparison of ages between ridge and reference holes may help determine whether the ridge was built on existing oceanic crust or was formed at the mid-ocean ridge. Because it is anticipated that greater geochemical variability may be evident than in the oceanic plateaus option, sampling would be augmented if possible by dredging (e.g., *Leclaire et al., 1987*).

The Greenland-Scotland Ridge, Walvis Ridge-Rio Grande Rise, and Chagos-Laccadive Ridge-Mascarene Plateau are obvious candidates for studying plume evolution across the COT and a transect could, in part, be integrated with existing holes. Before committing the drillship, however,

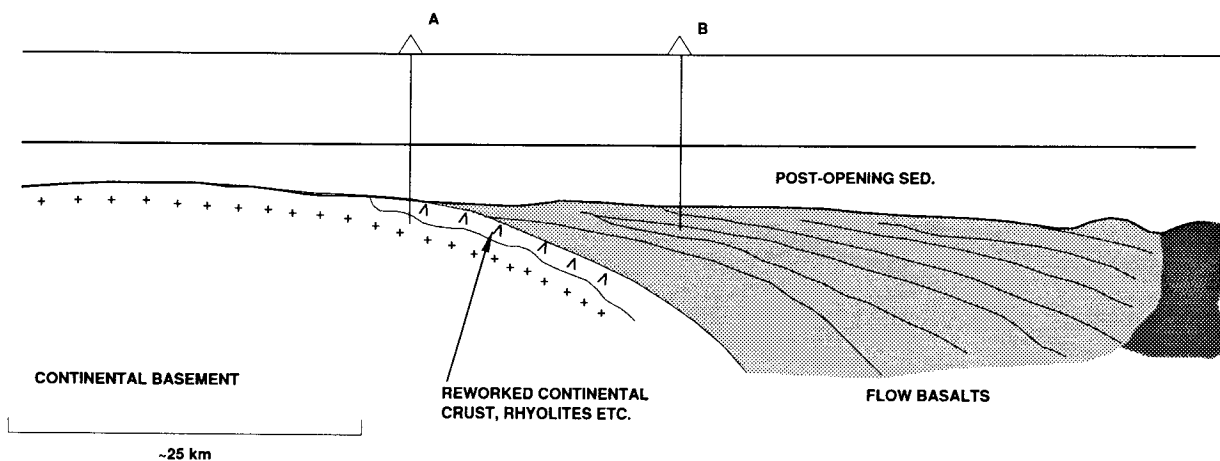


Figure 33. Transect drilling to model flexure and mechanical strength of the lithosphere in the vicinity of the COT on volcanic margins without major faulting during and after the main volcanic phase.

dredging and coring should be evaluated as to how they could complement drilling.

Ocean Plateau Drilling Strategy

Two strategies are recommended, and each would address the initiation, emplacement, and post-emplacement phases of oceanic plateau evolution, as well as their involvement in global change. One strategy would be to drill longitudinal and latitudinal transects of one of the two giant (area $\geq 10^6$ km²) oceanic plateaus, Kerguelen or Ontong Java. Another strategy would drill longitudinal and latitudinal transects on a plateau of purely oceanic origin (e.g., Manihiki, Shatsky, Hess) which represents one end-member in crustal composition (with well-studied CFB provinces as the other end-member).

The objectives of drilling, not already discussed with regard to volcanic margins and LIPs across the COT, would include: characterization of the eruptive styles (especially whether subaerial flows are present) and comparison with CFB provinces; determination of scales of heterogeneity through detailed geochemical work, and, in ideal circumstances, of continuity of flows (e.g. if two holes are close together), possibly allowing speculation about magma chamber characteristics and processes; interpretation of subsidence histories from sedimentary sections, especially on submarine ridges or plateau tops; recognition of evidence for the initial stages of volcanism (Sr and Nd isotopic compositions of chemical sediments, and the duration and episodicity of volcanism) from reference holes on normal oceanic crust adjacent to the plateau; characterization of age and composition of the oceanic crust on which the plateau was built from reference holes; and evidence in the reference holes for environmental effects, especially increased fluxes of CO₂ and SO₂.

The two giant oceanic plateaus, Kerguelen and Ontong Java, dwarf all other known LIPs. Each has been the subject of reconnaissance drilling campaigns which have provided the first prime samples for dating, petrology, and geochemical analyses. Initial drilling results have set the stage for more problem-oriented research. Foremost among these are the duration of the emplacement phase and petrological/geochemical heterogeneities. Kerguelen, with four basement holes, and Ontong Java, with three, are not adequately sampled to assess their ages or compo-

sitions. A strategy would be to properly sample one of the plateaus areally with longitudinal and latitudinal transects. At a minimum this would involve 1 site per 10⁵ km² (the size of Iceland, which has an age range of 0 to ~16 m.y.; *Moorbath et al.*, 1968), or ~10 sites for Kerguelen and ~15 sites for Ontong Java, not including reference holes. At least one of these sites should have basement penetration on the order of 1000 m, in order to test for composition and age variations. It might be possible to obtain and date a partial vertical section by sampling distal portions of lava flows, possibly intercalated with sediment, on the flanks of the plateau. Such a section, however, might be biased towards the most voluminous flows.

The longitudinal transect would be drilled, if possible, normal to magnetic lineations on adjacent oceanic crust. Reference holes in adjacent oceanic crust would also be required. The geochemical signatures of the two giant plateaus are distinctive, especially with regard to Pb isotopes, so assessment of the relative roles of different components (depleted asthenosphere, continental lithosphere, and various plumes) is feasible (*Alibert*, in press; *Storey et al.*, in press). Both Kerguelen and Ontong Java are characterized by the distinctive DUPAL anomaly (e.g., *Davies et al.*, 1989; *Mahoney and Spencer*, 1991, respectively).

Some major differences between Ontong Java and Kerguelen are crustal thickness, emplacement environment, and source history. Poorly constrained crustal thickness estimates from refraction studies are 40 km for Ontong Java (*Furumoto et al.*, 1976) and 20 km for Kerguelen (*Recq and Charvis*, 1986; *Recq et al.*, 1990; *P. Charvis*, pers. comm.). Based on 3 drill sites, Ontong Java appears to have been emplaced in a submarine environment. In contrast, the four drill sites on Kerguelen document subaerial emplacement and erosion. Evolution of the magma source for Ontong Java is not understood; it has been suggested, however, that Kerguelen is one manifestation of a long-lived (>100 m.y.) mantle plume, ranging from Bunbury Volcanics (Australia) through Naturaliste Plateau and Rajmahal Traps (India) to Kerguelen and Ninetyeast Ridge to Tertiary and Quaternary Kerguelen and Heard Island volcanism (*Davies et al.*, 1989). These differences between the two giant oceanic LIPs do not make it easy to choose one or the other as the higher drilling priority, and in fact might argue

for drilling both as part of integrated geological/geophysical studies.

A strategy to drill longitudinal and latitudinal transects on an oceanic plateau of the central Pacific (e.g., Manihiki Plateau, Shatsky Rise, Hess Rise) or the southern Indian Ocean (e.g., Del Caño Rise, Conrad Rise) offers the clearest opportunity to study a pure oceanic end-member of LIPs, apparently free of any continental influences. Problems addressable by drilling such a plateau are related to petrology and geochemistry, including initial magma composition, plume components, and magma differentiation, as well as to lithospheric behavior, including vertical tectonism. Regarding subsidence studies, it should be noted that the oldest reef-capped volcanoes within a given LIP are likely to record the longest history of vertical motions. Furthermore, if an oceanic LIP selected for drilling is Cretaceous in age, in order to recover the best record of vertical motion it may be advantageous to drill a drowned guyot rather than an atoll so as to recover Cretaceous section without having to penetrate Tertiary sediment. For this "pure" oceanic plateau strategy, we again recommend that the minimum areal coverage should be 1 site per 10^5 km², or ~5 sites not including reference holes.

Global Paleoenvironments

The principal strategy is to sample the commonly expanded and more complete sedimentary sections on the tops of oceanic plateaus, and to also drill downslope transects at the flanks of plateaus and across volcanic margins to record conditions at increasing paleodepths. This approach would be complemented by selected reference holes in adjacent basins to monitor environmental conditions prior to, during, and after the eruptive event(s). These three objectives may be combined into integrated paleoenvironmental transects that are entirely compatible with the transect drilling for magmatic and tectonic objectives at oceanic plateaus and volcanic margins.

Oceanic LIPs as Passive Sediment Repositories

A horizontal and vertical grid of drill sites on specific topographic highs in the Pacific Ocean is required to study Mesozoic paleoceanography. A horizontal array of two to three drill sites would test latitudinal changes, whereas two to three sites

on the flanks would assess vertical changes. The needed biostratigraphic resolution would be obtained from calcareous nannofossil biostratigraphy combined with that of planktonic foraminifers for soft as well as indurated sediment. These high resolution (i.e., to 0.5 m.y.) intervals include both mid- and Late Cretaceous targets. For the mid-Cretaceous, low-latitude highs include Shatsky Rise during the Aptian and the Mid-Pacific Mountains during the Late Cretaceous. Intermediate latitude highs include the Manihiki and Ontong Java plateaus.

Oceanic plateaus and submarine ridges far removed from the influence of terrestrial sedimentation offer ideal sites to test the OAE hypothesis, although volcanic margins preserve sediment which can contribute to solving the problems as well. Drilling offers the opportunity to define the depositional paleodepth of these C_{org}-rich strata, to determine the degree of oxygen deficiency, and to investigate the importance of carbon preservation vs. surface water productivity, the effect of volcanism on the carbon budget and the role of climate in the development of upwelling conditions that could enhance production and deposition of marine C_{org}. A minimum of two depth transects are needed, one in a high productivity, low latitude setting; the other at higher latitudes outside of equatorial influence. At least three drill sites are needed above, within and below the OAE that presumably is located at intermediate-water depths, i.e., 500-1500 m. Target plateaus include the Shatsky Rise for the equatorial site and the Manihiki Plateau, and possibly the Mid-Pacific Mountains, for the higher latitude site (Fig. 1).

A geographic and latitudinal array of samples across specific OAEs is needed for paleontologic and geochemical studies of patterns of Cretaceous evolution. Of prime importance is determination of a volcanic correspondence, i.e., ash beds, Ti signal, associated barite, sulfides, etc. The sampling should focus both on OAEs such as the short duration Aptian or Cenomanian-Turonian and the long duration Aptian-Albian. The broad array would also provide a means of developing models of speciation in the Pacific superocean and the smaller ocean basins before and after the mid-Cretaceous opening of the North and South Atlantic. For example, it could be

determined if evolutionary effects were more pronounced in small oceans or if they were broadly synchronous.

Similarly, drilling may shed light on Cretaceous extinctions, specifically the provocative Cenomanian-Turonian and Aptian-Albian events. Candidate areas are: Kerguelen Plateau, Ontong Java Plateau, Caribbean Plateau and the Mid-Pacific Mountains. To evaluate extinction crises, sampling criteria similar to those for K-T studies should be employed (see next paragraph).

Resolution of K-T boundary controversies requires complete K-T transition stratigraphic sections from low through high latitudes to sort out variable latitudinal and biochemical effects of mantle CO₂-induced carbon cycle perturbation upon K-T biotas. Such sections are expected on oceanic plateaus, and detailed sampling of the transition could provide additional clues to the causes of mass extinctions. Searches should be made for micro-, nannofossil and paleomagnetic stratigraphy; O, C and Sr isotopes; mineralogy of non-carbonate constituents; Ir and other Pt group elements; other trace elements such as Re, Se, As, and Sb; and shocked quartz and stishovite which would provide a signature of impact vs. volcanism. It is especially important to sample on a cm-to-cm basis well below and above the K-T boundary to monitor the extinction event with time and the events leading to it. It would be useful to have sections from different areas to establish geographic patterns of mass extinctions, and traverses across slopes of plateaus should provide evidence for patterns of extinctions with depth and environmental changes in the different water masses.

The Paleocene shift to modern deep circulation would be addressed by extending the ODP depth transect on Maud Rise to deeper levels, and by depth transects on other circum-Antarctic plateaus and on plateaus in lower latitudes.

Additional records of ice-rafted debris from plateaus near Antarctica, shallow enough to yield stable isotopic records from carbonate sequences, would allow estimation of continental ice volumes. Moreover, additional sites along Maud Rise, the Kerguelen Plateau, and potentially the yet unexplored Gunnerus Ridge and Conrad Rise would extend the sampling of Paleogene glacial sediment to evaluate the inception of Antarctic glaciation.

Oceanic LIPS as Active Instruments in Global Change

With respect to sea level changes, dates of maximum flooding surfaces on continental margins are available, and we recommend concentrating on dating the emplacements of large plateaus and ridges in which the volume-rate production of water-displacing rock was likely to have been rapid enough to cause a detectable shift in global sea level. Temporal correlation with the sediment record away from large plateaus may provide evidence for the effects of emplacements on the ocean and atmosphere. In any attempt to recover sea level history, it is always difficult to estimate the rate of relative sea level fall because its sedimentary record is an unconformity. However, if summit drilling is combined with drilling of flanking lowstand terraces, rates of fall can be constrained by the time differential between the dissolution surface and formation of the terrace. For deeply eroded reefs, it may be necessary to drill the apron in order to determine how much of the section was removed by subaerial erosion.

Geochemical effects of oceanic plateaus on the oceans and atmosphere may be assessed by drilling through the entire sediment pile overlying older, adjacent oceanic crust. We recommend focusing on large plateaus which potentially had the most significant effects. Geochemical anomalies, including isotopes, metal-rich sediment, and dissolution intervals, as well as ash layers, will illuminate the global effects of plateau emplacement.

In order to study the relationship between large-scale volcanism and biotic extinction, holes into oceanic plateaus and volcanic margins are needed to date their emplacements accurately, and recovery of pre-, syn-, and post-emplacment sediment is necessary to examine for and date extinctions. Again, a strategy of drilling the largest oceanic LIPs and older adjacent sediment sections is recommended as being most likely to test the relationship between emplacement and extinction.

Several LIPs are located in the vicinity of important paleoceanographic barriers and gateways which require proper investigation, particularly: 1) the history of the narrow Early and mid-Cretaceous oceanic passages connecting Tethys to the Weddell Sea via rifts between India and Antarctica and between Madagascar and Africa may be

recorded on oceanic plateaus within the passages. For example, Gunnerus Ridge (67°S, 34°E), a potential LIP near the junction between these passages in the Early Cretaceous, is a potential monitor; 2) the Greenland-Faeroe Ridge acted as a barrier against flow of deep water from the Norwegian Sea into the North Atlantic until Miocene time. It likely preserves a record of Paleogene oceanography of the Norwegian Sea, which was in part governed by delayed subsidence of volcanic constructions along the margins, prior to subsidence of the barrier; 3) the conjugate Yermak Plateau and Morris Jessup Rise separated in the Oligocene, allowing deep water communication between the Arctic Basin and the Norwegian Sea in the Miocene. Information from this area is required to begin to integrate the polar basin into global paleoceanography, and we fully encourage the work of international groups addressing sub-seafloor sampling in the Arctic Ocean Basin proper.

Two or more sites each are needed on the crest of a plateau, a volcanic margin, and a surmounting seamount in order to assess topographic upwelling. One site would be drilled in the center of the feature, a pelagic cap in the case of oceanic plateaus and surmounting seamounts, and one at the margin to detect edge effects. Oceanic plateaus, volcanic margins, and seamounts should be selected within specific time slices in different water masses, and for specific paleodepths as determined by benthic foraminifers, backtracking, and other means. Intensified currents due to eddies and internal waves may produce extensive areas of hard substratum. Seismic surveys should identify targets whose pelagic caps were eroded or reduced during the early phase of subsidence outside areas of equatorial or continental margin upwelling.

Summary of recommendations

- ◆ Workshop participants recognized the scientific importance of LIPs and that no offshore LIP has been the target of comprehensive drilling and site surveys to elucidate its origin, evolution, and environmental consequences. We recommend that volcanic margins and oceanic plateaus be an integral part of future scientific drilling programs to study fundamental Earth problems.
- ◆ The general lack of key geological information necessitates an approach which reconciles the need for both exploratory drilling and focused, problem-oriented boreholes. The Workshop recommends a principal drilling strategy based on transect drilling, supplemented by holes of “opportunity.” The transect concept is compatible with both magmatic and tectonic, as well as paleoenvironmental objectives at oceanic plateaus and volcanic margins. Although improved drilling capability is desirable, a significant increase in knowledge may be achieved with present drilling technology integrated with comprehensive logging programs and VSPs for deep holes.
- ◆ A drilling transect would normally consist of a series of holes sampling the key sedimentary, igneous, and metamorphic rock units on a volcanic margin or oceanic plateau, tied to reference holes in normal oceanic crust and/or on the adjacent continental margin. Supplementary drilling comprises holes drilled as part of other scientific programs or as “supplementary” science. Moderately deep (500-1000 m) basement penetration should be achieved to establish the igneous stratigraphy of each oceanic LIP, and we strongly recommend that all drill holes be continued at least 150 m into igneous basement to constrain age and petrology/geochemistry.
- ◆ On volcanic margins characterized by transient volcanism we propose to drill a transect of relatively closely spaced holes across the margin tied to reference holes outside the transient activity. If seismic coverage and quality are excellent on conjugate segments, it may not be necessary to drill, or to drill a complete transect, on both sides. A transect would include 4-7 holes plus reference holes. The transect should be augmented by selected holes to evaluate along-strike margin variability, in particular the influence of hotspots. The rifted volcanic margins in the North Atlantic are strong candidates for transect drilling. One should initially aim for transects with minimum sediment cover to ensure a considerable penetration into the extrusives.
- ◆ To study hotspot and plume source evolution from a CFB across a rifted volcanic margin to an oceanic plume, we propose a strategy of drilling along the strike of the plume trail with

reference holes in adjacent basin(s). The Greenland-Scotland Ridge, Walvis Ridge-Rio Grande Rise, and Deccan to Réunion hotspot track are candidates for drilling transects. However, one should also evaluate how dredging may complement a drilling program.

- ◆ One of the two giant oceanic plateaus, Kerguelen or Ontong Java, should be comprehensively drilled in longitudinal and latitudinal transects. Assuming one site per 10^5 km², 10–15 sites plus reference holes would be the optimal goal in order to examine variations in age and composition. A plateau of purely oceanic origin, e.g., Manihiki, Shatsky, or Hess, should be drilled to characterize the crustal composition of one LIP end member.
- ◆ Paleoenvironmental objectives would be expected to be achieved during the above transects and in drilling programs focused on the

cause and effect of oceanic and climatic variability (cf. ODP Long Range Plan: *JOI*, 1990).

- ◆ Because it is not yet specifically known what site density is optimal and because the transect approach requires time-consuming basement penetration and downhole experiments, we recommend that the first phase of drilling focus on selected holes to estimate the variability along the transect. Completion of the transect would then be contingent and dependent on the initial drilling results.
- ◆ Finally, the Workshop strongly endorses the view that successful drilling critically depends on high-quality preparatory work. In particular, drilling requires integrated geologic and geophysical studies (site surveys) on regional and site-specific scales.
- ◆ The recommendations for drilling are summarized in Table 4.

Table 4.
LIP Drilling Recommendation Summary

LIP Target	Main Objectives	Primary Strategy	Number of Sites	Main Site Survey Needs
Conjugate Volcanic Margins	Tectonics Lithosphere	Transect(s)	4 to 7 + reference holes	MCS, some 3D refraction
LIPs across the COT	Tectonics Lithosphere	Transect	~10 + reference holes	MCS, some 3D refraction dredges
"Giant" Oceanic Plateau	Tectonics Lithosphere	Transect	10 to 15 + references holes	MCS, some 3D refraction dredges
"Pure" Oceanic Plateau	Tectonics Lithosphere	Transect	~5 + reference holes	MCS refraction dredges
Paleo-environment	Ocean History, Sedimentary Processes	Transect, holes of opportunity	included in above	shallow, high-resolution MCS

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Large Igneous Provinces Workshop Agenda

Sunday, November 4 — Day One

- 7:00 – 8:15 Breakfast at Swope Center
 7:45 – 8:05 Van departs Swope Center to Clark Laboratory
- 8:30 – 8:45 Opening Remarks —Mike Coffin
 8:45 – 9:05 “Some remarks on volcanic rifted margins” —Dave Roberts
 9:05 – 9:25 “How do we locate plumes in continental areas?” —Keith Cox
 9:25 – 9:45 “Ocean plateaus—an overview” —Mike Coffin
 9:45 – 10:05 “Paleoenvironmental consequences of large igneous outpourings” —Jerry Winterer
- 10:05 – 10:35 Refreshment Break
- 10:35 – 10:55 “Geochemical features of ocean plateau basalts” —Mike Storey
 10:55 – 11:15 “Subsidence histories of guyots and mantle dynamics” —Marcia McNutt
 11:15 – 11:35 “How coincidental are flood basalts and mass extinctions?” —Jason Morgan
 11:35 – 11:55 “Volcanism at Cretaceous-Tertiary times and possible relevance to the associated mass extinctions” —Chuck Officer
- 11:55 – 12:15 “Oceanic plateaus as flood basalt provinces—is Wrangellia an example?”
 —Mark Richards
- 12:15 – 12:35 “Drilling a volcanic margin: status and a look ahead” —Olav Eldholm
 12:35 – 12:45 Working Groups and Mandates —Mike Coffin and Olav Eldholm
- 12:45 – 1:45 Lunch at Clark Laboratory
- 1:45 – 3:15 Working Group Meetings
- 3:15 – 3:45 Refreshment Break
- 3:45 – 5:00 Working Group Meetings
- 5:15 – 5:30 – 5:45 Van departs Clark Laboratory to Swope Center
 6:00 – 7:00 Refreshments at Swope Center
 7:00 – 8:00 Dinner (with Woods Hole participants and guests) at Swope Center

Monday, November 5 — Day Two

- 7:00 – 8:15 Breakfast at Swope Center
 7:45 – 8:05 – 8:25 Van departs from Swope Center to Clark Laboratory
- 8:30 – 10:30 Working Group Meetings
- 10:30 – 11:00 Refreshment Break
- 11:00 – 12:30 Working Group Meetings

12:30 – 1:30	Lunch at Clark Laboratory
1:30 – 2:00	Mid-workshop Progress Report —Working Group Leaders
2:00 – 3:15	Working Group Meetings
3:15 – 3:45	Refreshment Break
3:45 – 5:00	Working Group Meetings
5:15 – 5:30 – 5:45	Van departs Clark Laboratory to Swope Center
6:00 – 7:00	Refreshments at Swope Center
7:00 – 8:00	Dinner at Swope Center

Tuesday, November 6 — Day Three

7:00 – 8:15	Breakfast at Swope Center
7:45 – 8:05 – 8:25	Van departs Swope Center to Clark Laboratory
8:30 – 10:30	Working Group Meetings
10:30 – 11:00	Refreshment Break
11:00 – 12:30	Working Group Meetings
12:30 – 1:30	Lunch at Clark Laboratory
1:30 – 1:45	Introduction of Working Group Results —Mike Coffin
1:45 – 2:30	WG I—Petrology, Geochemistry, and Dating of Large Igneous Provinces —Keith Cox
2:30 – 3:15	WG II—Global Paleoenvironments —Jerry Winterer
3:15 – 3:45	Refreshment Break
3:45 – 4:30	WG III—Conjugate Volcanic Passive Margin and Plateau Development —Dave Roberts
4:30 – 5:00	Closing Remarks —Mike Coffin and Olav Eldholm
5:15 – 5:30 – 5:45	Van departs Clark Laboratory to Swope Center
6:00 – 7:00	Refreshments at Swope Center
7:00 – 8:00	Dinner at Swope Center

Wednesday, November 7 — Day Four

7:00 – 8:15	Breakfast at Swope Center
7:45 – 8:15	Drive to Clark Laboratory
8:30 – 12:30	WG leaders, Mike Coffin, and Olav Eldholm Meeting
12:30 – 1:30	Lunch (outside)
1:30 – 5:00	WG leaders, Mike Coffin, and Olav Eldholm Meeting
5:00 – 5:30	Drive to Swope
7:00 on	Dinner (outside)

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