Achievements and Opportunities of Scientific Ocean Drilling

The Legacy of the Ocean Drilling Program

A Special Issue of the JOIDES Journal
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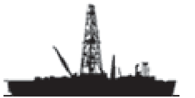
OCEAN DRILLING PROGRAM 1985-2002
Legs 100-199, Sites 625-1222

Map updates are available from the Ocean Drilling Program Science Operator website, http://www-odp.tamu.edu, at Texas A&M University. Leg 150X drilling along the shore of the New Jersey Margin was at Island Beach, Atlantic City, Cape May, Bass River, Ancora, Ocean View and Bethany Beach.



ACHIEVEMENTS AND OPPORTUNITIES OF SCIENTIFIC OCEAN DRILLING

The Legacy of the Ocean Drilling Program

A&O

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Photos from the Public Information pages of the Ocean Drilling Program Science Operator website (http:www-odp.tamu.edu) were used to create the cover art. The gray-hulled *JOIDES Resolution* was obtained from apromotional slide, and and the sunrise experienced by the Leg 198 shipboard party during drilling operations at Site 1028 (Shatsky Rise, western Pacific; September 2001) was found in the "Photos from the Ship" section. Summary location maps of sites drilled during the ODP (inside front cover) and the Deep Sea Drilling Project (inside back cover) were modified from the originals available at the ODP-TAMU website.

FOREWORD AND ACKNOWLEDGEMENTS

The Legacy of the Ocean Drilling Program

Keir Becker for the Editorial Review Board

Achievements and Opportunities of Scientific Ocean Drilling was initially organized at the August 2000 meeting of the JOIDES Science Committee (SCICOM) for the Ocean Drilling Program (ODP), partly in response to an Executive Committee (EXCOM) request that SCICOM begin documenting the scientific legacy of ODP as the transition to the Integrated Ocean Drilling Program (IODP) approached. The heart of the volume was to be a set of sixteen summaries representative of the full range of themes in the 1996 ODP Long Range Plan, *Understanding our Dynamic Earth through Ocean Drilling*. The organization of this volume, therefore, closely follows the development of themes in the Long Range Plan, which still is available electronically at the website of the Joint Oceanographic Institutions (http://www.joiscience.org).

An editorial review board was formed consisting of the 1999-2000 and 2001-2003 SCICOM chairmen (Bill Hay and myself), and more important, volunteer section editors for each of the four main themes. Bill and I gratefully acknowledge the contributions and editorial efforts of Larry Peterson, Harry Elderfield, Catherine Mevel, and John Tarduno, who worked with the authors to ensure representative and readable legacy contributions for this volume.

The contributions were envisioned to be written by single authors, or small groups of two or three co-authors, who could represent community-wide achievements. The original format guidelines limited the lengths of the articles to approximately four pages, but six pages seemed more appropriate and realistic once the initial contributions were submitted in 2001. The guidelines also called for up to four color figures and no more than twelve key references. We thank our authors, not only for their wonderful science summaries, but also for cooperating in the sometimes difficult task of meeting the format requirements.

The limit on the number of references was particularly painful for many contributors who would have liked to cite many more of their colleagues' studies. We adopted a policy originally suggested by one of the contributors to emphasize important ODP-related papers in the outside literature, and to achieve a reasonable limit on references. Mention of the results of specific legs was encouraged, but, with apologies to the scientific parties, we elected not to include overall citations to either the *Initial Reports* or *Scientific Results*, the *Proceedings of the Ocean Drilling Program* volumes for each leg. Where specific legs are mentioned in the articles, we strongly encourage the reader to consult the corresponding *Proceedings* volumes published by the Ocean Drilling Program, in College Station, Texas. More recent ODP volumes are available electronically at http://www-odp.tamu.edu/publications/.

A list of "ODP's greatest hits" was to have been distilled from the contributions to this volume by the editorial review board. However, during the same period, the Science Planning Working Group of the IODP Planning Sub-Committee compiled a brief but thorough and representative summary of "Major Achievements of Scientific Ocean Drilling" for the IODP Initial Science Plan, titled *Earth, Oceans and Life*. Rather than duplicate this comprehensive effort, we refer the reader to pages 10 through 16 of the Initial Science Plan, available electronically at http://www.iodp.org.

We also gratefully acknowledge the *JOIDES Journal* Editor/Designer, Henrike Gröschel, whose editorial and production skills are showcased in this extraordinary special issue. Finally, we must acknowledge the contributions of all the participants in the Ocean Drilling Program: it is your legacy that is represented in this volume!

RAPID CLIMATE CHANGE: OCEAN RESPONSES TO EARTH SYSTEM INSTABILITY IN THE LATE QUATERNARY

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A RAPID CLIMATE OSCILLATOR IN THE LATE QUATERNARY

Until recently most Earth scientists believed that past climate change occurred on relatively long time scales of tens of thousands of years or more. Most also thought that climate change was controlled largely by changes in the distribution of solar radiation, with Earth's orbital oscillations providing an external forcing to the climate system and pacing the so-called Milankovitch cycles. However, dramatic discoveries during the early 1990s changed this paradigm. Climatic records produced from the Greenland ice sheet and in nearby marine sediments of the North Atlantic altered the way Earth scientists thought about the operation of Earth's climate system and the relative sensitivity of this system to major climatic shifts.

Paleoclimate studies of Greenland ice cores (Dansgaard et al., 1993) were the first to reveal a remarkable sequence of major, rapid, millennial-scale oscillations in the climate system during the last ice age (Fig. 1), superimposed on the more gradual, orbitally-driven insolation cycles. Because of high accumulation rates of snow over Greenland, ice cores from this location are able to resolve climate changes occurring within decades or less, revealing late Quaternary climate behavior never before observed. The initial ice core work demonstrated that the climate oscillations (now known as Dansgaard/Oeschger [D/O] cycles) essentially reflect a "flickering" of the climate system between warm and cold states (Fig. 1), with air temperature shifts between these states estimated to be about 6° to 10°C. These shifts impart an almost bistable behavior in the climate system, with jumps between states occurring as briefly as a few decades or less (Alley and Clark, 1999). Even more remarkable was the discovery that the final switch from glacial to interglacial temperatures took place over a period of years to only a few decades at most (Alley and Clark, 1999). The oscillations also are recorded by significant changes in trace atmospheric greenhouse gases CO_2 and CH_4 in the ice cores.

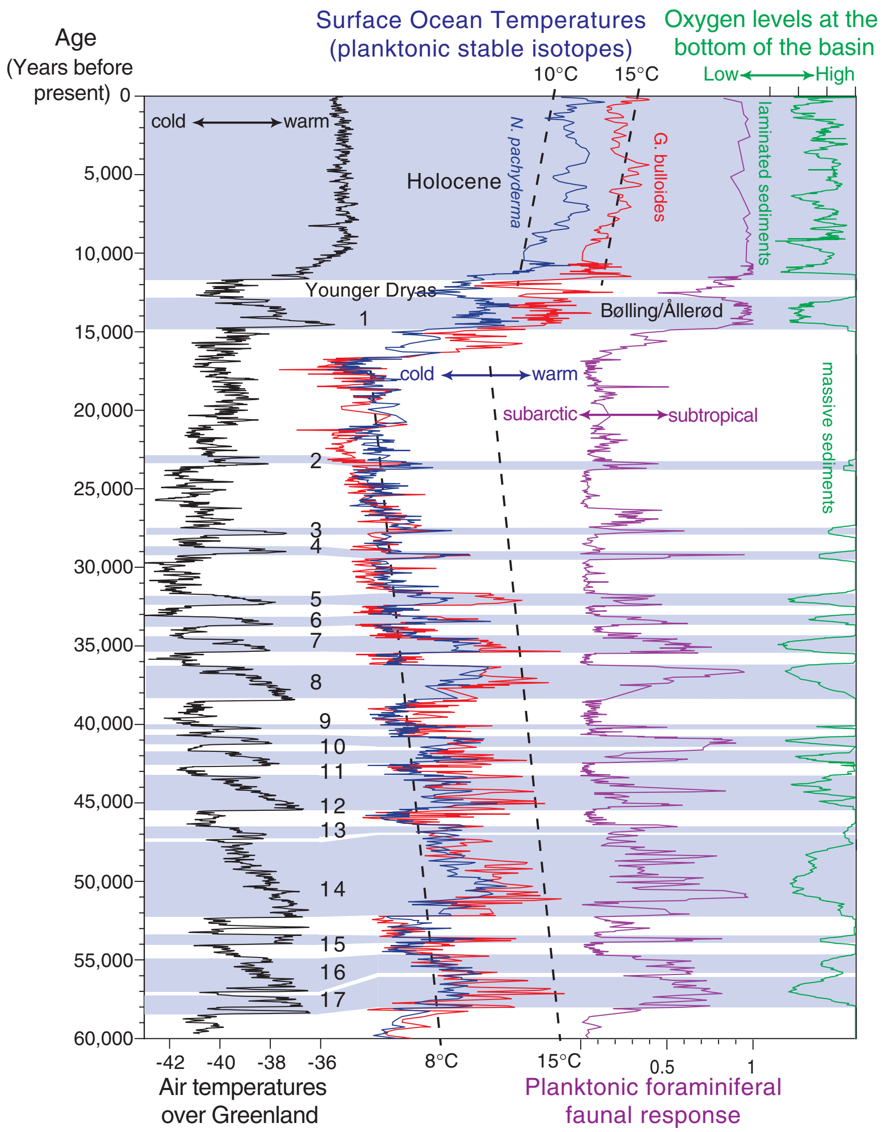

Figure 1. *Correlation between the GISP2 $\delta^{18}O$ air temperature record over Greenland (black) and planktonic foraminiferal and ventilation time-series for ODP Hole 893A (Santa Barbara Basin, California) for the last 60,000 years. $\delta^{18}O$ records for thermocline-dwelling foraminifer* N. pachyderma *are in blue and for surface-dwelling* G. bulloides *are in red (Hendy and Kennett, 2000). Variations in relative proportions of subarctic and subtropical planktonic foraminiferal assemblages (purple) provide a surface temperature time-series independent of $\delta^{18}O$. The Hole 893A bioturbation index (green) shows relative changes in bottom water oxygen levels (Behl and Kennett, 1996). Changes in all of the measured Hole 893A parameters clearly define the Dansgaard/Oeschger events (numbers 1-17) first recognized in the Greenland ice core record.*

The discovery of millennial-scale climate variability of this magnitude contributed to a sweeping reevaluation of the processes that drive major changes in the climate system, since no obvious external forcing exists that can cause change on these time scales. While the ice core discoveries generated much excitement, it was initially unknown if this climate behavior was limited to the North Atlantic, with the peculiarities of ocean overturning in this region, or if the climate changes extended to other oceans and other parts of the globe. Were the tropics involved in climate flickering? Do these processes reflect global climate changes? Knowledge of the regional extent of the ocean's role in climate behavior was a critical first step to understanding possible mechanisms for abrupt climate change. Investigation of other regions, especially oceans distant from the North Atlantic, was required. Ocean drilling became imperative since recovery of thick sediment sequences, deposited during the Quaternary at high sedimentation rates, was needed to resolve decadal- to millennial-scale climate change. Penetration of traditional piston cores was simply not long enough. Several locations offered the prospect of drilling for high quality records, including the Santa Barbara Basin off the coast of temperate southern California and the Cariaco Basin in the western tropical Atlantic. Studies of these two basin sequences represent an important legacy of the Ocean Drilling Program (ODP).

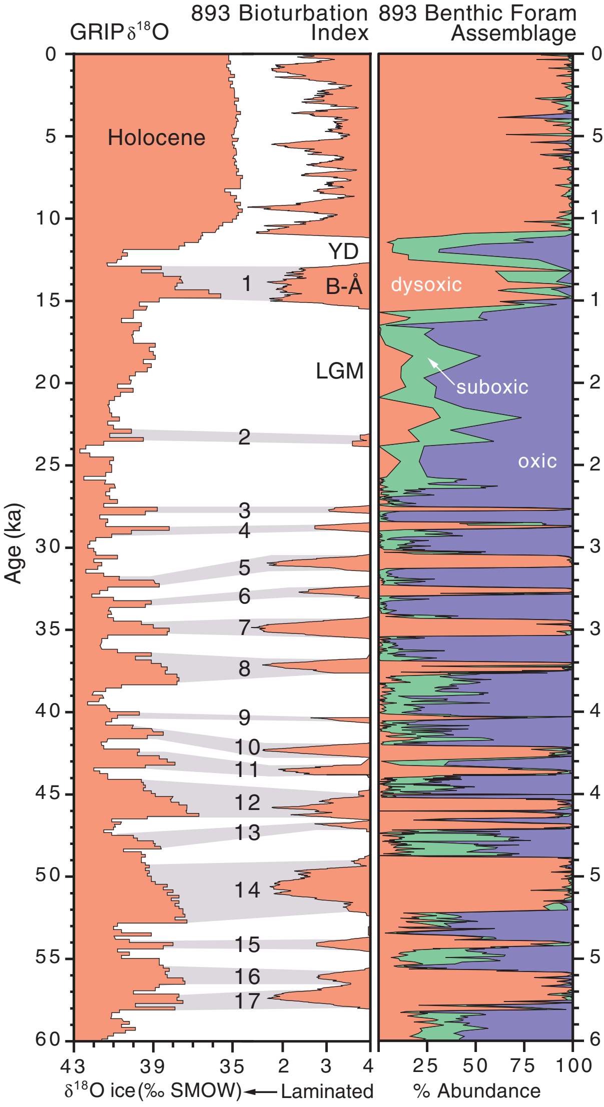

Figure 2. *Comparison of Site 893 (Santa Barbara Basin) bioturbation index (Behl and Kennett, 1996) and benthic foraminiferal assemblage data (Cannariato et al., 1999) with the $\delta^{18}O_{ice}$ time-series from the GRIP ice core. Note excellent correlation between periods of anoxia/dysoxia at Site 893 and each of the warm interstadials recorded at GRIP, indicating that deeper parts of the ocean were also affected by rapid climate changes of the late Quaternary.*

GLOBAL OCEAN INVOLVEMENT OF MILLENNIAL-SCALE CLIMATE CHANGE

Understanding of millennial-scale climate variability was greatly advanced by the drilling in 1992 of ODP Site 893 in the Santa Barbara Basin. This sequence (Fig. 1) represents the highest resolution sediment record of climate change during the last 160,000 years yet recovered from the oceans. Investigations immediately showed that the sequence preserved a record of major and rapid instability of the marine environment and ecosystem off coastal California during the late Quaternary (Kennett and Ingram, 1995; Behl and Kennett, 1996). This instability, observed over a wide range of time scales, is most dramatic at glacial terminations but also is clearly associated with a full sequence of interstadial events, or D/O cycles, during the last 80,000 yr (Fig. 1; Behl and Kennett, 1996; Cannariato and Kennett, 1999; Hendy and Kennett, 1999; 2000). Oxygen isotope ($\delta^{18}O$) and planktonic foraminiferal assemblages define rapid climate variability in Santa Barbara Basin surface waters, indicating significant temperature change in association with the D/O cycles. Sea surface temperatures increased and decreased very rapidly over intervals of 50 to 70 years or less during glacial terminations and at the beginning and end of D/O cycles, as in Greenland (Fig. 1). Inferred sea surface warmings of as much as 5°C within a few years in coastal California, and brief overshoots of as much as 3°C (Fig. 1), suggest some form of atmospheric amplification.

Despite limitations of the Santa Barbara Basin chronology, the similarities in speed, magnitude, and character of the Santa Barbara Basin and Greenland ice sheet records strongly indicate a synchronous climate response between the two regions (Fig. 1; Hendy and Kennett, 1999). The speed of the changes further implies that climate signals were transmitted via the atmosphere, and supports the involvement of rapid atmospheric and oceanic reorganizations on a major scale since changes were not limited to the North Atlantic region. That the Pacific Ocean, the largest global ocean, was as sensitive to, and strongly involved in, such climatic reorganizations holds critical implications relative to the processes that drive this change.

Early investigations of the Santa Barbara Basin sequence (Kennett and Ingram, 1995; Behl and Kennett, 1996) also provided critical data that indicated millennial-scale climate oscillations in the North Pacific were not limited to surface waters. Deeper parts of the ocean were clearly involved as recorded by equally rapid changes in oxygenation and ecology. Upheaval of the benthic ecosystem is reflected by oscillations between laminated and faunally-mixed sediments and by major changes in benthic populations (Fig. 2; Behl and Kennett, 1996; Kennett and Ingram, 1995; Cannariato and Kennett, 1999; Cannariato et al., 1999). Drilling during ODP Leg 167 in 1996 provided additional cores elsewhere along the California margin. Study of sequences in these cores demonstrated that millennial-scale oscillations in oxygenation state were not limited to the Santa Barbara Basin and other confined areas such as the Gulf of California (Keigwin and Jones, 1990), but were widespread on the open continental margin of southern California (Lyle et al., 2000). Dramatic changes in the strength of the oxygen minimum zone (OMZ) occurred on this margin in association with D/O cycles during the last 60,000 years (Cannariato and Kennett, 1999), with the OMZ weakening and perhaps even disappearing during cool episodes only to strengthen again during warm episodes.

What caused these changes in the OMZ? Results from several studies suggest a combination of changes in bottom water ventilation and surface water biological productivity, in turn controlled by changes in the strength and location of Pacific Intermediate Water production (Kennett and Ingram, 1995; Keigwin, 1998). Whatever the cause, results from these ODP sites have clearly shown that fluctuations in intermediate waters and the OMZ off California were as tightly linked to global climate patterns as were changes in the surface ocean. California margin ODP cores have thus strongly implicated broad involvement of Earth's environmental system, including the biosphere, in rapid millennial-climate changes. Widespread segments of the Earth System, including deep-ocean circulation as it affected the Pacific, were variously engaged in these abrupt climate oscillations.

TROPICAL INVOLVEMENT IN MILLENNIAL-SCALE CLIMATE CHANGE

As evidence continued to mount during the 1990s for synchronism of climate changes associated with the last deglaciation in regions far from the North Atlantic, the possibility was raised that a more global forcing mechanism was responsible for rapid climate change. However, little was known about the contribution of the tropics, if any. Prior to about 1995, high-latitude climate forcing dominated discussions on rapid climate change linked to the last deglaciation. A general consensus existed in the earth science community that the tropics changed little during the late Quaternary and contributed even less to ice-age climate variability.

This concept has now begun to change, partly as a result of studies of the Cariaco Basin in the southern Caribbean Sea (e.g. Peterson et al., 1991; Hughen et al., 1996). The Cariaco Basin, like the Santa Barbara Basin, contains superb records of Quaternary climate history owing to high rates of sedimentation and surface water biological productivity, and a general lack of sediment disturbance because of the largely anoxic conditions. Early investigations of short piston cores covering the last deglacial interval revealed evidence for abrupt, decadal oscillations in sea surface temperature and biological productivity that were found to be synchronous with climate change at high latitudes. These variations were interpreted to reflect the effects of changing trade wind strength on upwelling over the Cariaco Basin. However, since trade wind strength may be forced by large-scale sea surface temperature patterns related to changing thermohaline circulation, the concept continued to prevail of a dominant North Atlantic driving mechanism (e.g., Hughen et al., 1996). Nevertheless, the discovery of tropical involvement in rapid climate change at this site and others led to a greater focus on the potential role of the tropics in climate change. Based on simple climate theory alone, this role could be considerable given the importance of the tropics as the dominant source of heat and water vapor to the climate system.

Deep-sea drilling was required to more fully exploit the Cariaco Basin’s sediment record. ODP Site 1002, drilled in 1996, was the first tropical site to provide a long late Quaternary record (spanning the last ~550,000 years) of the required resolution to resolve decadal climate variability. Studies of these sediments have since revealed a complete sequence of D/O cycles recorded in multiple climate proxies for the last 90,000 years (Fig. 3; Peterson et al., 2000). Furthermore, the remarkable behavior of these tropical climate-related cycles is so similar to those of the Greenland ice cores (Fig. 3) and other sequences including the Bermuda Rise in the subtropical Atlantic (Sachs and Lehman, 1999), that synchronism via atmospheric transmission is strongly implicated.

The D/O cycles in sediments of the Cariaco Basin are clearly recorded by alternating light and dark intervals, expressed in Figure 3 by measurements of sediment reflectance. Intervals corresponding to the cold stadial intervals of the last glacial are represented by light, bioturbated sediments; warm interstadial intervals were characterized by deposition of dark, organic-rich, undisturbed sediments. Following previous investigations (Peterson et al., 1991; Hughen et al., 1996), changes in deep basin oxygenation and sediment organic content continued to be linked to changes in surface-water productivity. However, new evidence from Site 1002 also clearly showed that D/O cycles in Greenland ice were intimately tied to rapid oscillations in the riverine input of siliciclastic sediments (as measured by bulk Fe and Ti) to the Cariaco Basin. These oscillations are likely the result of changes in the position of the Intertropical Convergence Zone and its associated belt of convective rainfall. Periods of high input of continental sediment are in phase with the warm interstadials and indicate higher regional precipitation (Fig. 3); periods of low siliciclastic input are evidence of dry regional conditions during the colder stadials. These observations suggested for the first time that color/productivity cycles in the basin during the glacial were not the result of upwelling, but were instead driven by changes in river-borne nutrients to coastal waters of northern South America. More importantly, these new data provided the first direct evidence for rapid and frequent hydrologic changes in the tropics during the last glacial episode that are clearly linked to D/O cycles. Interstadials during the last ice age in this region were marked by high rainfall implying a higher water vapor content in the atmosphere, a powerful greenhouse gas and candidate feedback mechanism for the generation of abrupt climate change. With such discoveries, the tropical regions of Earth are being increasingly implicated as a potential source of millennial-scale climatic variability.

SUMMARY: THE INTEGRATED EARTH SYSTEM PERSPECTIVE AS AN ODP LEGACY

An enduring legacy of ocean drilling will be its irreplaceable contribution to our understanding of Earth System history, the evolution of the earth as a coupled system involving ocean, atmosphere, ice, lithosphere and biosphere. Ocean drilling has provided records crucial for understanding such coupling on a huge range of time scales, from tens of millions of years to decades. The field of paleoceanography was spurred on by the birth and development of ocean drilling and our current Earth System perspective grew largely out of paleoceanographic discoveries.

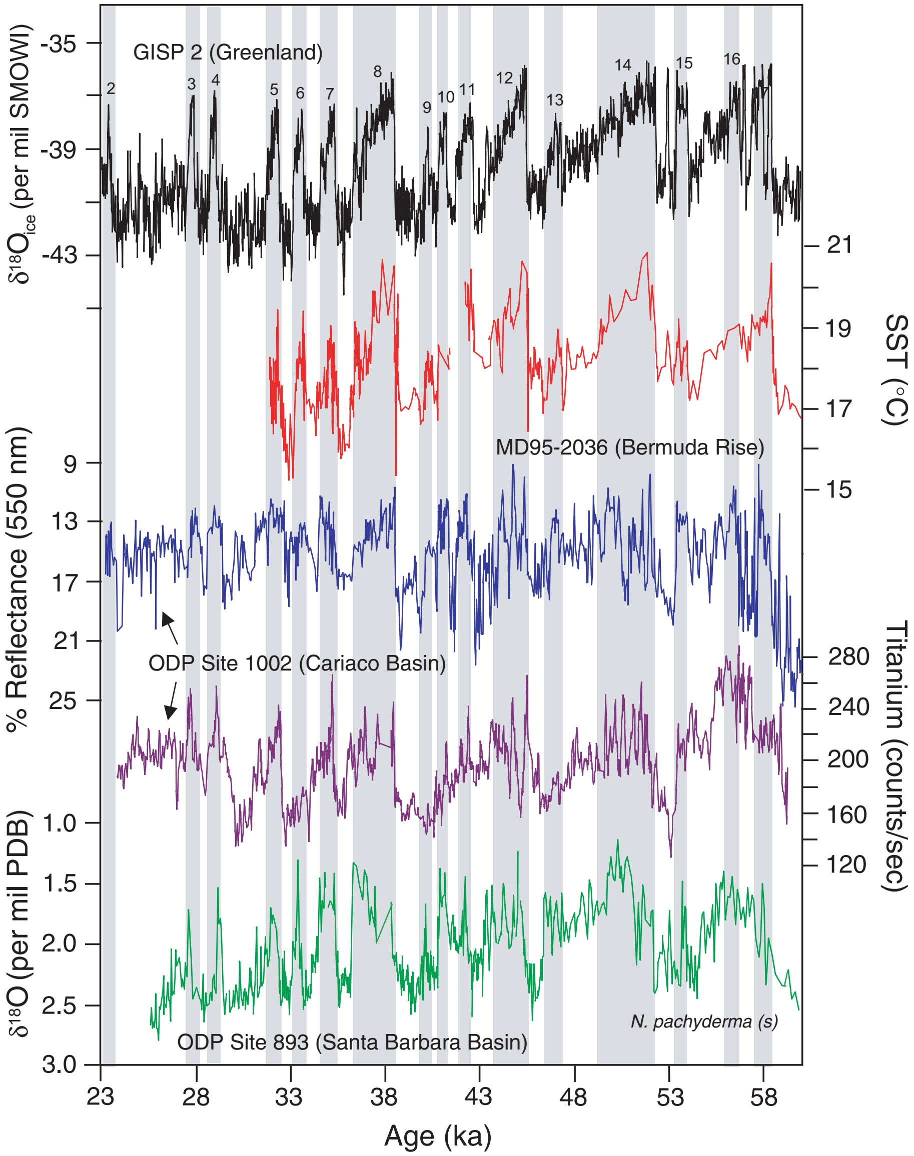

Figure 3. *Comparison of selected high-resolution climate time-series during Marine Isotope Stage 3 with the* $\delta^{18}O_{ice}$ *time-series (black) from the GISP2 ice core. Rapid oceanographic changes in the subtropical North Atlantic are recorded by alkenone-derived sea surface temperature estimates (red) from core MD95-2036 on the Bermuda Rise (Sachs and Lehman, 1999). In the tropical Caribbean, changes in sediment color (blue) and bulk titanium content (purple) at ODP Site 1002 (Cariaco Basin) also record rapid changes that are clearly tied to the high-latitude ice core record. Sediment color (reflectance) during this interval is largely the result of changing surface productivity while titanium is a measure of terrigenous content and indicates variations in regional preci-pitation and input from rivers that drain the northern coast of tropical South America (Peterson et al, 2000). The Site 893* $\delta^{18}O$ *record from Santa Barbara Basin, California, based on the planktonic foraminifer* N. pachyderma *(Hendy and Kennett, 2000; green) completes the comparison. These records, and a growing body of others, provide a compelling demonstration that coupled changes in the ice-ocean-atmosphere system are intimately involved in the phenomenon of rapid climate change during the late Quaternary.*

Most recently, and perhaps definitively, this contribution has been demonstrated by studies of climate change in the latest Quaternary. This result is ironic since ocean drilling as a tool was largely established to probe the lithosphere below superficial ocean sediment layers. Paleoclimatic investigations of the Santa Barbara and Cariaco Basins, in addition to a growing number of sites targeted elsewhere by the ODP, have clearly highlighted the global ocean as a major participant in the extremely rapid and variable climatic behavior first observed in Greenland ice records. These studies have revealed the ocean's remarkable capacity to switch between glacial and interglacial states within decades or less, a completely unexpected discovery that implicates the ocean as a source of major feedbacks that serve to reinforce or amplify the climatic shifts. Furthermore, the remarkable similarities in short-term climate behavior between such geographically distant regions argue strongly for synchronous teleconnections via the atmosphere as a mechanism for promulgating such rapid climate change. Hence, the speed of the climatic jumps and their magnitude essentially requires operation of a coupled Earth System.

Of course, these discoveries beg the question of ultimate cause - understanding the feedbacks and linkages within the global system that create such abrupt climate change represents one of the major current challenges in earth science. Ocean drilling will continue to be an indispensable tool for solving the puzzle of past climate behavior, and for creating future legacies that will lead to a better understanding of our Earth.

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EXCEPTIONAL GLOBAL WARMTH AND CLIMATIC TRANSIENTS RECORDED IN OCEANIC SEDIMENTS

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Richard D. Norris, Woods Hole Oceanographic Institute, and
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INTRODUCTION

Ocean drilling during the past fifteen years has recovered sediments deposited when the Earth was in a “greenhouse” state, with higher atmospheric contents of greenhouse gases, a near-total lack of glacial ice, and generally increased surface temperatures, particularly at the poles. The warm periods included both relatively long (million year, or m.y.) intervals of elevated temperatures, as well as “transient events” in which climate changed abruptly on time scales of several thousand years or less. Many of these warm intervals were probably due to injection of greenhouse gases into the ocean and atmosphere, in some cases on time scales similar to human industrialization and deforestation. Consequently, the study of past warm climates can reveal information on the stability of tropical sea surface temperatures, the relationship between biodiversity and climate, and the global effects of changes in the carbon cycle.

LONG TERM STABLE OXYGEN ISOTOPE RECORD

Deep ocean sediment archives continuously cored during Ocean Drilling Program (ODP) operations provide the historical records needed to determine perturbations in the global biogeochemical cycle associated with unique warm events in the geologic past. A recent compilation of the deep-sea stable oxygen isotope record from the Cretaceous/Paleogene boundary (~65 Ma, or million years ago) to present shows how Earth’s climate has shifted long term from the “greenhouse” world of the early Paleogene to the “icehouse”’ world of modern times (Zachos et al., 2001). This compilation pulls together data generated from more than forty ODP and Deep Sea Drilling Program (DSDP) sites and emphasizes the extent to which this long-term trend is dominated by rapid transitions to colder and more glaciated climates (Fig. 1). In the past it was difficult to quantify the degree of cooling represented by these oxygen isotope records because of the superimposed effects of ice volume increase. However, recent application of an exciting new independent paleothermometer, Mg/Ca in fossil foraminifera, suggests that the deep oceans were at least 12°C warmer 50 m.y. ago than they are today (Lear et al., 2000). Similarly, the first boron isotope records from these types of fossils, recently extracted from ODP cores, have been interpreted to indicate carbon dioxide levels much greater in the early Eocene greenhouse world than in modern times (Pearson and Palmer, 2000). ODP records also suggest that Earth was largely free of continental ice caps for much of the past 100 m.y.; indeed, significant Antarctic ice sheets appear to have originated only around 30 Ma. This hypothesis is subject to ongoing examination by ocean drilling, not only in mid-oceanic deep-water sites (e.g., ODP Leg 199), but also on the fringes of continents (e.g., the New Jersey margin, ODP Leg 174A) where the imprint of sea level and its driving forces, such as fluctuations in global ice volume, can be detected.

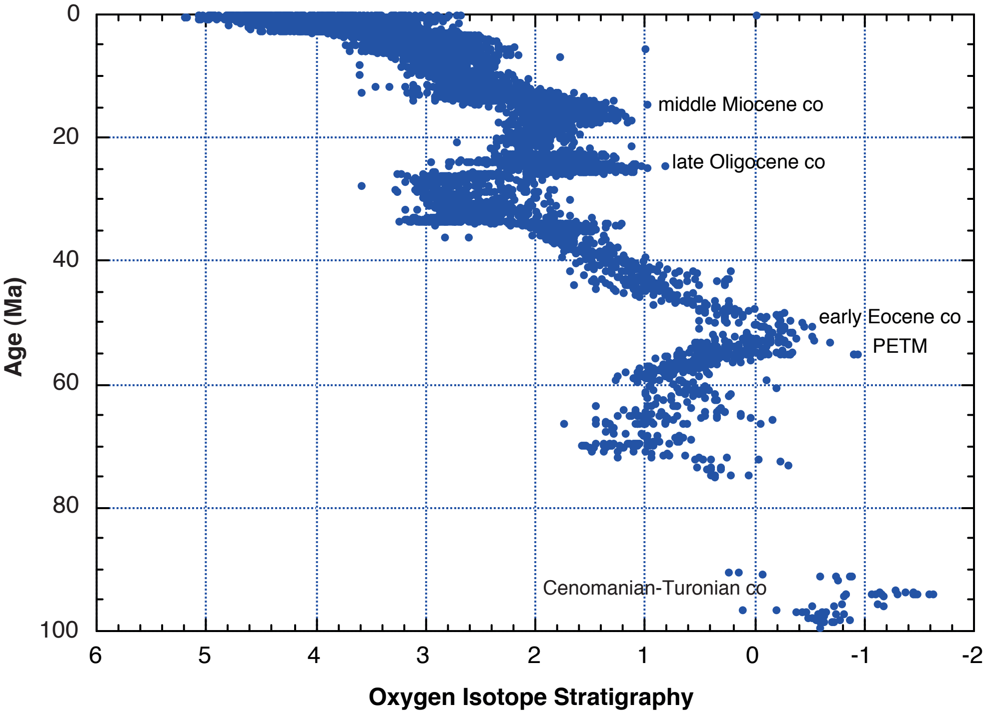

Figure 1. *Global deep-sea isotope record from cores recovered from numerous DSDP and ODP Sites. PETM = Paleocene-Eocene Thermal Maximum; co = climatic optimum. This record is based on a compilation of data by Huber et al. (1999), Norris et al. (2001), and Zachos et al. (2001).*

Additional data from ODP drilling during Leg 171B along the Blake Nose region of the North Atlantic (Huber et al., 1999; Norris et al., 2001) have been added to Figure 1 to extend the stable isotope compilation back into Cretaceous time. The most extreme warm conditions are indicated around the Cenomanian-Turonian boundary from intermediate waters of the proto-Atlantic. Although the record in this interval was not complete, Huber et al. (1999) have shown that the entire water column warmed by up to as much as 15° to 19°C. This is warmer than at any other time during the Cretaceous or Cenozoic and is consistent with paleontological evidence for extreme warmth in the Arctic.

TRANSIENT INTERVALS (RAPID CLIMATE CHANGE)

In recent years, certain key intervals of the Paleogene and Cretaceous have been recognized as times of rapid climate change and massive input of carbon into the sediments. One of the best-studied intervals is the Paleocene-Eocene Thermal Maximum (PETM), and the ODP has made great efforts to recover sediments from this interval. Leg 171B along the Blake Nose was the last leg to recover a record as complete as possible across the Paleocene/Eocene boundary (Fig. 2); multiple holes at Site 1051 provided the opportunity to study a complete record of the PETM (Norris and Röhl, 1999).

Why are "transient" climate events such as the PETM so important? Our society is concerned with the fate of fossil fuel carbon that we are presently adding to the atmosphere at a rate of 5×10^{14} mol C/yr. While we have a considerable understanding of how the global carbon cycle operates, we have no knowledge as yet of how a massive injection of fossil fuel will perturb the global carbon cycle when the world is already warm. Transient events such as the PETM provide the opportunity to study major upheavals of the carbon cycle that are similar to the present day.

HOW DO WE RECOGNIZE THESE EVENTS IN THE GEOLOGIC RECORD?

Carbon isotopes have proven especially useful in studies of the PETM. This particular phase of global warming was associated with a large and unmistakable decrease in isotope ratios that is widely attributed to massive release of the greenhouse gas methane from deep sea sediments, perhaps from the large-scale dissociation of methane hydrates (Dickens et al., 1995; Fig. 2). This carbon isotope excursion has been documented in planktic and benthic foraminifera in sediments of all oceans, in fossil tooth enamel, in carbonate concretions in terrestrial sequences of North America, and in terrestrial organic carbon in sediment from Europe and New Zealand (e.g., Kennett and Stott, 1991; for an extensive

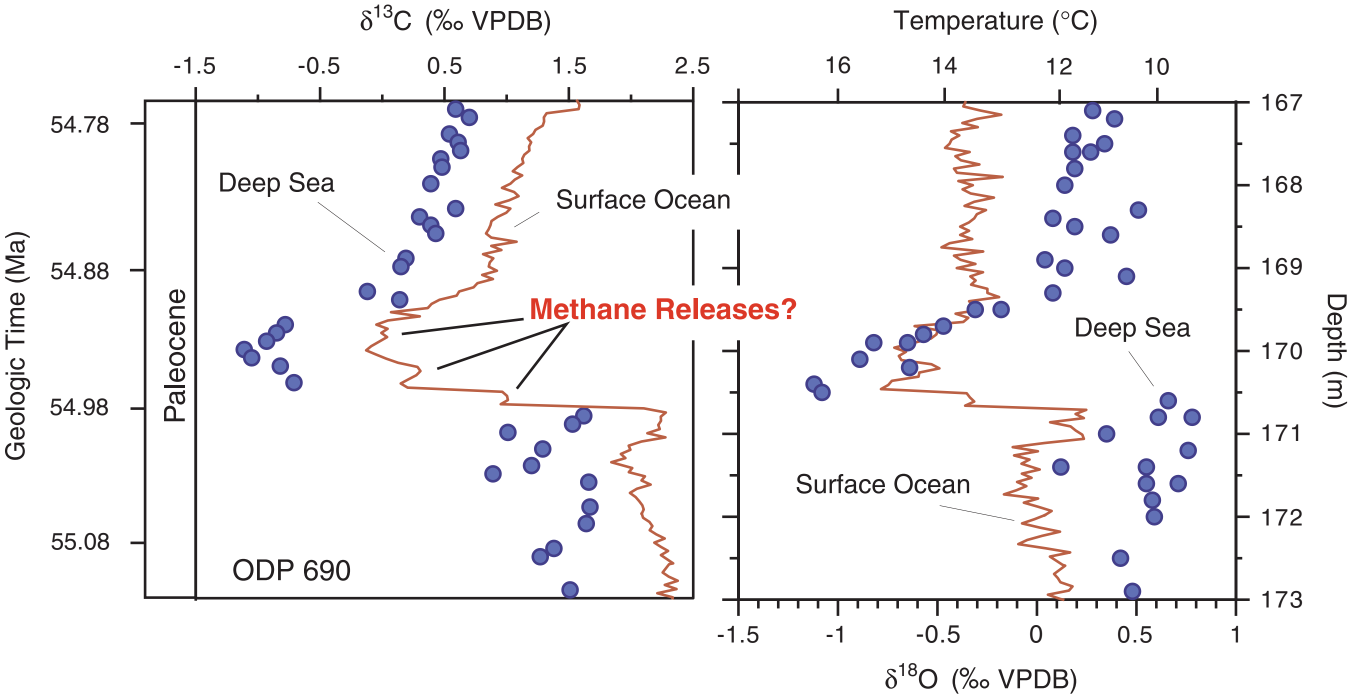

Figure 2. Stable isotope records of surface-ocean carbonate (red line) and bottom-dwelling foraminifera (blue circles) across the PETM at ODP Site 690 (Southern Ocean). The step-like changes in both carbon isotopes and temperature are believed to reflect massive input of greenhouse gases, such as methane, into the ocean and atmosphere at the start of global warming associated with the PETM. A major (~53%) extinction of deep-sea biota occurred at the same time as the change in ocean temperature and chemistry. The surface record probably reflects changes in isotopic fractionation due to changes in the nannofossil flora as well as temperature during the PETM.

reference list see Kroon et al., 2000). The detailed stable isotope analysis of several marine sections by Bains et al. (1999) suggested that a series of inputs of carbon, enriched in ^{12}C, at the start of the PETM lasted, in fits and starts, for ~50,000-60,000 years and were followed by the rapid uptake of CO_2 and termination of global warming. Work in ancient soils from the Bighorn Basin of northwest Wyoming shows that some of the internal structure of the PETM seen in marine records also is present on land and therefore must represent real changes in greenhouse gas input rather than artifacts in the deep-sea records. The PETM is especially intriguing because an immense quantity of CO_2 greatly enriched in ^{12}C was added rapidly to the ocean or atmosphere in an analogous fashion to ongoing anthropogenic perturbation (e.g., Dickens et al., 1995).

The keys to documenting and understanding transient climate events are the recovery of continuous records through the target intervals and the development of astronomically-tuned time scales. These "tuned" time scales are crucial for documenting the rates of both carbon input and carbon removal. The paleoceanographic community through ODP has made great progress in these endeavors. Kennett and Stott (1991) originally estimated the duration of the entire excursion to be around 200,000 years. Recently, Norris and Röhl (1999) provided the first astronomically-calibrated date of the PETM (about 54.98 Ma) and a chronology for the event itself using cyclostratigraphy. The new chronology provides extraordinarily detailed information about the injection event and the duration of the aftermath and recovery period, when carbon sequestering occurred somewhere in the system. Bains et al. (1999) suggest that the onset of the event was not a simple one-step injection of CH_4 but rather a stepwise event (Fig. 2). The return to initial conditions took place over about 120,000 years.

The Paleocene-Eocene Thermal Maximum is one of our best examples in the geologic record of global warming caused by rapid injection of greenhouse gases. Global warming at this time was associated with a mass extinction of deep-sea foraminifera (53% of species lost), and the first appearance of primates and horses in North America and Europe. The ultimate causes of these marked changes in climate and biota are, however, still poorly known. In particular, we still have only a sketchy idea of what triggered the massive release of greenhouse gases from the deep sea. Mechanisms ranging from asteroid impacts and giant submarine land slides to volcanic eruptions have been proposed. The PETM will remain a topic of intense debate as we head into a new phase of ocean drilling.

Oceanic Anoxic Events (OAEs)

The mid-Cretaceous featured even larger carbon cycle-linked perturbations to the ocean-climate system. Oceanic anoxic events (OAEs), defined by intervals of enhanced deposition of organic matter in marine environments, are usually deeply buried in the sediment column. However, undisturbed, complete sequences were recovered from ODP boreholes during Legs 143 and 171B.

There were arguably between two and five OAEs during the mid-Cretaceous. Each of these was different in geographic extent, but all recorded rapid changes in the carbon cycle and/or were associated with major changes in marine biota (see article by Bralower et al., this volume). Two of these events, the late early Aptian Selli Event (OAE-1a; about 120 Ma) and the Cenomanian-Turonian Boundary Bonarelli Event (OAE-2; about 93.5 Ma) are the most prominent and are characterized by the deposition of dark marls or shales enriched in organic carbon. Enhanced preservation of organic matter during the OAE events probably resulted from global expansion of the oxygen minimum zone. While the cause(s) of these events is widely debated, most authors acknowledge a complicated interplay between global warmth, increased surface water productivity and/or deep-water stagnation. Despite the uncertainties, all authors agree that the OAEs were associated with major steps in climate evolution because burial of excess organic carbon, by drawing down CO_2, must have had an influence on global temperatures.

Recent high-resolution work across some of the OAEs shows that each OAE is different and characterized by a complex sequence of apparently global biogeochemical interactions. ODP results, such as from Leg 171B, indicate that the OAEs occurred when the world was extremely warm. The best example is OAE-2 where the lightest $\delta^{18}O$ values have been recorded in the shells of benthic foraminifera (Fig. 1; Huber et al., 1999). A precursor anoxic event (OAE-1d) was investigated by Wilson and Norris (2001). The boundary interval for the Lower/Upper Cretaceous (late Albian-early Cenomanian) was recovered at Blake Nose. Here the planktic foraminifera are extremely well preserved in the rhythmically bedded sequence because they are entombed in clay-rich sediments. These fossils yielded $\delta^{18}O$ records that indicate pronounced variability in the thermal structure of surface waters in the western tropical to subtropical Atlantic Ocean, with maximum sea surface temperatures warmer than today. This variability culminated with the collapse of upper-ocean stratification during OAE-1d, contradicting both the traditional view that past warm periods were more stable than today's climate as well as explanations for global OAEs based on ocean stagnation. In contrast, ODP Leg 171B records from the early Albian (OAE-1b) suggest that ocean stagnation played a significant role in the case of more regionally expressed anoxic events (Erbacher et al., 2001).

Selli Event (OAE1a)

Excellent work has been done on the Selli Event (OAE-1a), with detailed stratigraphic studies carried out on both land sequences and marine sequences drilled by ODP (e.g., Leg 143). Most importantly, a marked negative carbon isotope anomaly now has been found in terrestrial material (Gröcke et al., 1999) similar to the negative $\delta^{13}C$ excursion found during the PETM. Based on ODP Leg 143 drilling, Jenkyns and Wilson (1999) found a pronounced negative carbon excursion in shallow-water marine carbonates drilled on two mid-Pacific guyots (Fig. 3). Thus, the negative excursion is clearly registered in both the marine and terrestrial realms, indicating that the whole of the ocean-atmosphere system was influenced by changes in the global carbon cycle. Contrary to the PETM, the negative carbon isotope anomaly is superseded by an abrupt positive $\delta^{13}C$ excursion (Fig. 3). This sequence of carbon isotope stratigraphy suggests that there was an initial phase of carbon release, possibly of mantle-derived CO_2 or by gas hydrate release, which gave rise to a distinct negative $\delta^{13}C$ excursion. This was then followed by carbon burial enriched in ^{12}C, possibly triggered by increased ocean surface productivity, which gave rise to the subsequent positive $\delta^{13}C$ excursion. It is not so clear what mechanism(s) may have been responsible for driving the OAE-1a event that has been linked to the Ontong Java-Pacific "superplume" event (Larson, 1991), although gas hydrate release also is an option.

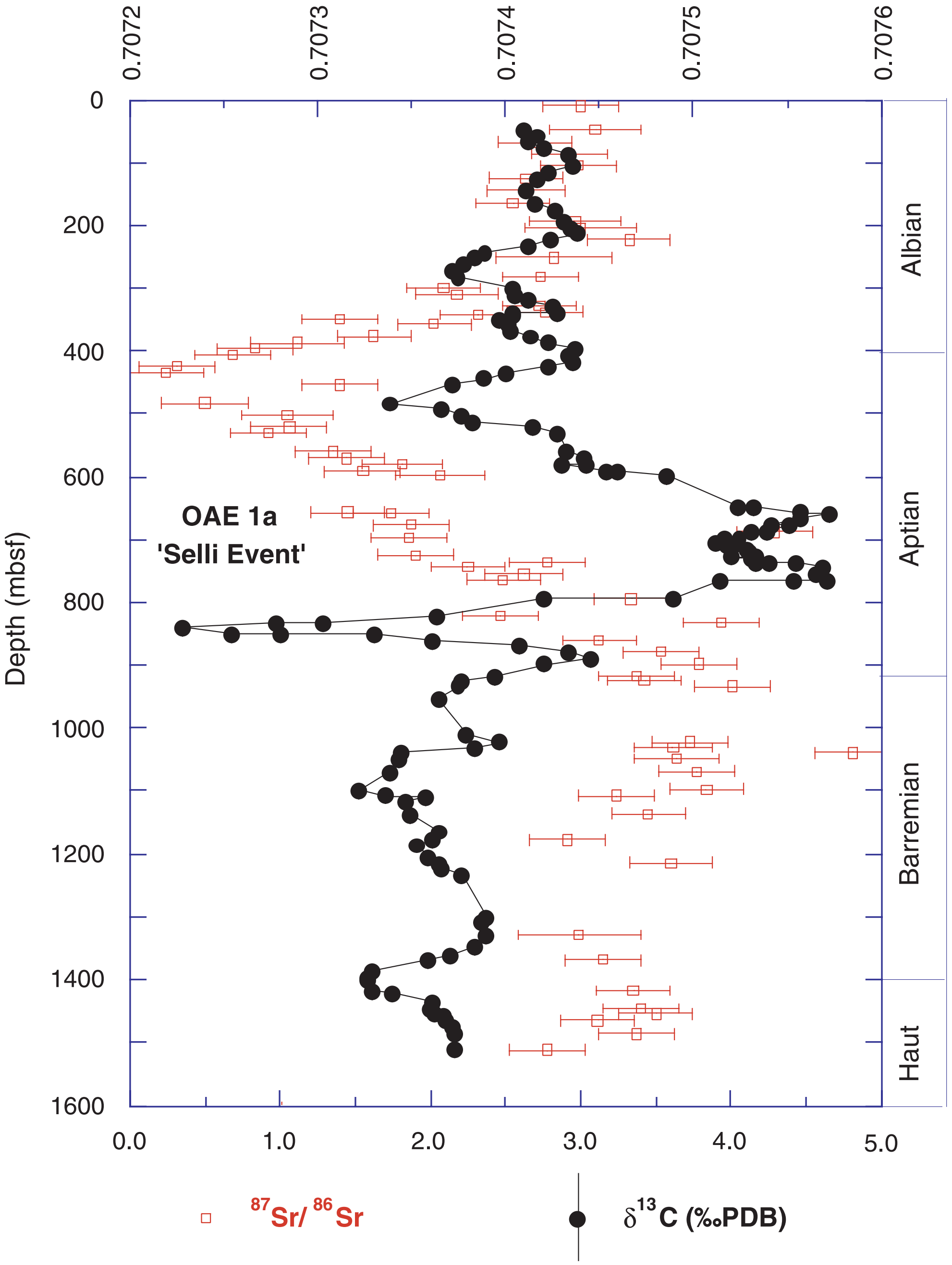

Figure 3. *Strontium ($^{87}Sr/^{86}Sr$) and carbon isotope ($\delta^{13}C$) stratigraphy of Cretaceous platform carbonates from Resolution Guyot (Jenkyns and Wilson, 1999), a "drowned atoll" from the mid-Pacific Mountains. Remarkably, the $\delta^{13}C$ records from these mid-ocean reef-like shallow water sediments (~5 m to 20 m water depth) can be correlated to the global seawater reference curves compiled from deep water sediments in European sections. Furthermore, in the case of Resolution Guyot, the drowned atoll preserves a "Livello Selli" horizon, a laminated organic-rich (~14% TOC) black shale, demonstrating the truly global nature of Oceanic Anoxic Event 1a.*

Cenomanian-Turonian Boundary (OAE-2)

Sediments rich in marine organic matter of Cenomanian-Turonian Boundary age have been recovered from all ocean basins. A positive carbon isotope excursion associated with OAE-2 has been attributed to increased ocean productivity, although it is still unclear whether this was stimulated by changes in ocean circulation or nutrient availability. It is interesting to note that a pronounced negative precursor has not yet been identified for OAE-2 in marine sections from Europe, but some sections (e.g, Japan; Hasegawa, 1997) show a slight negative trend prior to the positive excursion at the Cenomanian-Turonian Boundary. Thus, the sequence of events leading to changes in the global carbon cycle during OAE-2 may have been different from OAE-1a.

SUMMARY

We conclude that the Ocean Drilling Program has significantly contributed to our knowledge of certain key periods of extreme warmth. Many issues relevant to understanding the "transient" periods of rapid climate change have been addressed by drilling-based studies and these have highlighted the role of the global carbon cycle in their origin. Future drilling by ODP will undoubtedly further resolve outstanding issues surrounding extreme climate events. Scheduled ODP Legs 207 and 208 will attempt to recover complete records at Demerara Rise and Walvis Ridge in 2003. These legs have been specifically designed to provide answers to major remaining questions, which include: (1) what is the relationship between the PETM, OAEs and climate change? (2) were all such extreme events linked to greenhouse warming? and (3) do we observe similar $\delta^{13}C$ patterns across each event? For a more extensive list of questions and outstanding issues we refer the reader to the report of the ODP Extreme Climate Advisory Panel (Kroon et al., 2000).

The documentation of geochemical variability through and across these events from complete sediment sequences will provide answers to many of these questions. Both currently scheduled and future ocean drilling legs along depth transects ultimately will give insights into past geochemical gradients in the oceans. Modelers will then have the information to further highlight and understand the role of the carbon cycle in a greenhouse world.

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MILANKOVITCH AND CLIMATE: THE ORBITAL CODE OF CLIMATE CHANGE

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INTRODUCTION

The recognition of orbital cyclicity in the geologic record and its linking with cyclic variations in Earth's orbital parameters has been instrumental in improving our understanding of climate change. The Ocean Drilling Program (ODP) has provided the paleoceanography and paleoclimate community with an outstanding archive of high quality sediment records that allows climate variability to be documented throughout the Cenozoic and beyond. In the past two decades, orbital "fingerprinting" has advanced from the simple detection of cyclic signals in spectral diagrams to the development of complex ocean and climate evolutionary models (Fig. 1). Such models allow prediction and study of paths along which orbital signals propagate through the chain of ocean-climate subsystems.

THE PLEISTOCENE PERIOD: THE GRAND PICTURE OF ORBITAL FORCING

Much of the climatic cyclicity that is documented in the marine sedimentary record for the past one million years can be explained by linear responses of climate to

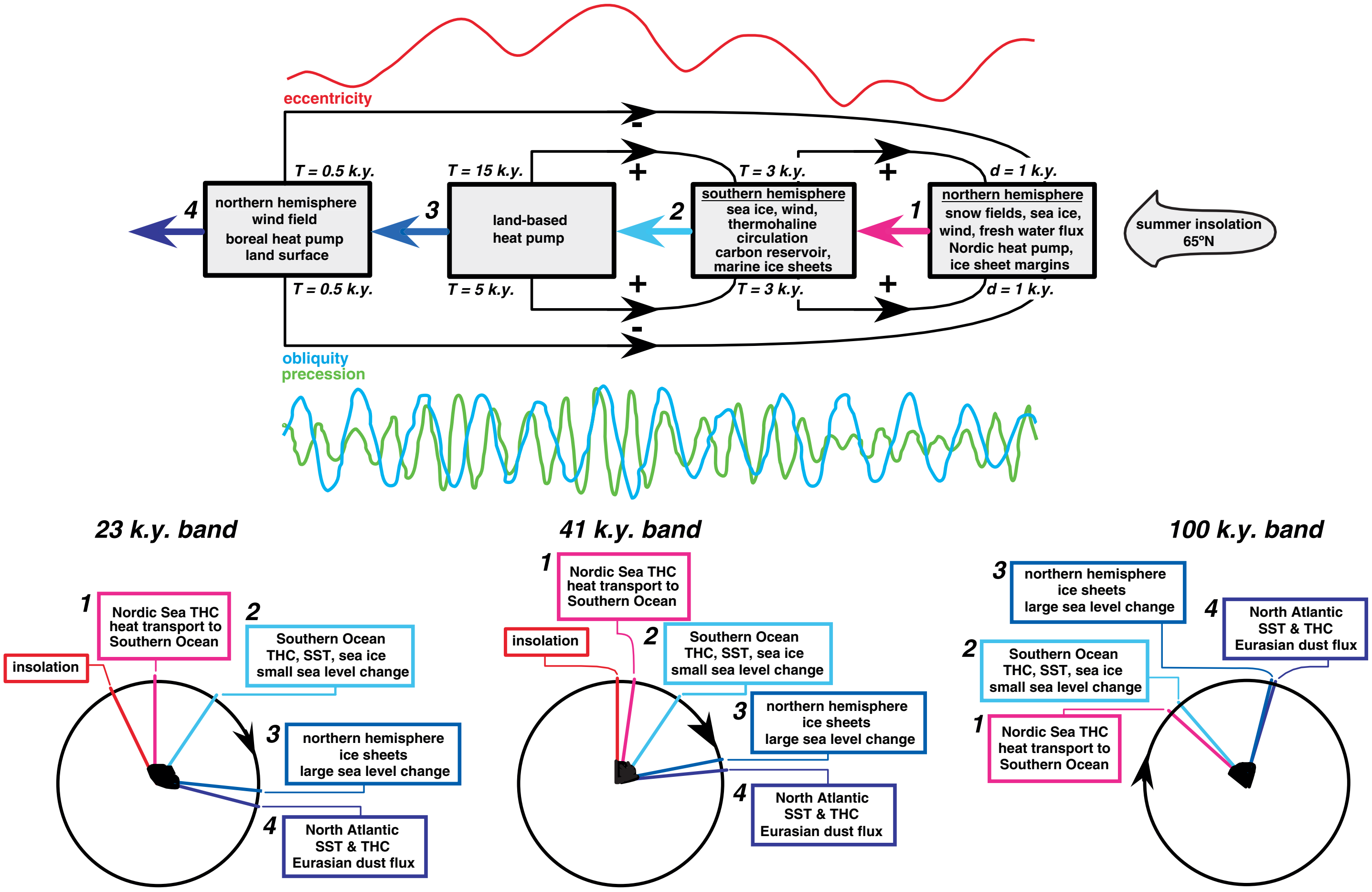

Figure 1. Propagation of orbitally-induced climate signals generated by incoming summertime insolation at 65°N at the main Milankovitch periodicities of eccentricity, obliquity and precession. Top panel: Ocean, land, atmospheric and inter-hemispheric climate component inertia are expressed in time constants (T) and delay time (d). Bottom panel: Phase relations of individual climate component responses relative to orbital forcing. The signal propagation scheme is derived from time-series analysis of paleoceanographic records that represent key variables involved with ocean-climate changes. The Arctic Ocean and Nordic Sea lead the field of response groups and hint at a role for thermohaline overturn in the northern North Atlantic as a primary transmitter of climate signals through the entire climate system. After Imbrie et al. (1992; 1993).

the 41,000-year orbital obliquity and 23,000-year orbital precession cycles. This conclusion has not remained unchallenged (e.g., Winograd et al., 1992). Other mechanisms have been invoked to explain some of the climatic variations (Muller and MacDonald, 1997) but the Milankovitch theory of climate change today receives more support than ever before. After nearly fifteen years of research into the role that orbital forcing plays in driving glacial-interglacial climatic cycles, marine paleoclimatologists summarized their findings in two comprehensive papers (Imbrie et al., 1992; 1993). These studies involved time-series analysis of paleoceanographic records spanning the past 800,000 years from geographically distributed coring sites.

A prominent outcome of this exercise was that climatic signals in the 23,000-year and 41,000-year bands of cyclicity contained in the records reflect a linear response of climate to orbitally modulated solar radiation. In addition, it was found that temporal relations between spectral peaks for time-series from the different coring sites could be used to examine leads and lags of individual climate components, and to map signal propagation pathways. This documentation of the phase sequencing led to a detailed picture of signal propagation through the combined ocean-climate system (Fig. 1). The pattern of responses that dominates the suite of records points to an early response to solar forcing of high northern latitudes. Climatic signals then propagate along a global path from high northern latitudes through a chain of subsystems that all have their own response times and patterns. An important outcome of these studies is recognition of the carbon cycle being intimately involved in orbitally paced climate changes. The active role of the ocean's thermohaline circulation in modulating climate change is particularly evident from these studies, a view that is supported by numerical paleomodeling which predicts amplification of the weak orbital forcing by strong positive oceanic feedbacks.

A long-standing enigma of the orbital theory of climate change is the prominent 100,000-year cyclicity observed in paleoceanographic records in the later part of the Pleistocene. While the phase sequence of signals contained in this frequency band appears to be geographically similar to those of obliquity and precession, insolation variations arising directly from orbital eccentricity variations are too weak to produce the 100,000-year climate cycles that dominate records of the past one million years. Thermohaline forcing through changes in deep water temperature has been proposed as one possible driver of the 100,000-year climatic cycle (Imbrie et al., 1993). Another viable source for the thermal energy needed to make ice sheets grow and decay is contained in the changing concentrations of greenhouse gases in the atmosphere. Support for a dominant greenhouse forcing of the 100,000-year climate cyclicity is derived from fine-scale cross-correlation of ice core paleoclimatic records with the marine $\delta^{18}O$ record. Using the ice core atmospheric $\delta^{18}O$ record as the correlation target for synchronizing ice core paleo-climatic records with the marine $\delta^{18}O$ record makes a strong case for ice volume lagging behind, and therefore responding to, atmospheric CO_2 changes in the 100,000-year cyclicity band (Shackleton, 2000). This reduces the 100,000-year cyclicity in marine records to a mere response function to atmospheric greenhouse forcing and disqualifies ice sheet dynamics in favor of atmospheric CO_2 as a primary player in driving the longer-term cycle of glacial-interglacial climatic change.

THE PRE-PLEISTOCENE PERIOD: PIECES OF THE PUZZLE

Much of the intricate picture that links ocean and climate change to orbital forcing evolved from records that span the last one million years. This reflects the large number of records available for this time period and the general interest of the paleoceanographic community in Quaternary ice ages in the 1980s. With the advent of improved ODP piston coring equipment, and on the basis of insight gained from the Pleistocene work, the interest of the community then shifted to older, pre-Pleistocene periods. The increasing availability of long, high-quality ODP cores made it possible to monitor spectral signals and phase sequences during the pre-Pleistocene both as a function of latitude and water depth. Paleoceanographic drilling legs have increasingly been designed as depth transects in which drill sites are spread across several thousand meters of water depth in a geographically restricted area. This strategy has proven very successful in that it has allowed synoptic mapping of water column variability through time and tracing of the differential response of surface-water vs. deep-water masses to orbital forcing.

Examples of open ocean depth transects are the drilling transects undertaken at Ontong Java Plateau (Leg 130) and Ceara Rise (Leg 154). Other regional paleoceanographic transects that expanded our knowledge of pre-Pleistocene ocean and climate variability and its linking with orbital forcing were the drilling campaigns of Leg 108 (Eastern Tropical Atlantic), Legs 113/120 (Weddell Sea/Kerguelen Plateau), Leg 117 (Oman Margin), Leg 138 (Eastern Equatorial Pacific), Leg 145 (North Pacific Transect), Legs 151/162 (North Atlantic-Arctic Gateways I, II), Leg 155 (Amazon Fan), Legs 160/161 (Mediterranean I, II), Leg 165 (Caribbean Ocean History), Leg 177 (Southern Ocean Paleoceanography), and Leg 181 (Southwest Pacific Gateways).

The common denominator to the scientific results from these legs is that orbital frequencies have been traced in paleoceanographic records back through the Cenozoic and beyond. Examples of the diverse regional and global processes targeted for study include coastal and open ocean upwelling regimes that fall under the control of trade winds and monsoons, variations in thermohaline overturn at high latitudes and their linking with thermal forcing and climatically modulated freshwater budgets, and past changes in ambient water mass chemistry linked to deep-ocean ventilation and local fluxes of biologically cycled nutrients. The records generated from these legs are almost unfailingly coherent with obliquity and precession and demonstrate that orbital forcing has exerted a primary control on climate throughout the Cenozoic.

Using the latest astronomical solutions for the quasi-regularity of planetary motion in our solar system, the orbital parameters can be calculated back in time over periods of several 10^7 years. Fine-scale paleoclimatic and sedimentary records from ODP sites and land sections have been used to calibrate the astronomical solutions back to 25 million years (m.y.) (e.g., Hilgen et al., 1999; Pälike and Shackleton, 2000). Such studies extended the geologically calibrated astronomical time series back to the mid-Cenozoic when physical boundary conditions that infringe on the behaviour of the climate system were distinctly different from today's.

The Miocene is widely considered a period in which the occurrence of continental ice sheets was limited to regionally restricted areas on Antarctica. Fine-scale benthic δ^{18}O records from late Oligocene to early Miocene sections at Sites 926 and 929 (Leg 154, Ceara Rise) show a distinctive cyclic pattern that mirrors orbital eccentricity and obliquity, underscoring the importance of orbital forcing at times when large ice sheets did not exist on our planet (Zachos et al., 2001). A transient period of glacial expansion, the so-called Mi-1 event 23.2 to 22.8 million years ago (Ma), proves a welcome test case to assess the contribution of orbitally modulated solar radiation to climate change under the non-analog conditions at the Oligocene-Miocene boundary. The event coincides with a 200,000-year long period of reduced variation of orbital obliquity that is paralleled by a prolonged minimum in orbital eccentricity (Fig. 2). This orbital configuration promotes an extended period of reduced seasonal insolation variations that results in warmer winters but, more importantly, at the same time causes summers to be colder. The resultant decrease in summer melting promoted the gradual buildup of ice volume and, ultimately, glacial expansion. Ice growth came to a halt and large-scale melting set in when orbital eccentricity and obliquity amplitudes started to increase around 22.9 Ma, which caused insolation during polar summers to increase and the extra ice that accumulated during the preceeding 200,000 years to swiftly melt away.

Abundant evidence now exists that orbital forcing was a key player in climate change during the Cenozoic, but orbitally modulated fluctuations of solar irradiance alone cannot explain the longer-term evolution of climate. An important component in the long-term Cenozoic cooling trend was plate tectonics and its influence on mountain uplift and ocean circulation. The gradual uplift of the Himalayas, for instance, has been directly linked with the rerouting of atmospheric flow paths and the onset of monsoonal circulation over the Indian Ocean (Ruddiman et al., 1997). The reconfiguration of oceans and continents, notably the opening and closure of oceanic gateways and associated changes in thermohaline circulation and heat transport, likewise played a role in setting the stage for global climate

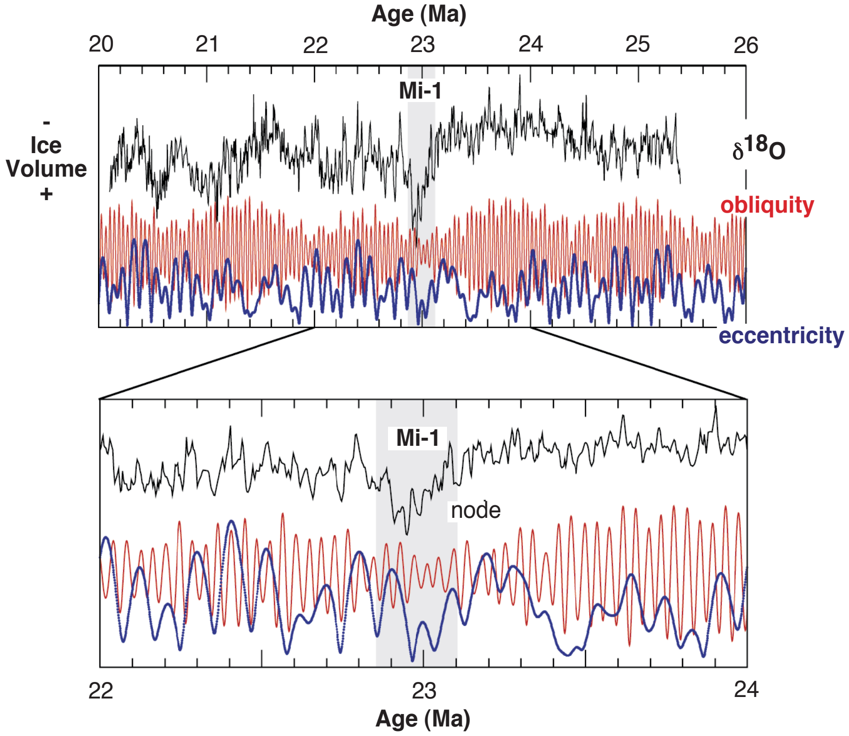

Figure 2. Orbital modulation of climate across the Oligocene/Miocene boundary documented in a benthic foraminiferal isotope record at ODP Site 926, Ceara Rise. Transient expansion of Antarctic ice volume during 23.2 to 22.8 Ma, the Mi-1 event, coincides with minimum orbital eccentricity and minimum obliquity amplitudes. A prolonged period of low climatic seasonality favored ice sheet growth because of reduced summer melting. The Mi-1 event serves as an example that transient climatic anomalies during the Cenozoic may be forced by rare but re-occurring orbital configurations that promote cold summers. From Zachos et al. (2001).

change. Early, ground-breaking studies linked Northern Hemisphere glacial expansion between 3.2 and 2.7 Ma with the closure of the Panama Gateway, which led to the full development of the Gulf Stream Current (Keigwin, 1978; 1982). As the theory holds, this provided the high-latitude Northern Hemisphere with sufficient moisture to allow ice sheets to expand. A notable outcome of ODP Leg 165 in the Caribbean expanded on the earlier insights in that fine-scale paleoceanographic records documented the contribution of orbital forcing to ocean and climate change during this period (Haug and Tiedemann, 1998). Closure of the Panama gateway overlapped with a node point in the amplitude modulation of orbital obliquity in such a way that intensification of Northern Hemisphere glaciations was coeval with an increase in amplitude of the orbital obliquity cycle (Fig. 3). Such increases translated into greater seasonal variability and, ultimately, increasingly colder summer climates that enabled a steady growth of ice sheets as summer melting was progressively reduced. This event set the stage for full-scale glacial-interglacial climatic changes that began some 1.5 m.y. later and dominated the late Pleistocene. Importantly, the mid-Miocene climatic history acted upon the evolution and cultural development of early hominids (Fig. 3; deMenocal, 1995). The advent of more arid, open conditions in subtropical Africa after 2.8 Ma promoted hominid speciation and thus provided for an important environmental stimulus in the progression of human evolution.

ORBITAL FORCING: QUO VADIS?

The past two decades have seen profound advances in our understanding of the linkage between orbital forcing and climate change. The success that the

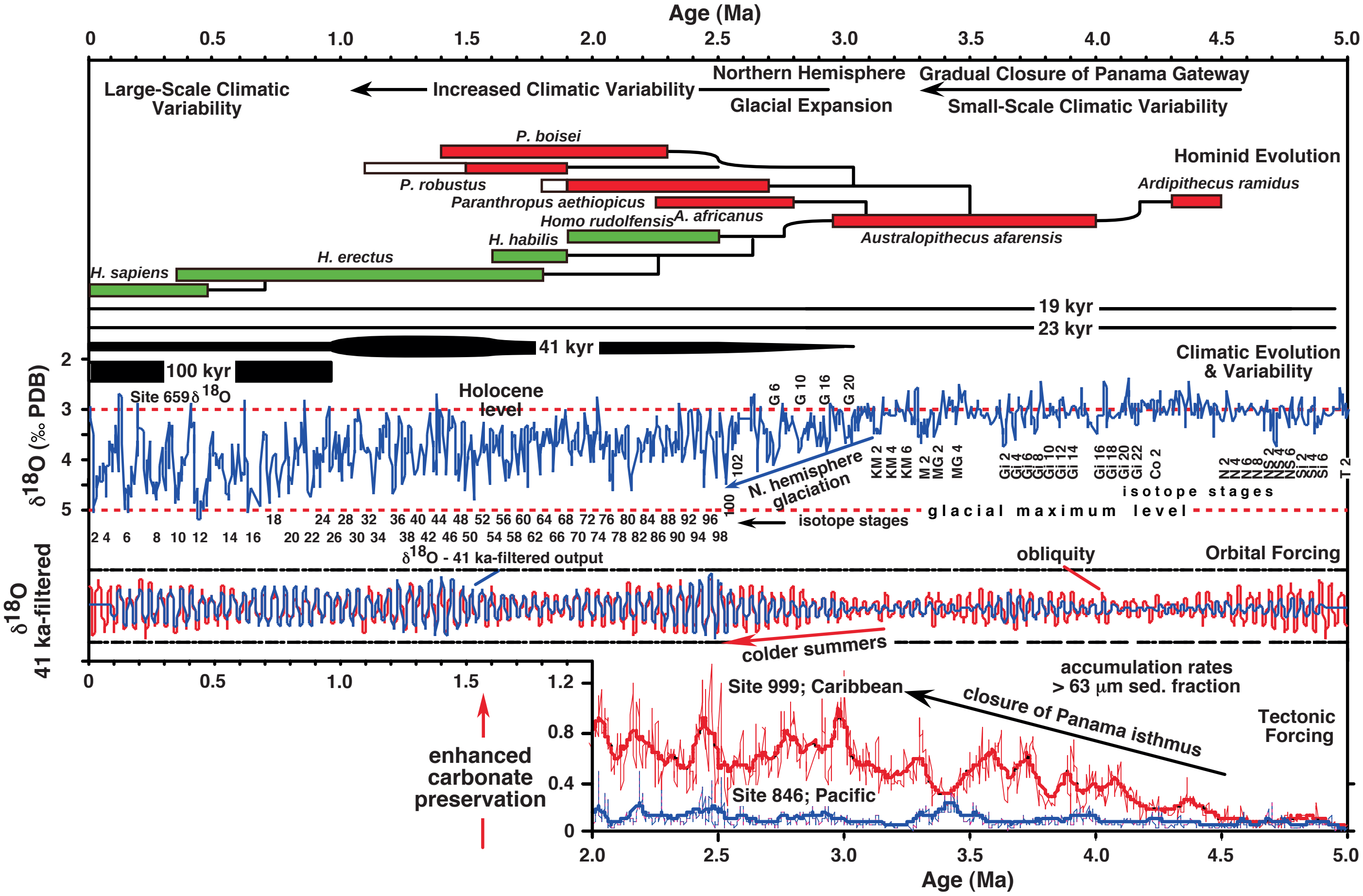

Figure 3. Climatic evolution over the past 5 Ma as seen in the benthic oxygen isotope record from ODP Site 659 (Tiedemann et al., 1994). Orbital forcing is visualized in the filtered signal of the isotope record that is coherent in period and amplitude modulation with the orbital input function. Northern Hemisphere glacial expansion 3.2 to 2.7 Ma coincides with progressively increasing amplitudes in orbital obliquity after the obliquity node at 3.3 to 3.1 Ma. The bottom panel shows sand fraction records from ODP Site 999 in the Caribbean and Site 846 in the eastern equatorial Pacific (Haug and Tiedemann, 1998). The gradual divergence between both records signifies enhanced basin-to-basin chemical fractionation that led to enhanced preservation of carbonate on the Atlantic as a consequence of Panama gateway closure. Top panel shows how hominid speciation in Africa followed the climatic change in response to intensified Northern Hemisphere glaciation and enhanced aridity in subtropical Africa (deMenocal, 1995).

Milankovitch theory has witnessed over recent years to a large extent was made possible by the ODP, which not only provided the coring technology necessary to retrieve long, high-quality sediment cores but also functioned as a primary platform for international, multidisciplinary collaboration. Despite the many successes and advances, there is still much to be learned. General circulation modeling, for example, and frequency demodulation of paleoceanographic records suggest the tropical ocean may act as an amplifier of orbital forcing on global climate (Clement et al., 1999; Rutherford and D'Hondt, 2000). Yet, the long-term evolution of the tropical ocean in general, and of the El Niño/Southern Oscillation in particular, on Cenozoic time scales is only marginally known. The important role of the tropical ocean in climate change is underscored by modeling studies that test the sensitivity to tropical sea surface temperatures of early Cenozoic greenhouse climates (Huber and Sloan, 2000). These models provide valuable guidance in refining paleoclimatic research strategies and defining localities in the tropical ocean for future drill sites that are particularly sensitive to climate change.

Analytical techniques have become available in recent years to measure stable carbon isotope ratios of molecular organic compounds and boron isotope ratios in foraminifera. These data enable the reconstruction of atmospheric pCO_2 back to the Miocene and Paleocene (e.g., Pearson and Palmer, 2000). Sedimentological studies have derived grain-size parameters that provide a direct link to the physical flow speed of near-bottom currents, thus extracting information from the sediment record on physical circulation, as opposed to chemical ventilation, of the deep ocean (Robinson and McCave, 1994; Hall et al., 2001). Nitrogen isotopes are now being used to decipher the ocean's nutrient inventory and water column denitrification in association with the glacial-interglacial history of nutrient flux and strength of oxygen minimum zones (Ganeshram et al., 2000). These and other novel methods and techniques quantitatively trace marine, terrestrial and atmospheric parameters that are relevant to climate. They directly complement isotope, faunal and sedimentological methodologies that are firmly embedded in the repertoire of routine paleoceanographic measurements. Advances in core logging tools today allow screening of cores and production of sedimentological records of unprecedented quality at a stratigraphic resolution that will for some time remain beyond what can realistically be achieved by more time consuming routine and novel analytical paleoceanographic methodologies. The new logging methods and analytical instruments need to be standardized to enable wider application at high resolution, and to document the orbital signature of these parameters and, more importantly, their phasing in relation to orbital forcing under an array of different climatic boundary conditions.

The ever-increasing stratigraphic resolution of paleoceanographic records enables us to trace orbital cyclicity as far back in the geological record as the Cretaceous, Jurassic, and even Carboniferous. According to traditional thinking, these were periods of climatic stability. The gradually evolving evidence has shown this concept of stability to be far too conservative, and has increasingly attracted attention to the Mesozoic and Paleozoic history of climate change. The future Integrated Ocean Drilling Program (IODP), with its multiple platforms, will be ideally suited to lead the way into these uncharted territories, and to provide the high-quality sediment cores required to decipher the orbital code of climate change for the distant past in Earth's history.

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THE ROLE OF ODP IN UNDERSTANDING THE CAUSES AND EFFECTS OF GLOBAL SEA LEVEL CHANGE

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> "Much of the record of historical geology from Cambrian time onward has been that 'the seas came in and the seas went out.'"
>
> *P.B. King, 1959, The Evolution of North America: Princeton, NJ, Princeton University Press, p. 6*

ODP AND THE SEA LEVEL PROBLEM

The Ocean Drilling Program (ODP) continues to pursue the long-standing challenge of understanding global sea level (eustatic) change and its effects on the stratigraphic record. Scientists and non-scientists agree that changes of this fundamental boundary between land and sea have profound impacts on the distribution of sediments, sources of mineral and water resources, the stability of nearshore ecosystems, and the safety of shoreline population centers. Therefore, understanding the rates, magnitudes and mechanisms controlling sea-level change has direct societal relevance. Determining this information is a challenging task because eustasy is complexly intertwined with the interacting effects of local basin history, sediment supply, and climate.

Oxygen isotopic measurements of deep-sea foraminifers provide a proxy of global sea level changes caused by the waxing and waning of continental ice sheets. The Deep Sea Drilling Project (DSDP) and ODP recovered long, continuous Cenozoic deep-sea sections suitable for $\delta^{18}O$ studies. However, the $\delta^{18}O$ record is a function of both temperature and ice volume changes; glacio-eustasy can be estimated only by assuming a thermal history. Consequently, it is necessary to calibrate this deep-sea proxy with a more direct record of sea level change.

Another method for deriving past sea levels is to use tropical coral reef and atoll records. The growth surfaces of ancient coral reefs provide a close approximation of sea level ("fossil sunshine") and reef records provide an excellent record of rising sea levels (e.g., Fairbanks, 1989). However, reef growth ceases during sea level falls, and the resultant karst surfaces are less useful for deriving a sea level history. Reef records also can be difficult to core and date successfully from a dynamically-positioned drillship such as the *JOIDES Resolution*.

Continental margins contain an extremely long (billion year) sedimentary record that directly records the effects of sea level change. However, the margin record is complicated by tectonics (subsidence/uplift) and changes in sediment supply. Sea level falls and tectonic changes both produce discrete, unconformity-bounded units on continental margins known as sequences. Sequences are the fundamental building blocks of the stratigraphic record. Researchers at Exxon Production and Research (EPR) made a revolutionary breakthrough in using seismic reflection profiles to identify sequences, an assumption tested by ODP, and to produce eustatic estimates using stratigraphic records (e.g., Vail et al., 1977).

Publication of the EPR sea level curve in the late 1970s spurred interest in eustatic history. DSDP first ventured into the sea level game by drilling the Irish (Leg 80) and New Jersey (Legs 93 and 95) passive continental margins specifically to test the "Vail curve". Whereas these legs were successful in dating sequences, they were relegated to water depths >1000 m, far from direct stratigraphic effects of sea level change at shallower depths. In the meantime, researchers at EPR broadened the application of sequence stratigraphy to include outcrop, well, and seismic studies. This effort greatly increased the number of potential Triassic to Recent sea level events, and produced a second generation sea level curve (e.g., Haq et al., 1987). The pioneering work of EPR remained controversial because the fundamental methods used to produce the curves were in question (e.g., Christie-Blick et al., 1990; Miall, 1991), and their database was largely proprietary.

In the early days of ODP, the community realized that integrated studies with publically available data sets were needed to evaluate eustatic changes. COSOD II (July 1987), a JOI/USSAC Workshop (1989), and the JOIDES Sea Level Working Group (1992) all recognized that sea level studies require a global array of data obtainable from ocean drilling. These groups identified four goals: 1) test the synchrony of sea level events; 2) estimate the amplitudes of changes; 3) evaluate various models that seek to explain the stratigraphic response to sea level oscillations; and 4) determine the mechanisms that control sea level. They recommended a three-fold approach to sea level studies, incorporating data from passive continental margins transects, deep-sea $\delta^{18}O$ records, and reef terraces and atolls. One recommendation was to compare sea level changes during the Oligocene to Recent "Icehouse World," when glacio-eustatic changes were clearly operating, and the older mid-Cretaceous to Eocene "Greenhouse World," a time that was then thought to be ice-free.

To address these issues, ODP had to drill in settings that were technically difficult for the *JOIDES Resolution*:

shallow-water, thickly sedimented continental shelves. Dynamic positioning within 3% of ambient water depth required by pipe strength is difficult in shallow water. Maintaining a 470-ft drillship in position over a target to ±1 to 3 m is a challenge even in the days of differential Global Positioning System (GPS) satellites. Hole stability in caving sands demands setting long casing strings, a virtually impossible task in such shallow water from a floating platform. Most importantly, drilling without blowout prevention in this environment demands addressing stringent safety and pollution prevention issues.

ODP accepted these challenges and ventured into shallow water, using the siliciclastic margin off the east coast of the U.S. as its test case. Leg 150 was designed to drill the New Jersey continental shelf and slope, targeting Miocene prograding, clinoformal sequences. However, safety considerations relegated actual efforts to the slope. The leg was successful in firmly dating Eocene to Recent sequences that were then tied to the deep-sea $\delta^{18}O$ proxy (Fig. 1; see summary and Fig. 7a in Miller et al., 1998). Despite this success, the lack of direct information on shallow-water facies precluded estimates of sea level amplitudes from Leg 150 drilling.

ODP demonstrated flexibility and innovation after Leg 150 by approving shallow shelf drilling during Leg 174A after an intense safety evaluation. Several sites into Pleistocene-uppermost middle Miocene strata on the New Jersey outer shelf sampled a few critical facies, and it was shown that the breakpoint or rollover approximates a paleo-shelf edge in 30 to 40 m of water. Another exciting result was the sampling of very thick (~550 m) marine Pleistocene sequences on the upper slope that were traced landward to the shelf boreholes where shallow-water strata were also sampled. However, Leg 174A was limited by poor recovery and lost bottom hole assemblies due to caving sands.

Recognizing that sea level objectives require transects across margins, ODP endorsed drilling onshore as part of an integrated study. Leg 150 slope drilling was

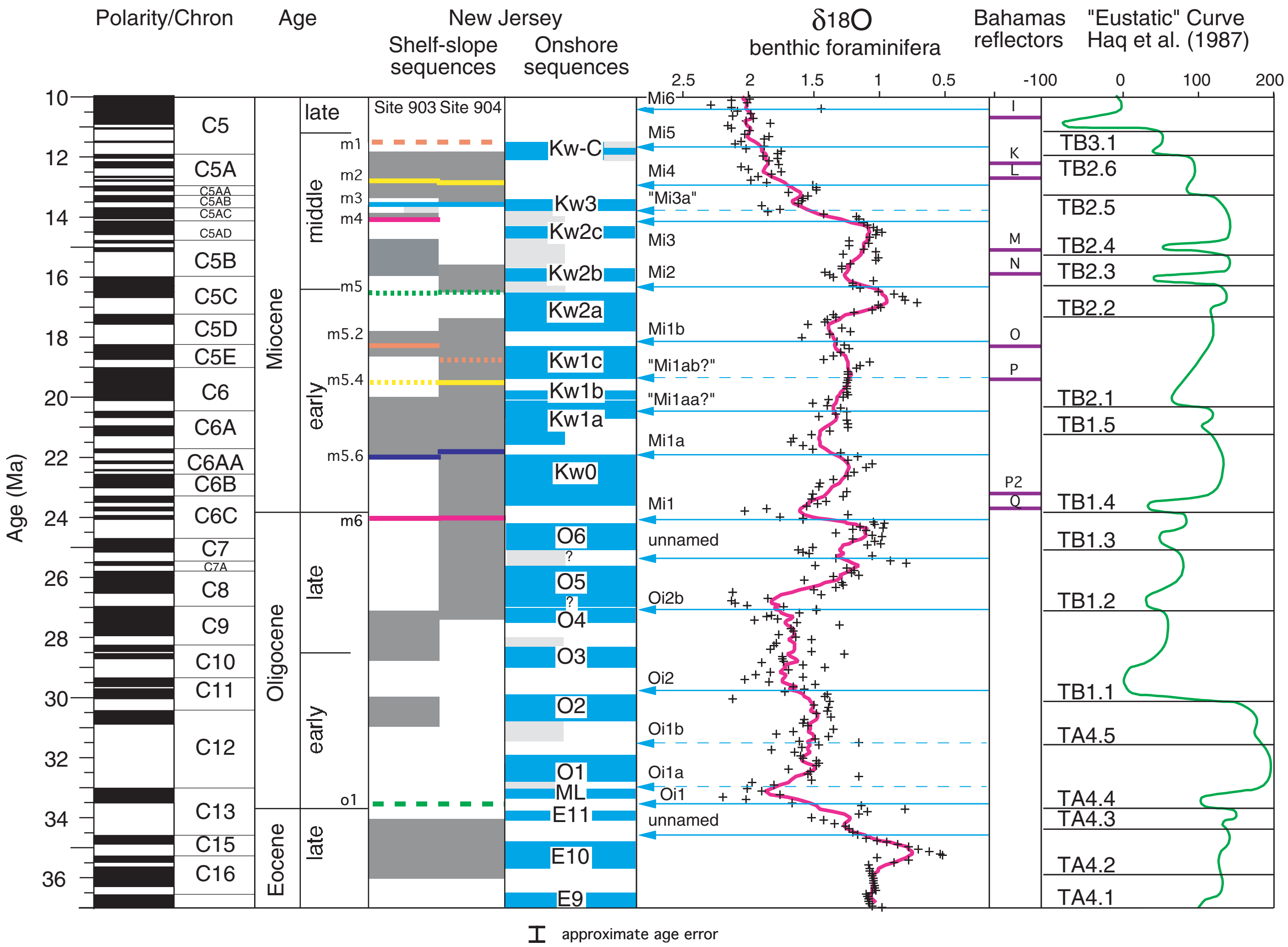

Figure 1. *Revised age comparison of Oligocene-Miocene slope sequences, onshore sequences, oxygen isotopes, Bahamian carbonate margin reflections, and the inferred eustatic record of Haq et al. (1987). After Miller et al. (1998).*

coupled to an onshore New Jersey drilling program, "Leg 150X." The ability to use telescoping casing strings, make short coring runs, and control weight-on-bit resulted in high core recovery despite the coarse-grained, unconsolidated sediments. This onshore "leg" sampled critical updip facies (Miller et al., 1998) that correlated with sequences on the slope (Fig. 1) and, with the $\delta^{18}O$ proxy of glacio-eustasy (Figs. 1 and 2), demonstrated not only that the sequences were regional, but also tied to a global proxy. Onshore New Jersey drilling continued with Leg 174AX drilling. One surprising result was that the Late Cretaceous to Eocene might not have been ice-free, as was previously widely assumed because sequence boundaries correlated with evidence for $\delta^{18}O$ glacio-eustatic lowering (Fig. 2). Studies of onshore boreholes provided estimates of eustatic variations using one- and two-dimensional backstripping (Kominz and Pekar, 2001; Fig. 3). Nevertheless, onshore drilling only sampled updip facies and missed critical lowstand deposits that are now buried beneath the continental shelf. Sampling these facies will probably require a supplementary drilling platform such as a jack-up rig.

While ODP was struggling to drill on heavily sedimened siliciclastic margins, drilling also was proceeding on carbonate margins along Australia, the Bahamas, and isolated northwest Pacific atolls. Legs 143 and 144 targeted the sea level records contained within atoll carbonate platforms in the northwest Pacific, but drilling operations were plagued by poor core recovery. However, downhole log records were used in conjunction with available core to demonstrate the existence of sea level fluctuations during the Cretaceous, although evidence of eustatic control is equivocal.

ODP drilling has been successful in dating sequences on carbonate margins, particularly in the Bahamas during Leg 166. Despite the differences in sedimentation style between carbonate and siliciclastic margins, ODP drilling documented that similar-aged unconformities occur in the Miocene in both carbonate (Australian and

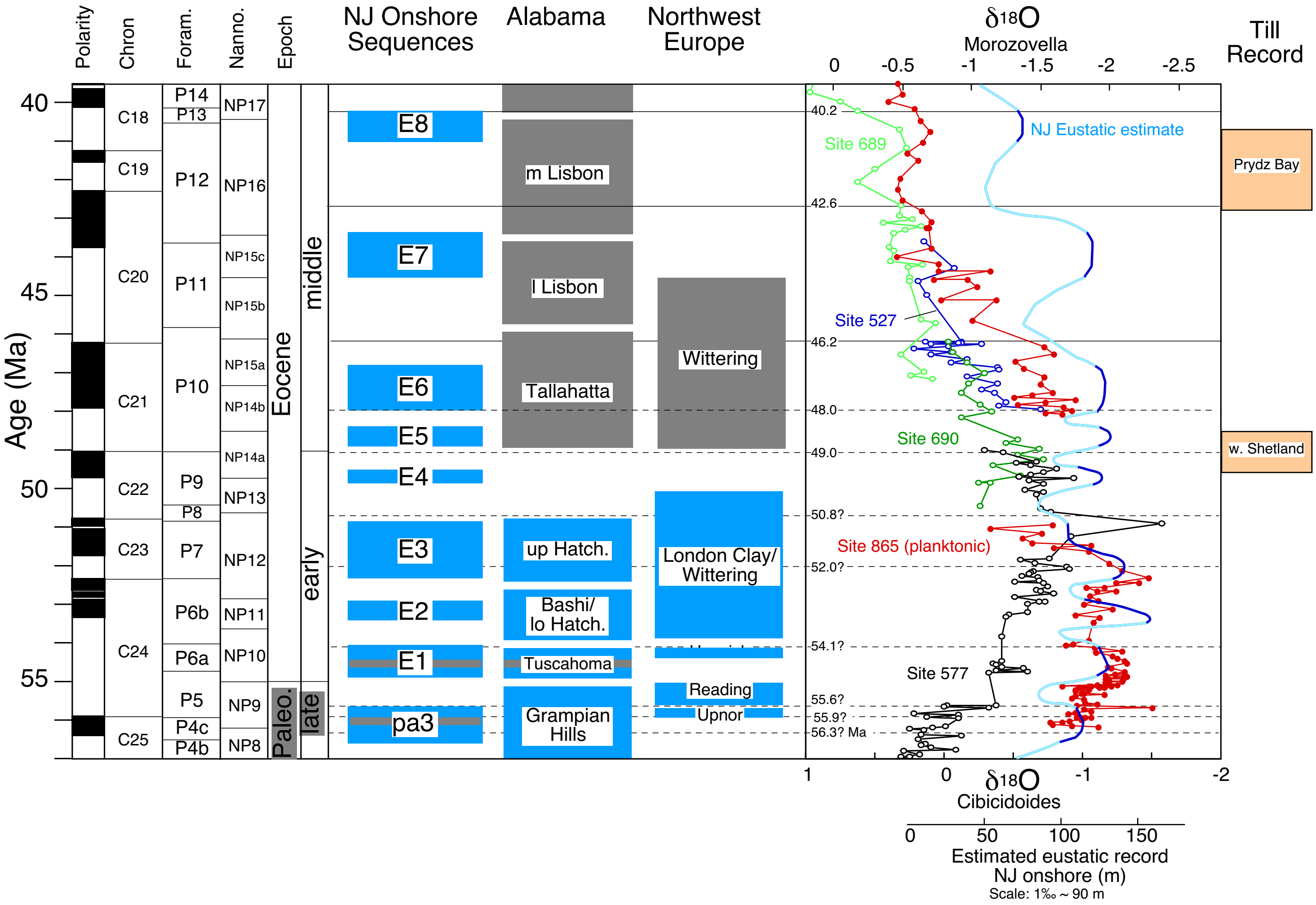

Figure 2. Comparison of Eocene onshore sequences (New Jersey, Alabama and northwest Europe), oxygen isotopes, New Jersey backstripped estimates, and till records in high southern latitudes. Blue boxes indicate time represented by sediments. Gray boxes indicate uncertain chronology. Modified by J.V. Browning and K.G. Miller (in prep.) after Miller et al. (1998) using backstripped estimates of Kominz et al. (1998; dark blue segments of NJ eustatic estimate curve in right panel) and scaling the lowstands (hiatuses onshore) to the oxygen isotopic record.

Bahamas) and siliciclastic (New Jersey) settings (Fig. 1). Bahamas drilling during Leg 166 and supplementary platform drilling also showed that a carbonate bank flank environment could develop sequences that are remarkably similar in character to those characterizing siliciclastic margins.

Drilling off Australia has provided insight into the effects of sea level change on the development of carbonate margins and platforms. Leg 133 demonstrated that eustatic fluctuations, paleoceanography, and subsidence controlled the initiation, growth, and demise of the Queensland Plateau, Great Barrier Reef, and Marion Plateau. Sequences seaward of the Great Barrier Reef slope contain a thick record of cyclically-deposited mixed carbonate-siliciclastic sequences. Deposition was controlled by sea level fluctuations modulated by the formation of the barrier reef system near the shelf edge (Feary et al., 1993). Leg 182 along the western Great Australian Bight was designed primarily to study cool-water carbonates, including evaluating the effects of sea level. It provided excellent Pliocene to Pleistocene records of a prograding carbonate shelf, documenting that sediment transport from the shelf to slope occurred during sea level falls, and that development of bryozoan-dominated mounds, the cool-water equivalents of coral reefs, occured only during lowstands (James et al., 2000). Leg 194 specifically targeted the amplitude of sea level change and was successful in providing an estimate of a major late middle Miocene eustatic lowering of 30 to 86 m.

ODP ACHIEVEMENTS

Planning of and drilling during ODP Legs 133, 150, 150X, 166, 174A, 174AX, 182, and 194 resulted in the following accomplishments:

1) Proved that the age of sequence boundaries on margins can be determined to better than ±0.5 million years (m.y.) and provided a chronology of eustatic lowering for the past 42 m.y. (Figs. 1 and 2);
2) Validated the transect approach of drilling passive continental margins and carbonate platforms (onshore, shelf, slope); future work should consider three-dimensionality by drilling of arrays (transects both perpendicular and parallel to depositional dip);
3) Tested and validated the assumption that the primary cause of impedance contrasts producing

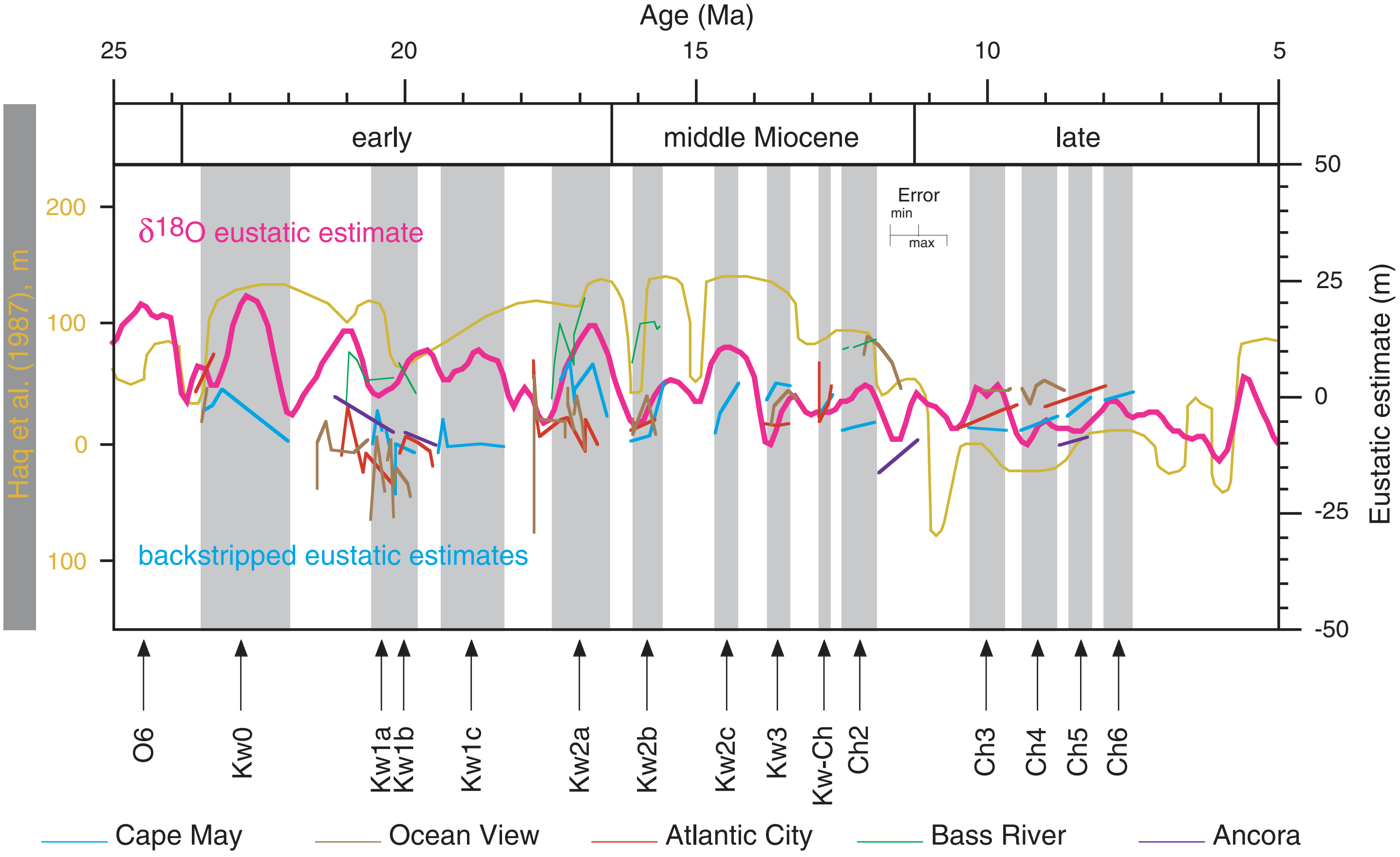

Figure 3. *Comparison of backstripped eustatic estimates from the New Jersey coastal plain (Legs 150X and 174AX; modified from Kominz et al., 1998) with an estimate using oxygen isotopes and the Haq et al. (1987) record. Note that the Haq et al. (1987) amplitudes are scaled to be one-quarter of the New Jersey and oxygen isotopic estimates (Miller et al., 1999; K.G. Miller, M.A. Kominz, J.D. Wright, and J.V. Browning, in prep.)*

seismic reflections on continental margins are stratal surfaces including unconformities;

4) Demonstrated that middle Eocene-Miocene sequence boundaries correlate with $\delta^{18}O$ increases, linking the formation of sequence boundaries to glacioeustatic lowerings (Figs. 1 and 2);
5) Provided evidence that Late Cretaceous to middle Eocene times may have had small- to moderate-sized ice sheets (30% of modern ice volume), in addition to the moderate to large ice sheets of the past 42 m.y.;
6) Showed that siliciclastic and carbonate margins yield correlatable, and in some cases comparable, records of sea level change (Fig. 1);
7) Evaluated the sedimentary response of both tropical and cool-water carbonate platforms to eustatic changes;
8) Provided preliminary amplitude estimates of approximately 20 to 85 m for m.y.-scale variations from the New Jersey margin that agree with oxygen isotopic estimates (Fig. 3), although they may be less than the best estimates derived from carbonate environments (30 to 86 m); and
9) Achieved orbital-scale, and, perhaps, suborbital-scale, stratigraphic resolution on continental slopes and carbonate platforms.

THE FUTURE

The ODP has provided a chronology of sea level changes for the past 42 m.y., established a causal link between sequence boundaries on margins and eustatic lowerings, and made progress toward estimating eustatic amplitudes. Although the ODP has drilled the New Jersey, Bahamas, and Australian margins, a lack of shallow-water drilling capability continues to limit understanding of global sea level change and sedimentary architecture. As a result, there are fundamental uncertainties in the rates, amplitudes, and mechanisms, for, and response to, eustatic change.

Rates of Sea Level Change

Though atoll drilling in Barbados has provided a detailed record of the rapid rise in sea level since 18,000 years ago (Fairbanks, 1989), the maximum rates of rise remain uncertain. The Barbados record contains two rises of >30 m in one thousand years each, but other records indicate that rates may have been even faster. Drilling suitable targets on passive margins should resolve the rates of these millennial-scale changes, both in the Holocene and in the older record.

Amplitudes

Despite ODP's success, the amplitude of sea level change remains one of the thorniest problems in reconstructing past boundary conditions of the Earth. ODP has demonstrated that the 400 m eustatic variations published by Vail et al. (1977) or even the >140 m variations published by Haq et al. (1997) are excessive. However, even in the Miocene, an interval sudied during six legs, amplitudes remain uncertain, ranging from 20 to 80 m to 30 to 86 m. Nevertheless, results of drilling for amplitude determination are encouraging, and it is clear that drilling arrays of boreholes on different margins in different settings will allow two- and three-dimensional backstripping that will undoubtedly provide firmer constraints on the amplitudes of eustatic change.

Mechanism

While ODP has confirmed the importance of glacioeustasy since 42 million years ago, other mechanisms were undoubtedly operative. For example, intra-plane stress has been invoked as a possible mechanism explaining eustatic change (e.g., Cloetingh, 1988). Borehole arrays on margins targeting stratigraphic intervals with large global tectonic events can be used to evaluate this mechanism and other non-glacioeustatic components. This approach may be particularly important for evaluating eustatic mechanisms for portions of Earth history that were essentially ice-free.

Using ODP drilling, we have pushed back the age of inception of continental glaciation into the Paleogene and possibly the Late Cretaceous. There are intervals such as the mid-Cretaceous through Triassic, for example, that must have been ice-free. Yet, large (>>10 m) and rapid (<< 1 m.y.) changes in sea level occurred during these intervals, not only as suggested by EPR workers (Haq et al., 1987), but also documented by others (e.g., Hallam's (1992) summary). The only known mechanism for causing these changes is glacioeustasy. Additional potential mechanisms can be evaluated by comparing estimates of Cretaceous-early Eocene sea level variations with near- and far-field tectonic events, global $\delta^{18}O$ records, and other possible causal events (e.g., basin dessication, large igneous province formation).

Response

As we increasingly understand eustatic variations, we can begin to understand the interaction of processes that control margin stratal architecture, the geometry of stratal surfaces including sequence boundaries and intrasequence stratal patterns. Nested acoustic images of continental margins reveal surfaces and seismic facies on various scales that reflect variations in eustasy, tectonics, and sediment supply. These effects can be evaluated by drilling margin sequences in different tectonic and sedimentary settings. The influence of tectonics can be evaluated by comparing the development of coeval sequences on passive margins, translational margins, and foreland basins. Facies models developed by EPR (Posamentier et al.,

1988) and others potentially provide a means of predicting the distribution of sediments within sequences and resources such as oil and water. To develop and test predictive facies models, sequences and facies within sequences must be sampled on carbonate, mixed carbonate-siliciclastic, and siliciclastic margins across a wide spectrum of sediment inputs.

SEA LEVEL AND IODP

Ongoing efforts to understand global sea level changes and their effects on the stratigraphic record will require continued innovation and the use of new drilling tools. Despite valiant efforts, the *JOIDES Resolution* and its successor, a dynamically-positioned riserless drillship, will not be suitable platforms for drilling in shallow water and setting long casing strings. Supplementary alternative platforms such as jack-up rigs, semi-submersibles, and anchored geotechnical drillships will provide the right tools. The success of this approach was demonstrated by the Bahamas Drilling Project, an integral component of Leg 166 drilling. As we move into IODP, these supplementary platforms, and other mission-specific platforms for drilling in the Arctic Ocean and other challenging areas, should constitute the third leg of a stool, and complement drilling by the successor to the *JOIDES Resolution* and the riser drillship, *Chikyu*, currently under construction for IODP.

ACKNOWLEDGEMENTS

This paper represents a direct outgrowth of planning studies ranging from COSOD II to COMPLEX and drilling studies during the ODP legs cited herein. I acknowledge the input of a broad scientific community (the ODP “Friends of Sea Level”) for developing the ideas presented here, though I take full responsibility for the emphasis on and interpretations of the successes of ODP. I particularly thank J. Austin, Jr. (Leg 174A co-chief), D. Feary (Leg 182 co-chief), A. Isern (Leg 194 co-chief), G. Mountain (Leg 150 co-chief), J. Browning, and M. Katz for comments on this paper, and M. Kominz, J. Wright, and J. Browning for sharing unpublished data used in Fig. 3. Onshore New Jersey drilling was supported by the ODP, NSF Continental Dynamics and Ocean Drilling Programs, and the New Jersey Geological Survey.

> “Oh, I could tell you why the ocean's near the shore,
> And then I'd sit, and think some more”
> *The Scarecrow, The Wizard of Oz (1939)*

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BIOTIC EFFECTS OF ABRUPT PALEOCENE AND CRETACEOUS CLIMATE EVENTS

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INTRODUCTION

In the last 125 million years, a series of substantial environmental perturbations had major impacts on the composition, distribution, and stability of marine and terrestrial ecosystems. This interval was marked by particularly radical changes in the protistans. Groups such as the diatoms and planktic foraminifera became fundamental parts of marine food chains during this time. Other groups such as the calcareous nannoplankton and radiolarians underwent wholesale changes in species composition and assemblage structure. The underlying causes of the long-term (millions of years, or m.y.) evolutionary changes are complex (see summary in Leckie et al., in review). Research over the last decade has established that these groups also were transformed by environmental changes that took place over short time scales (thousands of years. or k.y.). In particular, short-lived global warming events led to dramatic changes in the nature of global carbon cycling while sparking significant biotic turnover (e.g., Kennett and Stott, 1991; Erba, 1994; Erbacher and Thurow, 1997; Leckie et al., in review). We focus here on the biotic consequences of a major warming event in the late Paleocene and ocean-wide anoxic events in the Cretaceous. Recent efforts of the Ocean Drilling Program (ODP) have led to significant advances of our understanding of both of these intervals.

THE LATE PALEOCENE THERMAL MAXIMUM: SIMULTANEOUS EXTINCTION AND RADIATION

One of the most extreme and abrupt warming episodes occurred in the late Paleocene at ~55.5 million years ago (Ma), just prior to the Paleocene/Eocene boundary. This event, known as the Late Paleocene Thermal Maximum (LPTM; Zachos et al., 1993), lasted for ~200 k.y. The LPTM interval was originally identified in core recovered from ODP Site 690 on Maud Rise, Weddell Sea (Kennett and Stott, 1991), but has since been detected in numerous Deep Sea Drilling Project (DSDP) and ODP sections. The deep oceans warmed by ~5°C in less than 10 k.y. during the LPTM. Surface ocean temperatures increased by ~4° to 8°C with the most substantial changes, at high latitudes, reflecting profoundly altered atmospheric circulation. The carbon isotopic composition of the ocean and atmosphere decreased by 3‰ to 4‰ coeval with the warming event, suggesting a massive perturbation to the global carbon cycle. The large magnitude and rate of the carbon isotope excursion is most consistent with a sudden dissociation of methane hydrates from continental margin sediments (Dickens et al., 1995). Methane would have immediately contributed to greenhouse warming, and oxidation of this gas would have depleted the deep ocean of oxygen (Suess, this volume).

The carbon isotopic signature of the LPTM has been identified in both marine and terrestrial deposits, greatly enhancing stratigraphic correlation worldwide. The ubiquity of this geochemical signal indicates that the effects of the LPTM were felt by the entire global biosphere. Climatic changes associated with the LPTM triggered rapid turnover in marine benthic and planktic organisms (e.g., Kennett and Stott, 1991; Kelly et al., 1998), as well as a major paleobiogeographic reorganization among land mammals (Koch et al., 1995). Deep-sea environmental change, most likely lowered oxygen levels and reduced flux of organic carbon out of the photic zone, led to an abrupt extinction in epifaunal benthic foraminiferal communities (e.g., Thomas, 1998). Ocean drilling has helped us document this extinction event in different environments and latitudes.

The response of surface-dwelling marine organisms to LPTM environmental changes was fundamentally different to that displayed by the benthic foraminifera: planktic foraminifera and nannoplankton diversified rapidly during this event (Kelly et al., 1998; Cramer et al., 2000). This rapid (<10 k.y.) diversification gave rise to a number of novel morphotypes known as "excursion taxa" since they are restricted stratigraphically to the carbon isotope excursion interval.

Studies of ODP sections have shown that tropical foraminiferal species migrated to higher latitudes during the LPTM. Open ocean nannoplankton assemblages also experienced an abrupt transformation at the onset of the event (Bralower, in review; Fig. 1). This change was largely transient, and most elements of the pre-LPTM flora returned at the end of the event. However, the LPTM appears to have had long-term effects on nannoplankton, leading to the extinction of *Fasciculithus*, a dominant component of Paleocene assemblages. The major assemblage shift during the LPTM suggests a short-term change from colder, more productive surface waters to warmer, more nutrient-poor conditions.

Open ocean planktic foraminiferal assemblages also indicate increased oligotrophy during the LPTM. Planktic foraminiferal genera with stable isotope signatures most similar to those of modern species that host algal symbionts flourished during the event; algal symbiosis has enabled foraminifera to colonize stable, nutrient-poor water masses. However, benthic foraminiferal assemblages recovered in cores from shelf sites are thought to be indicative of eutrophic conditions (Thomas, 1998). A bloom of the dinoflagellate *Apectodinium* sp. in coastal to hemipelagic environments during the LPTM suggests increased productivity or temperature (Crouch et al., 2001). The combination of benthic and planktic biotic data indicates increased sequestration of nutrients in shelf environments during the LPTM.

The magnitude and transient nature of the carbon isotope excursion provides an opportunity to differentiate *in situ* foraminiferal shells from those reworked into LPTM samples; the unusually low $\delta^{13}C$ values of the LPTM were imparted to only those shells that grew during this global warming event (Kelly et al., 1998). Stable isotope analyses of individual planktic foraminiferal shells collected from an LPTM record recovered at a tropical Pacific location (ODP Site 865) were used to show a succession of temporal "snapshots" through the LPTM interval (Fig. 2). The use of this discriminatory technique reveals stratigraphic patterns of faunal change among the planktic foraminifera that would have otherwise remained obscured by the deleterious effects of sediment-mixing processes.

The single-specimen isotope data clarified the planktic foraminiferal response to LPTM conditions and confirmed the presence of a distinctive suite of novel "excursion taxa" (Kelly et al., 1998). The morphological evolution of these excursion taxa was paced by LPTM warming and occurred at rates previously unknown among planktic protistans. This abrupt diversification took place within lineages that occupied relatively shallow depth-habitats (i.e., oceanic mixed layer) in depth ecologies suitable for photosynthetic symbionts. We can only speculate on the exact nature of the environmental causes of this morphological diversification; however, deepening of the euphotic zone due to increased oligotrophy is the favored scenario.

The time series of single-specimen isotope data reveal a form of ecological selectivity in the planktic foraminiferal response (Fig. 2). For instance, none of the specimens of the deep-dwelling genus (*Subbotina*) recorded *in situ* carbon isotope values. This suggests that deep-dwelling (thermocline) species were eliminated at this tropical, open-ocean site during the LPTM. Conversely, one shallow-dwelling genus (*Acarinina*) appears to have thrived throughout the entirety of the LPTM, while another shallow-dwelling genus (*Morozovella*) suffered a temporary collapse in its populations at the onset of the LPTM. The enhanced stratigraphic resolution provided by the single-specimen isotope data has clarified the complex population dynamics that unfolded during the LPTM, giving us added insight into the role of paleobiogeography and paleoecology in the evolution of new plankton species.

The rate of LPTM warming is considered to have been comparable to that experienced by Earth over the last century (Dickens et al., 1995). The background climate at the onset of the event was substantially warmer

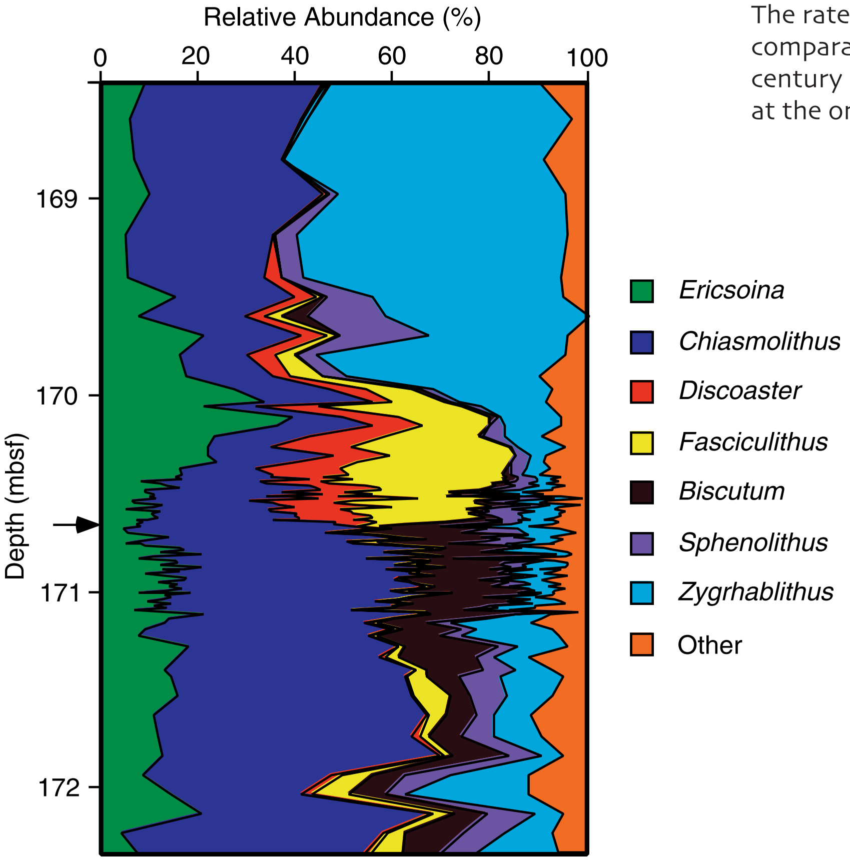

Figure 1. *Nannofossil assemblage changes in the LPTM interval at ODP Site 690, Maud Rise, Weddell Sea. The position of the onset of the event as indicated by the carbon isotope excursion is shown by the arrow at left. This horizon is characterized by a dramatic shift from taxa that are characteristic of colder, more eutrophic waters (e.g.,* Biscutum, Chiasmolithus*) to those indicative of warmer, more oligotrophic waters (e.g.,* Discoaster, Fasciculithus*). In the later part of the event, the genus* Zygrhablithus *appears to replace* Fasciculithus*. Data from Bralower (in review).*

than present. It is not possible to use the LPTM as a realistic case study to predict possible biotic consequences of current global warming. However, the event demonstrates that groups of organisms, even those that are closely related, respond to abrupt global warming in diverse ways.

CRETACEOUS OCEANWIDE ANOXIA: INSTRUMENTAL EVENTS IN MICROPLANKTON EVOLUTION

Cretaceous Oceanic Anoxic Events (OAEs) led to the widespread deposition of organic carbon (C_{org})-rich sediments, informally known as "black shales", in the oceans (e.g., Jenkyns, 1980). So far, at least seven possible OAE intervals, generally 0.5 m.y. to 1 m.y. in duration, are known: in the Toarcian (Middle Jurassic), early Aptian, Aptian/Albian boundary, middle Albian, late Albian, at the Cenomanian/Turonian boundary and in the Coniacian-Santonian. C_{org}-rich sediments have been recovered by the Deep Sea Drilling Project (DSDP) and ODP at sites in all of the ocean basins, and from a variety of paleodepths and latitudes. Investigations of these deposits over the last thirty years have played an instrumental role in our understanding of the causes of OAEs and the burial of vast quantities of C_{org}.

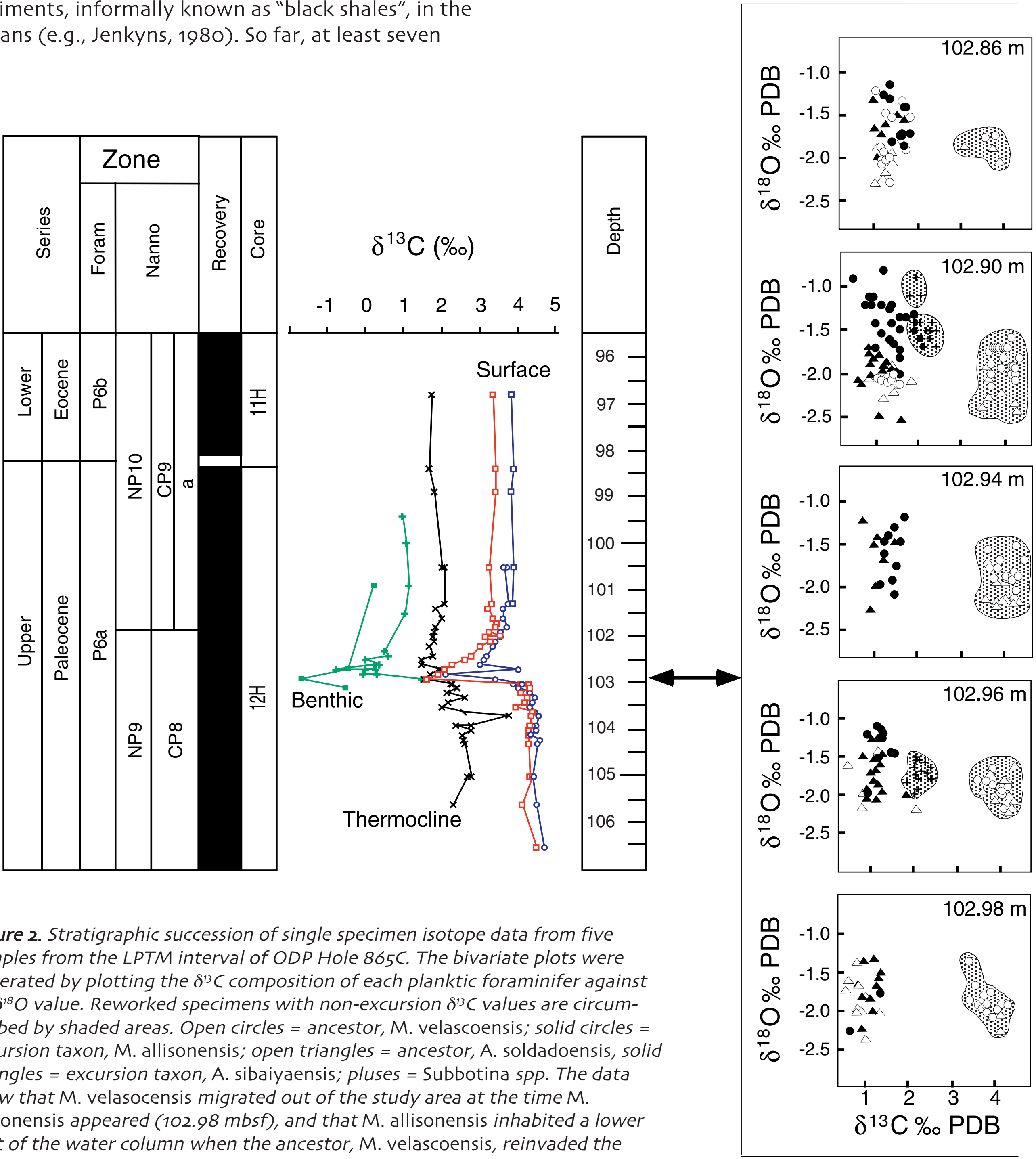

Figure 2. *Stratigraphic succession of single specimen isotope data from five samples from the LPTM interval of ODP Hole 865C. The bivariate plots were generated by plotting the* $\delta^{13}C$ *composition of each planktic foraminifer against its* $\delta^{18}O$ *value. Reworked specimens with non-excursion* $\delta^{13}C$ *values are circumscribed by shaded areas. Open circles = ancestor,* M. velascoensis*; solid circles = excursion taxon,* M. allisonensis*; open triangles = ancestor,* A. soldadoensis*, solid triangles = excursion taxon,* A. sibaiyaensis*; pluses =* Subbotina *spp. The data show that* M. velasocensis *migrated out of the study area at the time* M. allisonensis *appeared (102.98 mbsf), and that* M. allisonensis *inhabited a lower part of the water column when the ancestor,* M. velascoensis*, reinvaded the study area (102.96 mbsf). Data from Kelly et al. (1998).*

There has been a long debate as to whether Cretaceous C_{org}-rich deposits resulted from high surface-water productivity or effective preservation of C_{org} in warm, stagnant deep waters. Although this issue is still controversial, it is clear that the anoxic events were different in their geographic distribution and environmental changes. The C_{org}-rich deposits have long been shown to be associated with positive $\delta^{13}C$ excursions presumably recording the increased rate of burial of ^{12}C-enriched sediments (e.g., Arthur et al., 1987). Recently, a sharp negative isotope excursion precursor has been observed immediately below the organic-rich deposits of several of the prominent OAE intervals. This has led to the postulation of a methane hydrate trigger (e.g., Jahren et al., 2001), analogous to the LPTM. High quality oxygen isotope data are scarce; thus, evidence for warming during OAEs is mostly indirect.

The mid-Cretaceous (Barremian-Turonian) OAEs had a profound effect on the evolution and extinction of marine nekton, plankton and benthos (Fig. 3; see also an overview in Leckie et al., in review). Well-preserved assemblages from DSDP and ODP sites from a range of depths and latitudes have been crucial in our under-

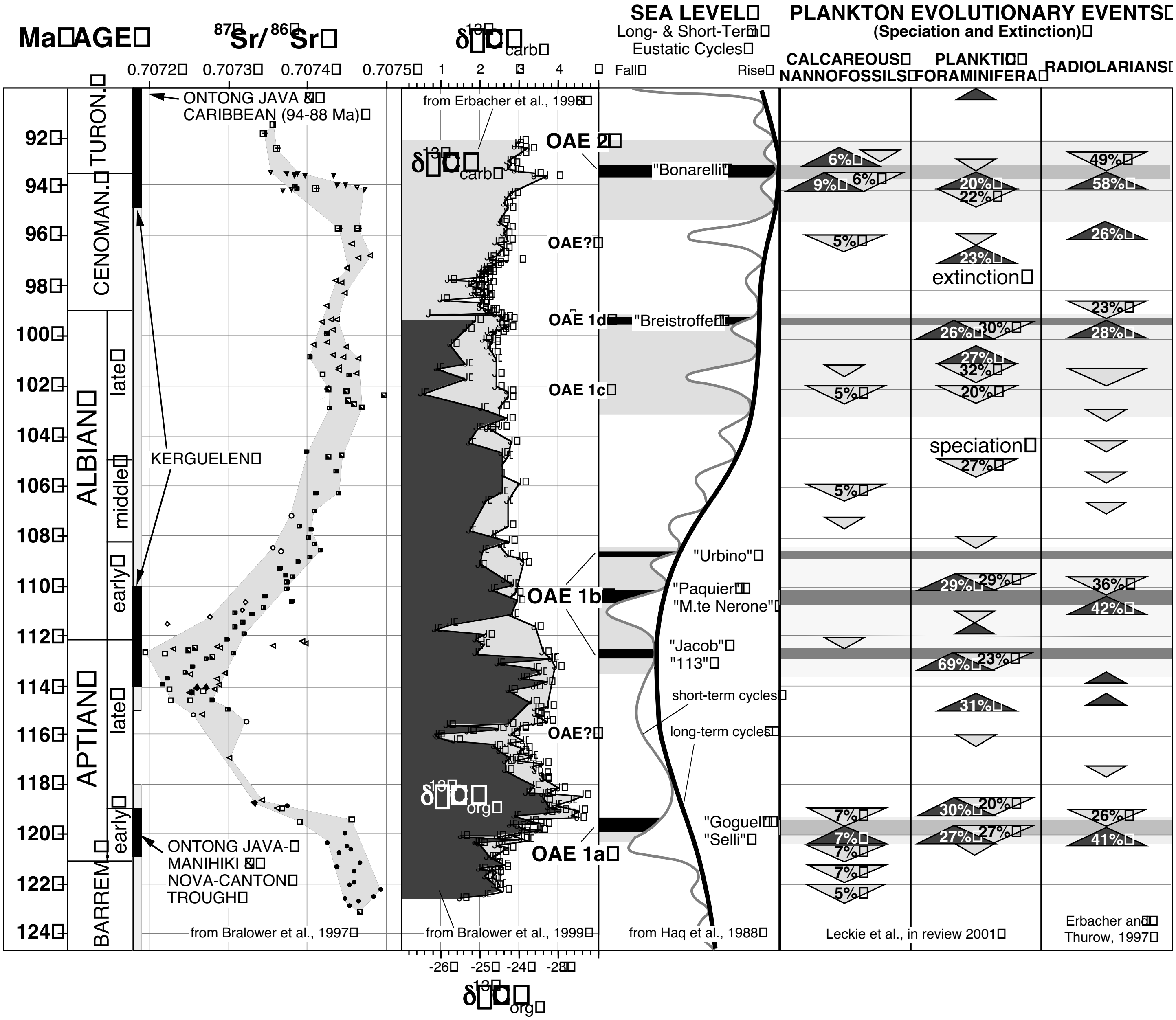

Figure 3. The mid-Cretaceous record of biotic change in the context of major black shales and Oceanic Anoxic Events (OAEs), the carbon isotopic record, changing global sea level, seawater strontium isotopes, paleotemperatures from DSDP and ODP sites on Blake Nose, western North Atlantic, and emplacement history of submarine large igneous provinces (see Leckie et al., in review for sources of data).

standing of these effects. OAE intervals often are characterized by unique, low-diversity planktic foraminiferal assemblages that show morphological adaptations to radically changed surface ocean nutrients and temperature (e.g., Premoli Silva et al., 1999). These biotic changes across the C_{org}-rich intervals strongly suggest corresponding changes in the chemistry and physical characteristics of the upper water column. All of the mid-Cretaceous OAEs are associated with accelerated rates of turnover (extinction and speciation) in the siliceous and calcareous plankton (Fig. 3; Erbacher and Thurow, 1997; Leckie et al., in review).

The dramatic appearance of several genera of benthic foraminifers characteristic of intermediate water depths during Aptian-Albian times appears to have been triggered by changes in water column structure that led to the development or expansion of mid-water niches. The OAE at the Cenomanian/Turonian boundary caused a major extinction of benthic foraminifers, probably as a result of extreme oxygen depletion in regions affected by expanded oxygen minima.

One of the most dramatic turnovers in the nannoplankton took place at ~120 m.y. in the early Aptian around the time of an event known as OAE1a. This event has been recovered in a number of different DSDP and ODP sites. The OAE involved the temporary collapse of the nannoconids, a group of nannoplankton that had dominated assemblages for the previous 20 m.y. (the "nannoconid crisis"; Erba, 1994). A possible explanation for the crisis was that emplacement of the Ontong Java Plateau, which coincided with this event directly or indirectly, caused a change in the thermal or nutrient structure of oceanic surface waters. Alternatively, a decrease in surface-water alkalinity may have inhibited the calcification of these large nannoplankton (e.g., Leckie et al., in review). Nannoplankton assemblages from OAE1a are characterized by taxa adapted to eutrophic conditions (Erba, 1994), although this does not appear to be the case for all of the OAEs.

The causes of the profound changes in microplankton communities during the mid-Cretaceous are not well understood (see summary in Leckie et al., in review). However, it is clear that the biotic turnover was strongly affected by environmental change. In particular, the consequences of rising sea level and global warming during Albian-Turonian times included several significant changes in marine habitats. Large epicontinental seas, such as the Western Interior Seaway of North America, served as gateways to the high latitudes that led to faunal and floral exchange across large latitudinal ranges. Nutrient partitioning between epicontinental seas or flooded coastal plains and the open ocean changed significantly as sea level rose. Increased rates of hydrothermal activity, changes in continental weathering, increasing water column stratification and nutrient partitioning between surface and deep waters had major ramifications for marine communities. Taken together, the cumulative effects of climate, ocean fertility, ocean circulation, water column stratification, and carbonate chemistry controlled plankton populations and their capacity to produce organic carbon and/or carbonate.

SUMMARY

Ocean drilling has helped us determine how environmental changes affected marine communities on long and short time scales during the Cretaceous and Paleogene. Identification of the exact organismal responses to the multitude of changes is difficult to discern. However, there is growing evidence that primary and secondary producers at or near the base of oceanic food webs have been profoundly affected by abrupt warming events. These events have influenced biodiversity and the marine carbon cycle in a variety of ways, each with its own climatic and oceanographic consequences. Perturbations to the ocean biological pump have been triggered by a host of linear and non-linear forcing functions.

Understanding the exact mechanisms that caused abrupt changes in marine communities requires a far more extensive array of sites from more diverse oceanic settings than currently available. In particular, high-resolution, high-sedimentation-rate records are needed to observe the exact temporal relationship between the environmental change and the biotic response. Records from high-latitude sites and marginal seas such as the Arctic should provide some of the most pronounced environmental changes and will help us understand their full range of effects on marine communities. Future ocean drilling will thus be instrumental in advancing our knowledge of the biotic responses to abrupt climatic change.

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SEDIMENTATION PROCESSES ON TERRIGENOUS CONTINENTAL MARGINS

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INTRODUCTION

Many Ocean Drilling Program (ODP) boreholes have been drilled on continental margins, but most have been directed at issues other than sedimentation processes. The sedimentological community is concerned with the nature of processes that deposit sediment on the seafloor and the character and distribution of the resulting facies. Ocean drilling has been important for our understanding of those sedimentary processes that because of their rarity or scale are difficult to monitor in real time. These include turbidity current deposits, mass-transport deposits, and contourites, hemipelagic sediments influenced by deep ocean circulation. In addition, numerous regional studies of sedimentation on continental margins have been made possible by the chronology and lithologic groundtruth for seismic profiles provided by ODP boreholes.

The greatest advances in understanding turbidity and current deposition were made during ODP Leg 155, when a series of shallow holes were drilled on the Amazon deep-sea fan. These holes provided lithologic groundtruth for the growth pattern of the fan inferred from seismic reflection profiles. They also provided a chronology and demonstrated that, other than the cessation of fan growth at extreme sea level highstands, sea level change exerted little influence on fan facies. Contrary to the seismic model, drilling showed that more than one channel could be active at any time. Changes in width and depth of channels and the amount of silt in levee sediment probably reflect fluctuations in river sediment supply. Sands are deposited in channels, on lobes, and in interchannel depressions following avulsion, but none show pronounced cyclicity in bed thickness or grain size. Autocylic channel processes dominate the deposition of turbidite facies rather than allocyclic changes in climate or sea level.

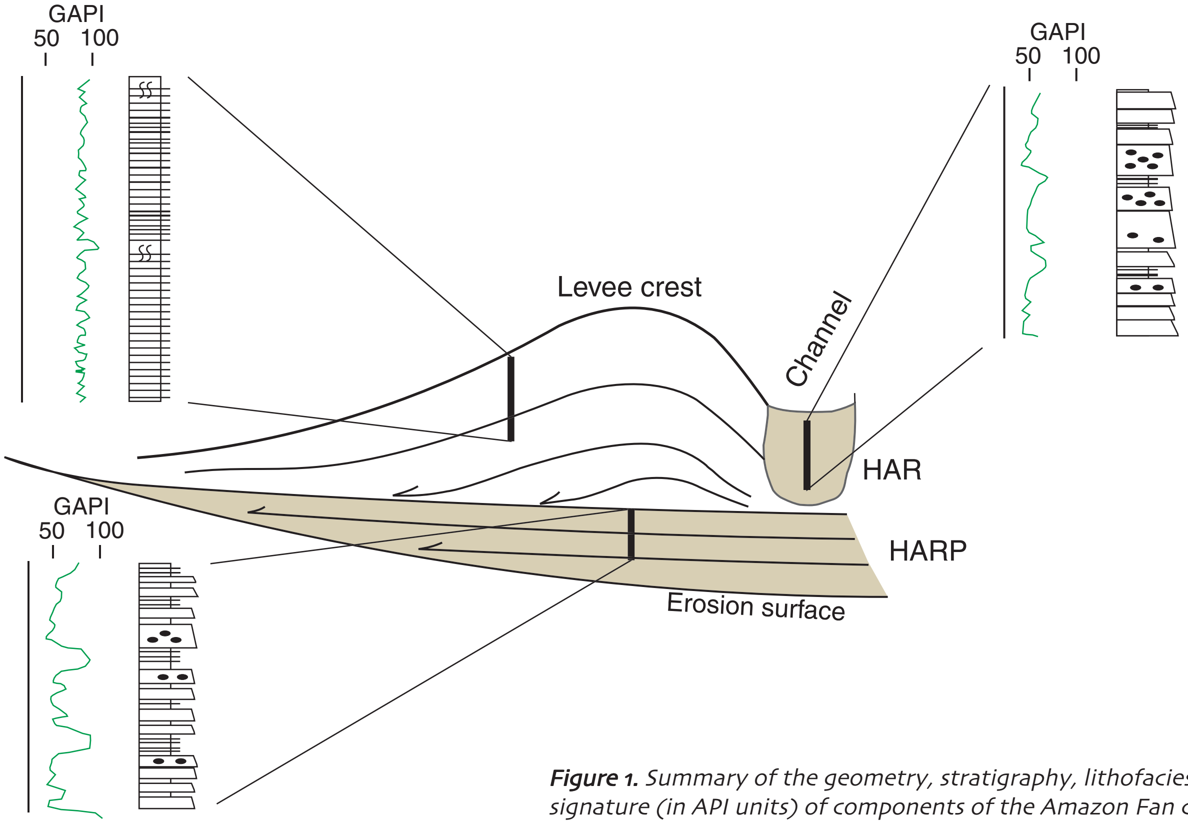

Figure 1. *Summary of the geometry, stratigraphy, lithofacies and gamma-ray signature (in API units) of components of the Amazon Fan channel-levee system based on seismic profiles, cores, and wireline logs (reproduced from Fig. 16; Pirmez et al., 1997). Note a sheet-like sandy succession formed by redistribution of upfan channel-floor sands into an interchannel low following avulsion (high-amplitude reflection packets, or HARPs), down-lapping mud/silt deposits of an aggrading levee, and aggrading channel-floor sands of the new channel segment (high-amplitude reflections, or HARs). Each column represents ~30 m to 50 m of section.*

The Amazon Fan has become the reference example for both the scientific community and the oil industry for understanding large passive-margin fans, such as the Zaire-Congo, Mississippi and Indus. High-amplitude reflection packets (HARPs) of sands, 5 m to 25 m thick and deposited in interchannel depressions (Fig. 1), were identified on seismic records. These features have proved important in the interpretation of a number of deep-water oil plays in, for example, the Gulf of Mexico (Hiscott et al., 1997).

ODP also has provided key information for understanding turbidite deposition in small volcaniclastic basins in arcs (e.g., Leg 126) and on small sandy deep-sea fans (e.g., Site 1015 in the California Borderland), allowing definition of facies distribution and establishment of a link between sea level and initiation processes for turbidity currents (Hiscott et al., 1992; Piper and Normark, 2001). In addition, existing ODP holes drilled through turbidite sands allowed a synthesis to be made of reservoir-scale properties of sands on deep-sea fans and their relationship to fan morphology and processes of turbidity current initiation (Piper and Normark, 2001). Drilling also has provided information on the contribution of turbidity currents to the general level of nepheloid layer deposition in the ocean (Stow and Wetzel, 1990).

Many of the most intractable problems of turbidity current deposition are concerned with the processes of transport and deposition in high-concentration flows, leading to the deposition of thick bedded sands and gravels. In general, ODP has avoided drilling in thick sands for technical reasons. Where thick sand beds have been recovered, sedimentary structures rarely survive drilling disturbance. The possibility of comparison of deep-sea core material with ancient rocks is, therefore, limited.

ODP drilling has been successful in refining our understanding of major slide deposits in the seabed. These deposits, observed on many continental margins, are commonly 50 m to 150 m thick and testify to occasional catastrophic failure on the margin. Such major slides are a risk to human safety, as a result of accompanying tsunamis, and to seabed installations including

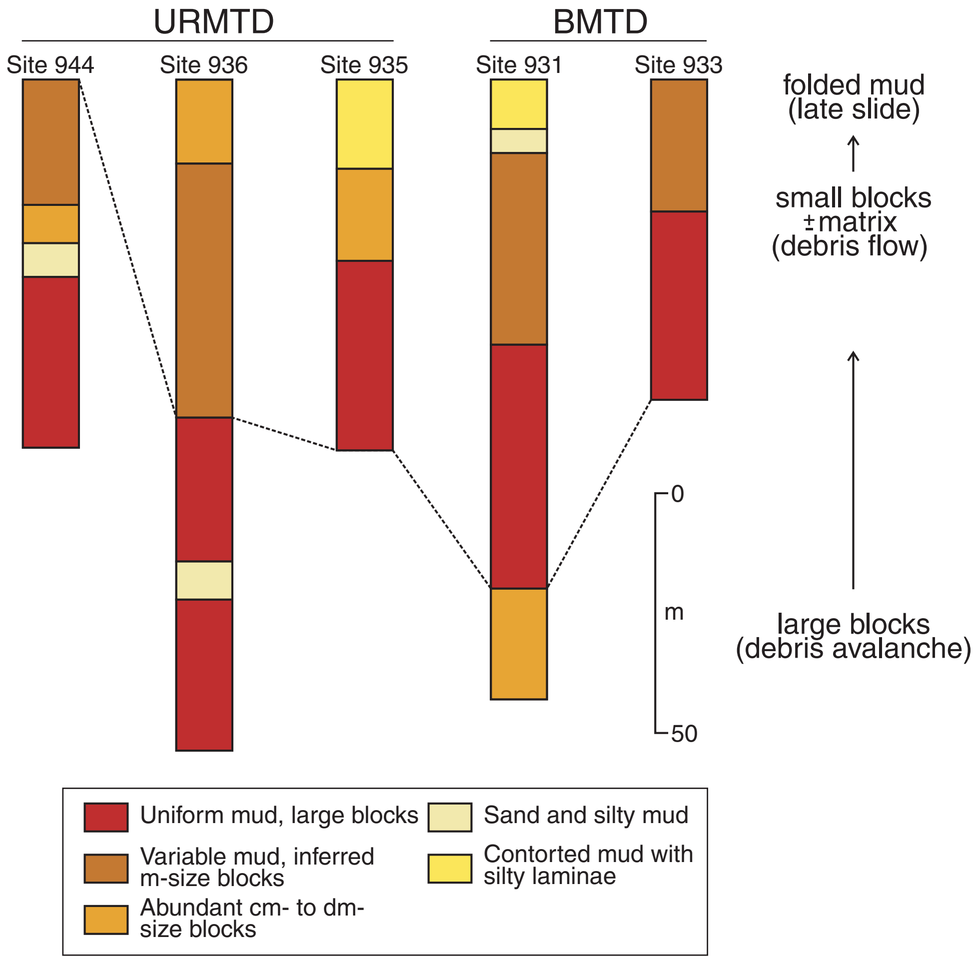

Figure 2. *Summary of lithologies in correlative mass flow deposits, Amazon Fan (after Fig. 14; Piper et al., 1997). URMTD = Unit R mass-transport deposit; BMTD = bottom mass-transport deposit.*

oil wells and telecommunication cables. Although the slide surface may be pricked by traditional ship-based piston coring, only deep-sea drilling allows the full thickness of a slide to be penetrated. Unresolved questions about slides concern their source area, whether they are initiated by slope failure or retrogressive slumping, the process of transport, and the triggering mechanism. Thick slide deposits have been intersected on the Mississippi and Amazon Fans. On the Amazon Fan, slides with volumes of 1000 km^3 are typically 100 m thick, and consist of large blocks derived by retrogressive failure. Some of these blocks show repetitive stratigraphy. Micropaleontology indicates a source on the continental slope. Chronology suggests that the slides were related to times of falling sea level, when dissociation of gas hydrates on the continental slope would increase slope instability. Results of Leg 136 demonstrated that turbidity currents generated by catastrophic landslides on the flanks of Hawaiian volcanoes flowed at least 250 km from the source, and flowed over 500 m-high topographic barriers.

ODP drilling also has played an important role in exploring the different types of diamictite that have accumulated under different glacial conditions in the major prograding sequences at the edge of glaciated continental shelves. During Leg 119 to Prydz Bay, Antarctica, scientists identified sedimentary criteria used to distinguish diamictites deposited as waterlain till close to an ice margin, in a proximal setting beneath a floating ice shelf, from more distal facies where coarse sediment is supplied by icebergs (Hambrey et al., 1991). On warmer glaciated margins, drilling has demonstrated the presence of catastrophic jokulhlaups off the Columbia River (Zuffa et al., 2000). However, more drilling is needed to understand proximal glacial processes associated with the major glacial discharges that produce Heinrich events.

ODP drilling has increased our understanding of deep-sea thermohaline circulation and sediment transport and deposition by bottom or contour currents along continental margins and in deep oceanic basins. Although it is now well known that bottom-current deposits, or contourites, form a significant proportion of continental margin sediments, the long term effects of deep oceanic circulation on marine sedimentation and sediment accumulations, known as sediment drifts, are still misunderstood. A great advance concerning the typical lithologies that build sediment drifts through time resulted immediately prior to ODP. Scientists on board the *Glomar Challenger* during Leg 94 of the Deep Sea Drilling Program (DSDP) documented the history of sedimentation on Feni and Gardar Drifts under glacial, interglacial and preglacial conditions (Kidd and Hill, 1986). Their results were contrary to previous ideas describing contrasting sediment grain sizes and accumulation rates resulting in periods of intensification of bottom current activity. Thus, surprisingly, both Feni and Gardar Drifts mainly consist of bioturbated, homogeneous to thin-bedded pelagic-type sediments with occasional 1 mm-thick laminae (Hill, 1986). Classical "contourite" facies previously described in the literature (Stow and Lowell, 1979) were never recognized. Small variations in grain size were observed between glacial and interglacial cycles, but resulted in the absence or occurrence of foraminifers and in increase or decrease of the coarse (>63 mm) terrigenous fraction. Overall rates of accumulation were only slightly greater than average pelagic accumulation rates in the Atlantic. Therefore, no clear evidence for current control of sedimentation was observed on either the Feni or Gardar Drifts. Later ODP legs to sediment drifts, such as Legs 151, 152, 162, 172, 177 and 178, had similar sedimentologic findings.

Another problem addressed by ODP concerns the enigmatic giant wavy bedforms termed sediment waves. Sediment waves are observed in most of deep-sea turbidite and contourite environments throughout the world. Although hydrodynamic processes involved in their construction are probably different, turbidite and contourite sediment waves have many similar features, such as their morphology and size, their orientation to the current direction, and their surprising capacity to migrate upslope and upcurrent. Sediment wave construction alternates through upslope progradation and vertical aggradation stages that have been thought to correspond to different flow dynamic conditions (Migeon et al., 2001). DSDP Leg 93 and ODP Leg 155 results clearly underlined a systematic change in sedimentary facies and grain size from progradation and aggradation stages observed in seismic reflection data, and showed that these stages are clearly connected to the hydrodynamic conditions over the waves. Leg 94 also characterized progradation stages with higher sedimentation rates. Facies and grain-size data were collected through entire thicknesses of a turbidite during Leg 155 and a contourite sediment wave during Leg 172. Re-examination and comparison of these data would be useful in addressing the unresolved problems of sediment-wave initiation and gravity-flow and bottom-current dynamics involved in sediment-wave construction.

Still unanswered is the question of how to discriminate fine-grained turbidites from silty contourites; data collected during several legs are currently under study. Such discrimination is of particular importance for our understanding of deep-sea sedimentation, the construction of continental margins and the reconstruction of paleo-current directions. For example, both contourites and turbidites were described in cores of Legs 172 and 178 and then analyzed, but robust criteria for distinguishing these two sediment types are still lacking.

Scientific ocean drilling has provided the means to delineate sediment facies character, age and distribution on continental margins from core samples. These parameters would otherwise be inferred from seismic reflection profiles and sampled in sparse cuttings from exploration oil wells. ODP cruises have allowed testing of hypotheses on facies distribution, the controls on continental margin architecture by sea level change, climate change and tectonism, and the nature of catastrophic sedimentation processes. High sedimentation rate continental margin sites are the repositories of important paleoclimatic proxy data, including both terrestrial and marine taxa.

In the past decade, ocean drilling has provided data that have revolutionized our understanding of how continental margins have developed. However, only a few sites have been directed at understanding sedimentation processes. In general, a series of numerous shallow holes would be the best approach to address many outstanding questions on how sediment is transported at the seabed and the nature of the resulting facies. Alternative platforms may provide a cost-effective way of operating such programs.

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THE DYNAMICS AND SIGNIFICANCE OF FLUIDS WITHIN THE SEAFLOOR

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INTRODUCTION

Fluids are present throughout Earth's crust and act as a primary medium of exchange between Earth's interior, lithosphere and hydrosphere. Flowing fluids carry enormous fluxes of energy, magma, and solutes between these reservoirs. Fluids contribute to production of continental crust, generation of explosive volcanism, lubrication of plate boundary faults, formation of hydrates and mineral resources, and development and support of remarkable biological communities. Fluids affect the properties of sediments and basement rocks through which they move and are stored as a result of diagenesis, heat transfer, and stress-strain relations. These strong couplings present challenges to resolving the roles of fluids as agents of change, but have led to exciting scientific discoveries through ocean drilling.

Essentially all studies of fluid flow within the seafloor deal with at least one of these four topics: (1) driving forces, (2) hydrogeologic properties (transmissive and storage), (3) fluxes, and (4) fluid sources. In quantifying these properties and processes, researchers grapple with spatial and temporal scaling issues, and the common challenge of reconciling interpretations based on different approaches and assumptions. In many cases, laboratory and *in situ* measurements are used as input or constraints for sophisticated models. Results of such models often lead to ideas for new approaches or techniques. The following highlights selected from recent studies of seafloor fluids are based largely on results of Ocean Drilling Program (ODP) experiments.

TECHNICAL APPROACHES

Core material recovered from ODP boreholes provide valuable insights to conditions and processes occurring in the subsurface, particularly by allowing collection and analysis of pristine material. Core samples also present challenges for interpretation of crustal processes. Storage and transmissive properties are known to be scale dependent, and seafloor hydrogeologic systems are heterogeneous, often requiring measurement at the scale and crustal volume of interest.

One valuable legacy of ODP is the development of sophisticated tools for measuring fluid conditions and processes within the seafloor. These tools include logging instruments, packers, flowmeters, and long-term seafloor observatories (CORKs: Circulation Obviation Retrofit Kits). Logging tools create continuous records of formation properties. The addition of logging-while-drilling technology, where logging tools are incorporated into the bottom hole assembly, has let scientists access more hostile environments. Flow meters allow quantification of the rates at which fluids move into or out of the formation surrounding a borehole and provide important constraints on crustal hydrostratigraphy. Drillstring packers are used to isolate parts of boreholes, monitor and manipulate fluid pressures, and quantify formation responses to perturbations. CORK observatories allow boreholes to be sealed and monitored for years at a time, to recover from the disturbance due to drilling, to produce high-quality fluid samples, and to evaluate large-scale crustal properties. The case studies described below have benefited from a mixture of conventional and cutting-edge technical approaches and modeling.

CASE STUDIES

Basement Hydrogeology

Studies of core samples allow researchers to understand the distribution of rock types and alteration, but recovery in basement (particularly in young basalt) is often <20% and generally fails to represent the large-scale fracture patterns common in basement. Borehole studies have provided some of the most valuable, quantitative information on ocean basement rocks. Borehole packer and flowmeter measurements were conducted within basement boreholes during the Deep Sea Drilling Project (DSDP), and these tools have been modified and refined and have continued to provide valuable information during ODP.

A summary of basement permeability estimates from drillstring packer and flowmeter experiments (Fig. 1) illustrates several notable trends (Fisher, 1998; Becker and Fisher, 2000). Although tests in a wide variety of basement ages have indicated a wide range of permeabilities, the data are remarkably consistent within the measured depth intervals. The greatest permeabilites appear to be restricted to the upper few hundred m of the seafloor and tend to be concentrated within intervals having a thickness on the order of tens of m. Caution must be used in interpreting these data in terms of crustal-scale fluid flow because of assumptions in interpretation, scaling of hydrologic properties, and the limited view of crustal conditions based on testing of individual boreholes.

Case Study - Ridge Crest Hydrogeology: Drilling into "zero-age" crust has been a challenging goal for ODP. Considerable technical effort has yielded several promising approaches for bare-rock work; but the greatest successes in ridge-crest drilling have been on sedimented ridges. Sedimented ridges are unique environments where the rate of magmatic emplacement is insufficient, relative to that of sedimentation, to allow basalt extrusion onto the seafloor. Instead, basaltic magma rises from depth and spreads laterally below the seafloor, forming an interlayered sediment-sill complex. The low-permeability sediments capping these systems limits the exchange of fluids, heat and solutes between the crust and overlying ocean, but allows unique opportunities to drill, core, sample and install observatories within some of the youngest seafloor.

Two ODP cruises visited Middle Valley, a sedimented rift at the northern end of the Juan de Fuca Ridge (Fig. 2A). Two holes were cased and sealed in Middle Valley during ODP Leg 139, establishing the first CORK observatories. Hole 858G was drilled in the Dead Dog vent field, within a few tens of meters of several clusters of active chimneys discharging hydrothermal fluids at temperatures up to 280°C. Dead Dog vent field is well-defined by side scan sonar surveys as an elongate area of high acoustic backscatter 400 m by 800 m on a side (Fig. 2B). The hole penetrated 260 m of sediment and 175 m of basal-tic basement interpreted as a buried volcanic edifice. Hole 857D was drilled 1.6 km south of the Dead Dog vent field through 470 m of sediments and 500 m of alternating sediments and sills; the deeper section here was thought to include a part of the hydrothermal reservoir. Geophysical and flow meter logs and packer experiments were completed, and both holes were sealed with CORK observatories (including thermistor chains, fluid samplers, and pressure gauges) and left to equilibrate. The observatories were visited by submersible and remotely-operated vehicle over several years, and reinstrumented during ODP Leg 169.

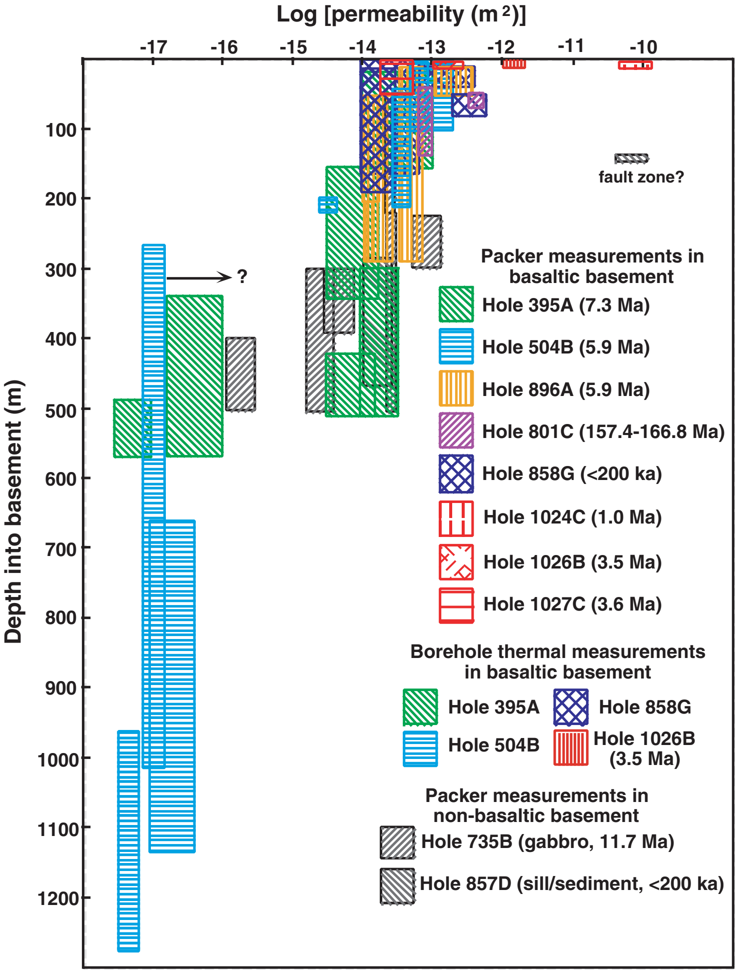

Figure 1. *Compilation of bulk permeabilities in oceanic basement from packer and thermal flow meter measurements (Fisher, 1998; Becker and Fisher, 2000). Data were collected in DSDP and ODP holes having a range of crustal ages and compositions, as noted. Range in depths into basement indicates either the full open interval of the tested borehole (for most tests), or a smaller interval (thought to contain the greatest permeability) identified on the basis of lithologic or well logs. Range in individual bulk permeability values indicates estimated uncertainty.*

Pressure records downloaded from the observatories after fourteen months suggested that basement fluids in Hole 858G were overpressured relative to seafloor hydrostatic conditions by 180 kPa, while fluid pressures in Hole 857D were underpressured by 400 kPa. This pattern makes some sense, since basement fluids in an area of active venting should be overpressured, and the fluids within the reservoir need to be underpressured in order to draw recharge. But this distribution of under- and overpressures also seems to suggest that fluids within basement should flow away from the vent field at depth. In fact, the *in situ* gradient in the fluid impelling force is from the reservoir area (Hole 857D) towards the vent field (858G), as determined by correcting the seafloor pressures measured at the observatories for differences in fluid temperature and density with depth (Fig. 2C; Stein and Fisher, 2001). Based on the assumption that vigorously-convecting fluids at depth are isothermal at 280°C, the temperature-corrected difference in pressure head between the two sites is only 1.7 m. This remarkably small head difference between sites 1.6 km apart suggests that hydrothermal basement in this area must be extremely permeable.

A large-scale basement permeability estimate was made for this region using a technique commonly applied to pumping wells on land (Stein and Fisher, 2001). Holes 858G and 857D are considered to be observation wells located 50 m and 1600 m, respectively, from the center of the well field (the "pumping well"). Based on the temperature-corrected head difference between the observation points and an aquifer thickness of 10 to 1000 m, the basement bulk permeability necessary to supply fluid to the vents is 10^{-12} to 10^{-10} m^2, with the higher permeability value corresponding to the thinner aquifer (Fig. 2D). A value of 10^{-10} m^2 also was estimated for a 5 m-thick to 10 m-thick interval based on packer and flowmeter experiments and other observations (Becker et al., 1994).

Case Study - Ridge Flank Hydrogeology: While high-temperature hydrothermal circulation at seafloor spreading centers results in spectacular vent fields, biological communities and ore deposits, basement below most of the seafloor hosts fluid flow at slower rates and lower temperatures. This "ridge-flank" circulation involves much larger global fluxes of fluid and heat and results in significant geochemical exchange for several elements. ODP Leg 168 explored aspects of ridge-flank hydrogeology through drilling and experiments along a transect of crust aged 0.9 to 3.6 million years (m.y.) (Fig. 3A).

Four sites instrumented with CORK observatories have been revisited several times to service instruments, collect fluid and biological samples, and download pressure and temperature data. The resulting data sets demonstrate the dynamics of distinct fluid processes within oceanic ridge flanks. Two CORKs were installed 2.2 km apart into a buried basement ridge-trough pair at the eastern end of the transect. The buried ridge CORK, at Site 1026, penetrated 250 m of sediment and 20 m of upper basement, while the buried trough CORK, at Site 1027, penetrated 600 m of sediment and 40 m of basement. Under purely conductive conditions, upper basement temperatures at Site 1027 would have been about 40°C warmer than those at Site 1026, but *in situ* temperature measurements indicated that uppermost basement at these sites was practically isothermal. This condition requires vigorous fluid convection in basement. The relatively small pressure gradients detected between the two CORKs suggest that effective basement permeability must be very high.

CORK experiments along the Leg 168 transect also have demonstrated that crustal fluid pressures at flank sites 10s to >100 km from earthquake epicenters respond to seismic events (Davis et al., 2001). After filtering CORK pressure records to remove the influence of barometric pressure changes and tides, distinct signals remain that

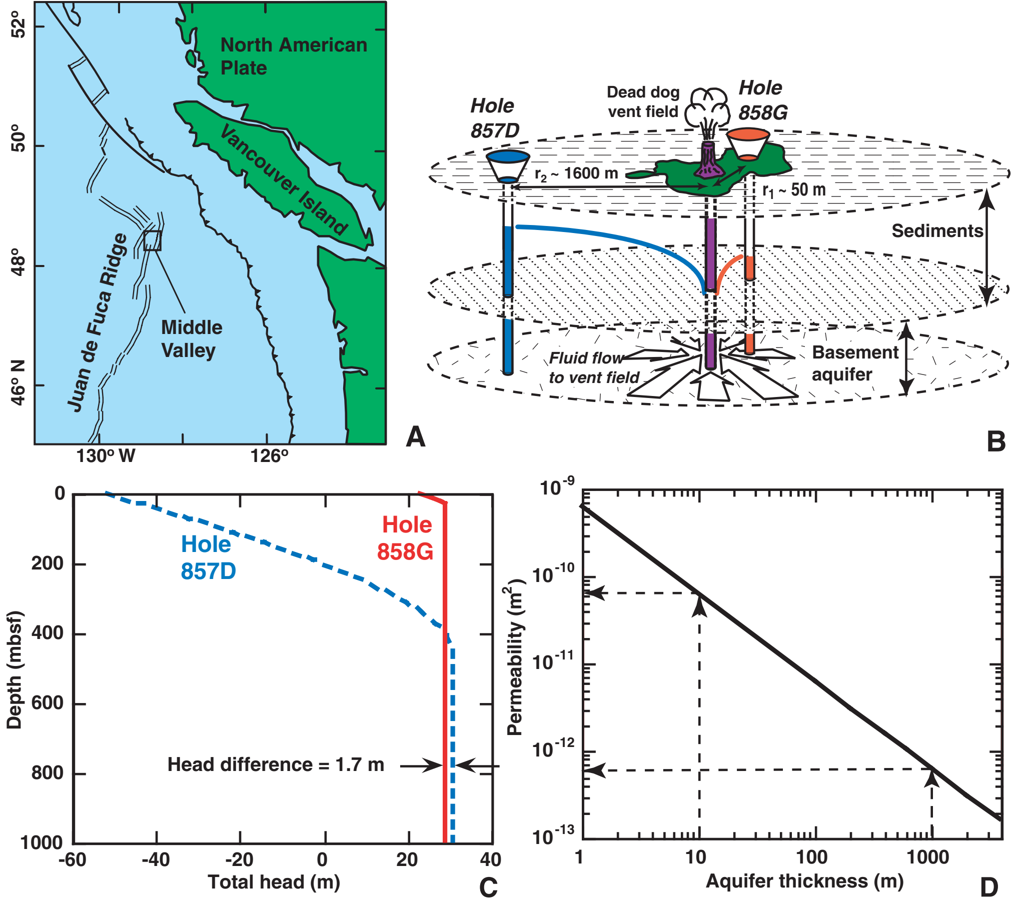

Figure 2. A. *Location of Middle Valley on the northern Juan de Fuca Ridge.* ***B.*** *Cartoon showing CORK observatories and the Dead Dog vent field. The green shaded region indicates the extent of the vent field, as mapped with side-scan sonar. Hole 858G is located within the vent field, and Hole 857D is located outside the vent field. Total fluid flux from the vent field is related to bulk basement permeability, based on the measured fluid pressure (corrected for local thermal gradients) and distances from the CORKed holes to the center of the vent field.* ***C.*** *Measured pressures (above hydrostatic in Hole 858G, less than hydrostatic in Hole 857D) are corrected for variations in fluid density, based on borehole temperatures, allowing calculation of the difference in effective pressure head between the two boreholes of about 1.7 m. This is the driving force available to move fluid at depth from outside the vent field to the base of the vent system.* ***D.*** *Given this head difference and possible aquifer thickness of 10 to 1000 m, bulk permeability on the order of 10^{-12} to 10^{-10} m^2 is required to supply observed vent discharge. A value at the upper end of this range was estimated from packer experiments in Hole 857D (see Figure 1). Modified from Stein and Fisher (2001).*

correlate with independently-detected seismic events along plate boundary faults. An October 1996 event along the Nootka Fault led to an abrupt decrease in fluid pressure at Site 1027, followed by a gradual rise back to background values (Fig. 3B). A June 1999 event near the spreading axis of the Juan de Fuca Ridge lead to an abrupt rise in fluid pressure at Site 1024, followed by a slow decay of the pressure perturbation (Fig. 3C). The latter event is interpreted to have been associated with seafloor spreading along the ridge crest 20 km west of Site 1024. The strain is believed to be equivalent to that associated with a magnitude 6 seismic event, suggesting that a large fraction of the spreading was aseismic. The stresses associated with these events are thought to be transmitted through crustal rocks, and the gradual decay of pressure results from the hydrologic properties of the upper crust (Davis et al., 2001).

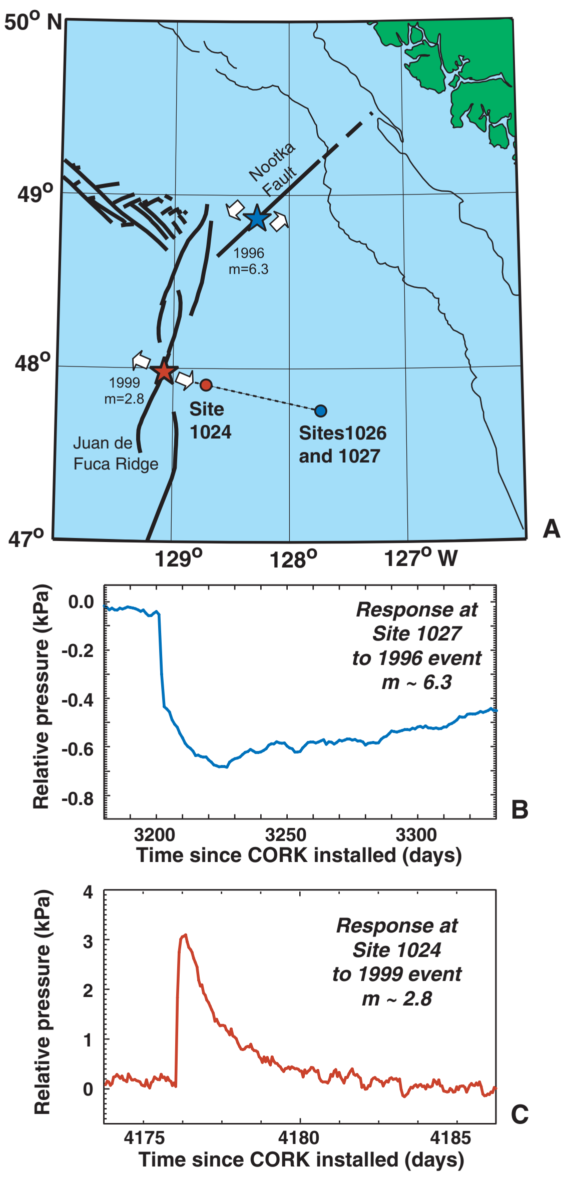

Figure 3. *Examples of the response of crustal fluid pressures to co-seismic strain along the edges of the Juan de Fuca Plate, north-eastern Pacific Ocean. Modified from Davis et al. (2001).* ***A.*** *Index map showing locations of ODP Sites 1024 and 1027, at western and eastern ends of the Leg 168 drilling transect (dashed line), where CORK observatories were installed. Stars indicate two seismic events, a magnitude 6.3 event along the Nootka transform fault in October 1996, and a magnitude 2.8 event near the spreading axis of the Juan de Fuca Ridge in June 1999.* ***B.*** *Pressure response of crustal fluids at Site 1027 to the 1996 event.* ***C.*** *Pressure response of crustal fluids at Site 1024 to the 1999 event.*

Sediment Hydrogeology

Seafloor hydrogeologic studies in sedimented settings present unique challenges. Sediments tend to be much more compliant than basement rocks, and are greatly modified by drilling and coring operations. Sediments contain pore fluids that yield geochemical information about diagenesis and hydrologic processes. Like many basement rocks, some sedimentary formations are fractured, requiring *in situ* hydrogeologic testing because laboratory analyses of small samples do not include critical flow pathways. In this section I highlight two examples that illustrate how our understanding of seafloor hydrogeology in sedimentary environments has been advanced by ODP experiments.

Case Study - Active Margin Hydrogeology: The Barbados accretionary complex has been visited for scientific ocean drilling during DSDP Leg 78A and ODP Legs 110, 156 and 171A. The primary focus of these expeditions was to understand the processes controlling deformation occurring at this active margin, with an emphasis on the décollement, the low-angle, plate boundary fault separating the accretionary wedge of the Caribbean Plate from the subducting sediments and basement of the North American Plate (Fig. 4A). The earliest drilling expeditions to this area concentrated on coring and sample analysis, in part because borehole measurements were extremely difficult within unstable formations. Leg 110 introduced packer technology to this environment, and Leg 156 included completion of the first successful packer experiments along a tectonic plate boundary.

Holes 948D and 949C were drilled into the toe of the accretionary complex during ODP Leg 156 (Fig. 4A). Both holes were cased through the decollement, and wire-wrapped, perforated casing was used to conduct drillstring packer experiments (Fisher and Zwart, 1997). These tests were complicated by unstable hole conditions and changes in background pressure during testing. After *in situ* testing was completed, the cased holes were fitted with CORK observatories. The CORKs were revisited by submersible eighteen months later, and Hole 949C was subjected to "artesian well" hydrologic tests by opening and closing the fluid sampling valve (Screaton et al., 1997). CORK records of fluid pressures in Hole 949C during Leg 171A provided an additional test of sediment properties between two boreholes based on excess pressures generated while drilling nearby Hole 1046A (Screaton et al., 2000).

Results of these tests yield a range in décollement permeabilities, from 10^{-17} m² to 10^{-13} m² (Fig. 4B). At the low end of this range, the borehole results are consistent with laboratory tests of fine-grained material recovered from the same locations, suggesting that these values may represent background, intergranular permeabilities. At the higher end of this range, the values are close to those suggested by steady-state numerical models of large-scale fluid flow and accretionary wedge dewatering. The highest-quality packer and single-hole CORK test results suggest a dependence of formation permeability on pore fluid pressure, with differences in permeability of five orders of magnitude as fluid pressure varies from hydrostatic to lithostatic (Fig. 4B). This result is intriguing because it may help to explain how excess fluid pressures and fluid flow may be coupled through non-linear changes in formation properties. The cross-hole test conducted during ODP Leg 171A resulted in greater apparent permeability at low pore fluid pressures than suggested by the trends deduced from the other tests (Screaton et al., 2000).

Case Study - Passive Margin Hydrogeology: Relatively little work has been done during ODP to elucidate hydrogeologic processes along passive continental margins, but drilling along the New Jersey margin on ODP Leg 174A provided new insights as to how fluid excess fluid pressures and fluid flow are coupled in this setting. Site 1073 was drilled through 650 m of Oligocene to Holocene sediments in 640 m of water (Fig. 5A). Sediment porosities were found to be anomalously high, leading to an interpretation that pore fluids were overpressured relative to hydrostatic (Dugan and Flemings, 2000). Fluid pressures below the Miocene-Pliocene boundary (Fig. 5B) were calculated to be within 95% of lithostatic values.

The creation of fluid overpressures requires the application of stress at sufficiently high rates that fluid can not escape rapidly enough to maintain hydrostatic conditions. In passive margins, this can result from generation of hydrocarbons or other diagenetic processes, topographic forcing associated with an adjacent continental area, or through rapid sedimentation of fine-grained material. The latter process is thought to be primarily responsible for generation of excess pressures at ODP Site 1073 (Dugan and Flemings, 2000).

Results of two-dimensional modeling of coupled sediment deposition, mechanics, and fluid flow in this setting suggest that excess fluid pressures are expected to develop within relatively permeable Miocene sediments below a cap of lower-permeability Pliocene sediments. Fluid specific discharge (volume flux/area) at the seafloor above the shallow section is relatively slow at <0.05 mm/yr; considerably greater fluxes of >5 mm/yr are predicted near the toe of the Miocene strata (Fig. 5C). Local velocities could be even greater, depending on the nature of permeability heterogeneity and subsurface pathways. These fluxes are geochemically significant and could support seep communities without requiring a direct connection between continental (meteoric) waters and the continental slope. The models also suggest that the continental slope in this region may be broadly overpressured, and could lead to rapid (even catastrophic) slope failure and the creation of submarine canyons.

MARINE HYDROGEOLOGY OPPORTUNITIES IN FUTURE SCIENTIFIC OCEAN DRILLING

The ocean drilling work described here includes a variety of approaches used to understand and quantify

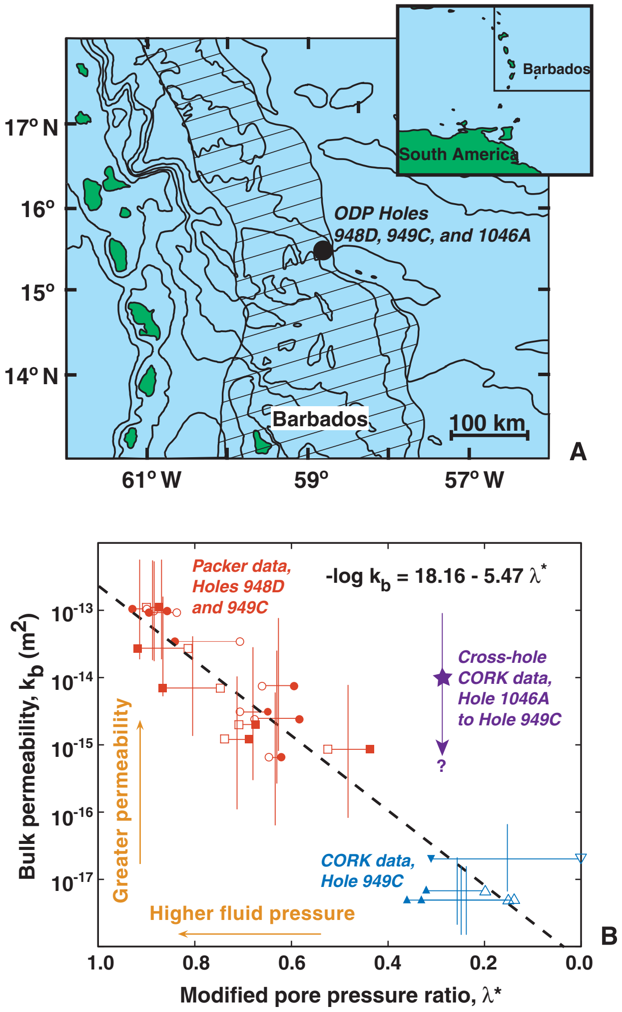

Figure 4. A. *Location of ODP Sites 948, 949 and 1046 at the toe of the Barbados accretionary complex (striped region).* ***B.*** *Bulk permeability versus fluid pressure, including packer and CORK results (Fisher and Zwart, 1997; Screaton et al., 1997; 2000). Fluid pressures are represented by the modified pore pressure ratio,* $\lambda^* = (P_m - P_H)/(P_L - P_H)$*, where* P_m *= measured fluid pressure,* P_H *= hydrostatic pressure,* P_L *= lithostatic pressure. Lithostatic pressure will have* $\lambda^* = 1$*, and hydrostatic pressure* $\lambda^* = 0$*. Vertical bars indicate estimated uncertainties in test interpretations. Packer and single-hole CORK symbols are open for pressure at start of test, and filled for pressure at end of test. The dashed line indicates a least-squares best-fit (see equation) to the highest-quality packer and single-hole data.*

the influences of subseafloor fluids on geological processes. These process-oriented studies focus on the dynamics of fluid-crust interaction, a strategy that has pushed the limits of available technology and required an interdisciplinary view of seafloor hydrogeology. Future studies will build on this foundation, and continue to benefit from technical development, long-term observation at a range of spatial and temporal scales, and active experiments. Advances in instrumentation, including miniaturization, new sensors, increased data storage capacity, and reduction in power requirements, will allow more information to be analyzed at higher data rates and with greater precision.

For example, new borehole observatory systems will monitor and allow sampling within multiple depth intervals. Although monitoring of natural processes will continue to provide useful and exciting results, future experiments also will include active perturbation of hydrogeologic systems, allowing interpretation of system dynamics with greater confidence, and "smart" monitoring technology that varies the rate of data and fluid sampling during events of interest. Future hydrogeologic studies also will link seafloor and subseafloor observations and sampling, and will include a combination of geological, biological, chemical and physical components.

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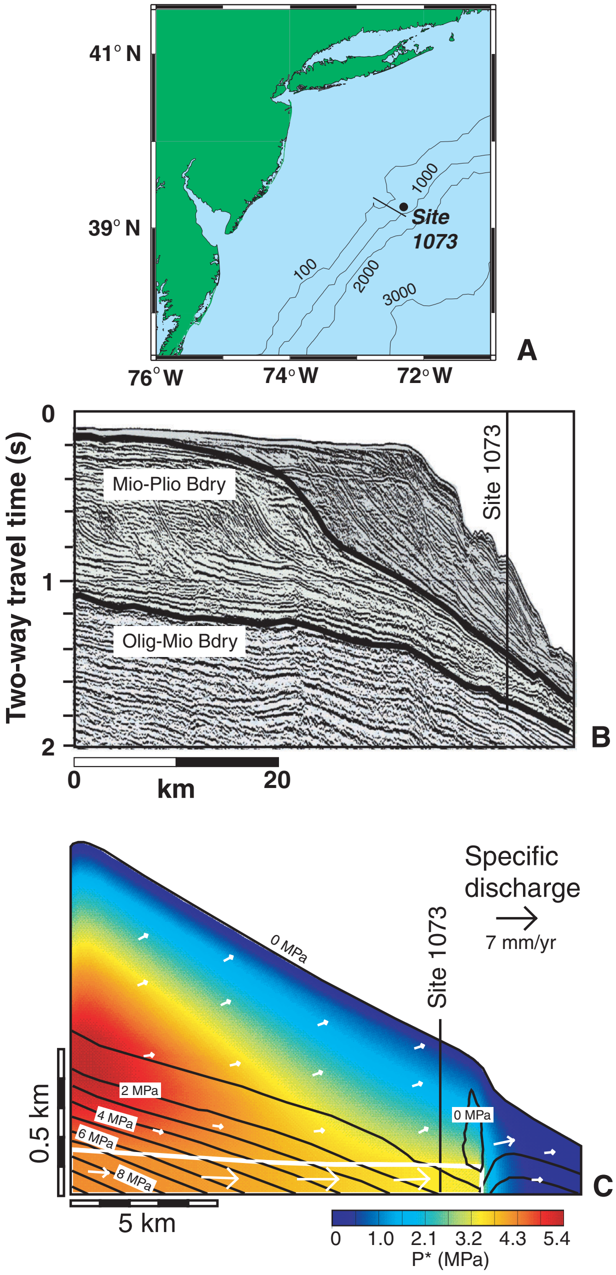

Figure 5. A. *Index map showing location of ODP Site 1073 on the continental slope, New Jersey margin. Thin line perpendicular to slope indicates location of seismic line. Contour depths in meters.* ***B.*** *Seismic line showing regional stratigraphy and stratigraphic interpretation.* ***C.*** *Results of two-dimensional model of coupled sedimentation, compaction and fluid flow. Contours indicate effective stress, colors indicate overpressures (P*), and vectors indicate fluid flow after 1 million years of sedimentation. White line indicates Miocene-Pliocene boundary. Note generation of excess fluid pressure near the toe of the Miocene strata, as well as relatively rapid fluid discharge in this area. Modified from Dugan and Flemings (2000).*

THE EVOLUTION OF AN IDEA: FROM AVOIDING GAS HYDRATES TO ACTIVELY DRILLING FOR THEM

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INTRODUCTION

Over the past decade and a half the Ocean Drilling Program (ODP) has contributed to an amazing turnaround in the perception of marine gas hydrates, one of the hottest topics in geoscience today. In 1986, the JOIDES Pollution Prevention and Safety Panel (PPSP) recommended:

> *"In theory, the gas-hydrate stability zone may be drilled without danger of gas release..., however, a gas-hydrate layer may cap and seal reservoir rocks which are filled with gas.... In view of these considerations...the PPSP policy has been that drilling should not be carried into the strata underlying the gas-hydrate stability zone...".*

The same panel softened its view in 1992:

> *"Indirect evidence for gas hydrate occurrence in deep sea sediments is the bottom-simulating seismic reflection (BSR) that is sometimes present at the base of the gas hydrate stability zone. Previous safety advice was that drilling should not continue beneath the theoretical depth of methane hydrate stability.... Subsequent reinterpretation indicates that quantities of free gas beneath the gas hydrate stability zone should be minor, and that the gas pressure should be controlled at hydrostatic by equilibrium with gas hydrate. Based on this reinterpretation, PPSP has approved drilling beneath visible BSRs in geologic settings that are otherwise considered safe...".*

Now, eight years later, the ODP community has an even more enthusiastic view as stated in the COMPLEX Report:

> *"Ocean drilling revealed the hydrate system, ...recovered hydrates, fluids, and gas as well as tantalizing evidence of their effects on the subsurface environment...and will continue to provide crucial evidence about it.... Thus, there is a challenging new opportunity for a future integrated program of ocean drilling to establish an ocean-wide network of hydrate sampling sites...the only avenue for us to gain insight into how the processes of hydrate formation and release affect the global biogeochemical cycle and how they are related to tectonic processes".*

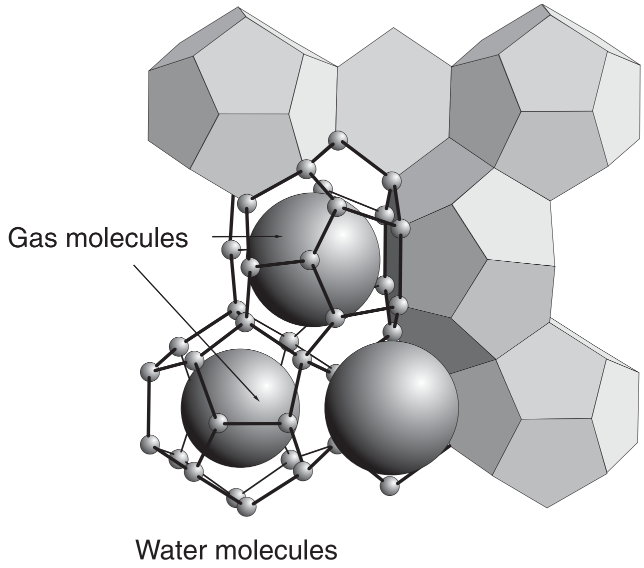
What has happened, and why has gas hydrate gone from a phenomenon to be avoided to one of the most important initiatives of the future Integrated Ocean Drilling Program (IODP)?

This overview begins with general information on the structure and composition of gas hydrates, and then addresses their stability in the marine environment and evidence for their existence in sub-seafloor acoustic records and the Cl anomaly pattern. The final discussion is on the role of gas hydrate as a methane store that fuels unique seafloor and subseafloor ecosystems, affects global climate, and may provide a potential energy resource for the future.

STRUCTURE AND COMPOSITION

It has long been known that natural gas hydrates occur globally in marine sediments, in permafrost regions, and in the continental ice sheets (Kvenvolden et al., 1993). They are solid compounds similar to ice crystals where cages of water molecules enclose molecules of natural gases (Fig. 1). The gases mostly are methane but also include ethane, propane and butane, as well as carbon dioxide and hydrogen sulfide (Sloan, 1990). Three types of crystal structures are found in nature; type I and II belong to the cubic system, and type H to the hexagonal crystal system (Fig. 1). The formation of gas hydrates depends on the presence of sufficiently high gas content, elevated pressure, and low temperature. Their dominant component, methane (CH_4), is largely a diagenetic product of fermentative decomposition of organic matter or of bacterial CO_2 reduction in sediments. Methane also is sometimes formed, along with higher hydrocarbons, by thermocatalytic conversion of organic material in the deeper subsurface. In the

Figure 1. *Gas hydrate of type I structure. Small spheres are tetrahedrally-linked water molecules which comprise the cages; large spheres are gas molecules. Four (5^{12})-cages are shown, one at each corner composed of twelve five-sided polygons known as pentagonal dodecahedra, and two ($5^{12}6^2$)-cages in the center facing each other, composed of twelve five-sided and two six-sided polygons. The (5^{12})-cages are present in all three gas hydrate structure types.*



latter case, the methane migrates from these deeper sources, often from hydrocarbon reservoirs, into the hydrate stability zone. The largest deposits of gas hydrates are found along continental margins where formation of methane is favored by rapid sedimentation and high contents of sedimentary organic matter providing extensive microbial fermentation.

THE HYDRATE STABILITY ZONE AND THE BOTTOM SIMULATING REFLECTOR

Gas hydrates respond rapidly and completely to changes in pressure and temperature by re-equilibration or dissociation. Compositional changes in the environment also exert a significant role on stability. Salinity reduces it, whereas trace gases enlarge the stability field when the temperature is kept constant (Sloan, 1990). The effects are not linear but increase with total pressure. A five-fold increase in salinity, for example, requires the equilibrium pressure to increase by about 13 bar at 300 m of water depth and by about 40 bar at 700 m of water depth (Fig. 2). This increase is equivalent to a change of >200 m in the hydrate stability zone (HSZ). On the other hand, incorporation of about 3 mol-% H_2S at 700 m of water depth lowers the equilibrium pressure by the equivalent of 15 m. These effects lead to considerable uncertainties in the predicted depth of the HSZ, a fact that is not widely appreciated.

Hydrogen sulfide (H_2S) strongly affects the stability of gas hydrates (Fig. 2). Since reports on the H_2S content vary widely, the shift of the HSZ and bottom-simulating reflections (BSRs) can be large. For example, during Leg 146 drilling at the Cascadia Margin, hydrates with from 0.05 mol-% to 10 mol-% of H_2S were found; no H_2S was reported from hydrates of the Blake Ridge during Leg 164 drilling, and the H_2S level of Chilean margin hydrates likewise appeared very low during Leg 141. The other extreme comes from a Leg 182 report postulating gas hydrates with 10 mol-% to 30 mol-% H_2S in the sediments drilled off the Eucla Margin of South Australia. It is possible that very little H_2S is actually present in the hydrate lattice, and that rather high amounts might be trapped in the pore space. With these uncertainties, technological advances in drilling and maintaining hydrates under *in situ* conditions will continue to be essential. Only then can we gain basic knowledge about their distribution and correlation with the acoustic response of subseafloor hydrate deposits.

The presence of gas hydrate in sediments beneath the sea floor is usually identified from a BSR, a negative polarity compressional (p)-wave reflection parallel to the seafloor that is imaged at the base of the HSZ. Previously, the BSR was assumed to result from the contrast between the high acoustic impedance of hydrate-filled sediment overlying a lower impedance hydrate-free zone. However, seismic modelling studies, new data, and high-resolution wide-angle multi-channel seismic reflection (MCS) data have shown that the development of a strong BSR requires the presence of certain amounts of free gas beneath the hydrate-cemented sediment (Mienert et al., 2001; Pecher et al., 1996; Bangs et al., 1993; Fig. 3). Leg 164 data support these interpretations; a BSR is present in a zone containing free gas immediately beneath the hydrate, but no BSR is present where free gas is absent (Holbrook et al., 1996). Thus, although the presence of a BSR means that gas hydrates are present, the converse is not true. The absence of a BSR does not mean there are no hydrates.

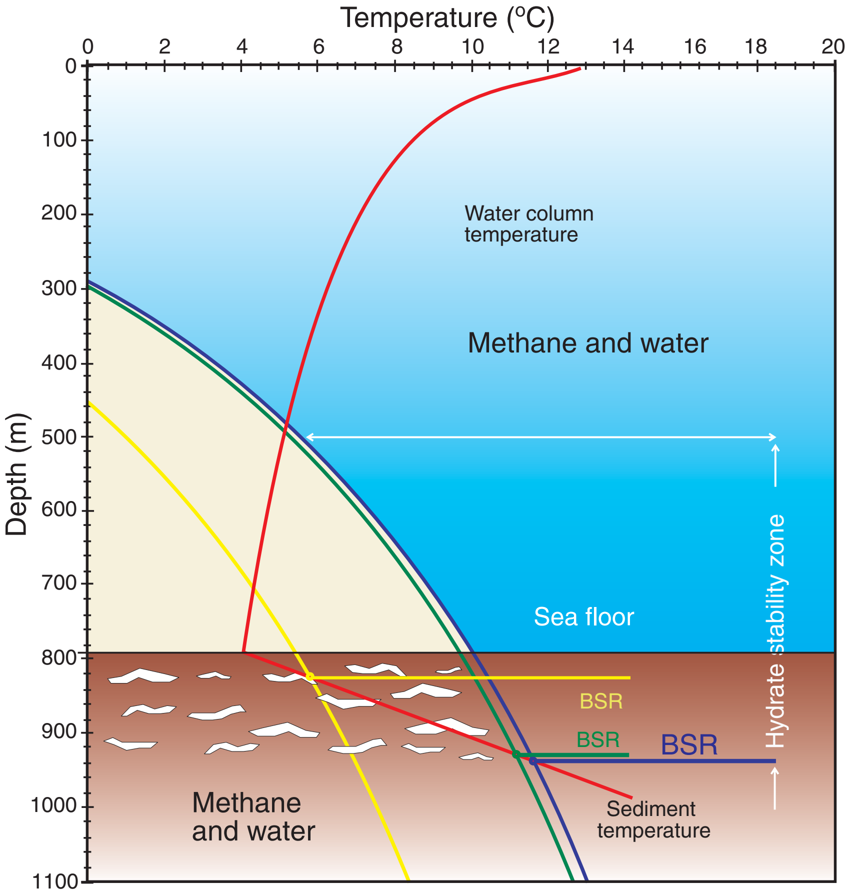


Figure 2. *Stability and phase boundaries of gas hydrates superimposed on depth-temperature distribution (red) in the ocean and the upper sediment column. Also shown are the phase boundary of pure methane hydrate at normal seawater salinity (green), the phase boundary of methane hydrate with 3 mol-%* H_2S *at seawater salinity (blue), and the phase boundary of pure methane hydrate in five times sea water salinity (yellow). Intersections of temperature profiles with the phase boundaries define the hydrate stability zone (HSZ) and the bottom simulating reflection (BSR) for each of the three hydrate compositions.*

CHLORIDE-ANOMALY PATTERN AND THE "MISSING SALT"

Direct retrieval of gas hydrates on board ship, without maintaining *in situ* conditions, is usually a matter of pure luck. Hydrate samples that "survive" have begun to dissociate or might be contaminated. Hence, their composition and physical properties can only be characterized in a limited way. Nevertheless, significant advances have been made in understanding marine gas hydrates from the beginning of the Deep Sea Drilling Project (DSDP Leg 67 and Leg 76) and continuing through ODP (Legs 112, 141, 146, and 164, the latter having been dedicated to gas hydrate sampling). Along with actual pieces of recovered gas hydrate, indirect evidence for their presence exists in pore fluids through the well-known artifact of negative Cl anomalies. Gas hydrates were first indicated, later documented, and eventually quantified by chloride anomalies. These anomalies result from the release of hydrate water during core retrieval, causing dilution of the normal pore-fluid salinities and chlorosities. This effect is known as "freshening" among the ODP community.

From such freshening of fluids, it is estimated that 10% to 15% of the available pore space in the Chilean and Cascadia accretionary sediments is occupied by hydrate. On the Blake Ridge, it is estimated to increase from 1.4% at the ridge flank to at least 2.1% at the crest (Matsumoto, 2000). We still largely rely on this Cl anomaly as the best evidence for the presence of hydrates, although new data from hydrates exposed at the seafloor suggest that the calculation of the amount of hydrate has been significantly underestimated due to residual chloride trapped within the hydrate pore space (Suess et al., 2001). The same has been observed when synthesizing hydrates in NaCl solutions. It is unknown whether trapped ions also are present in deep hydrates.

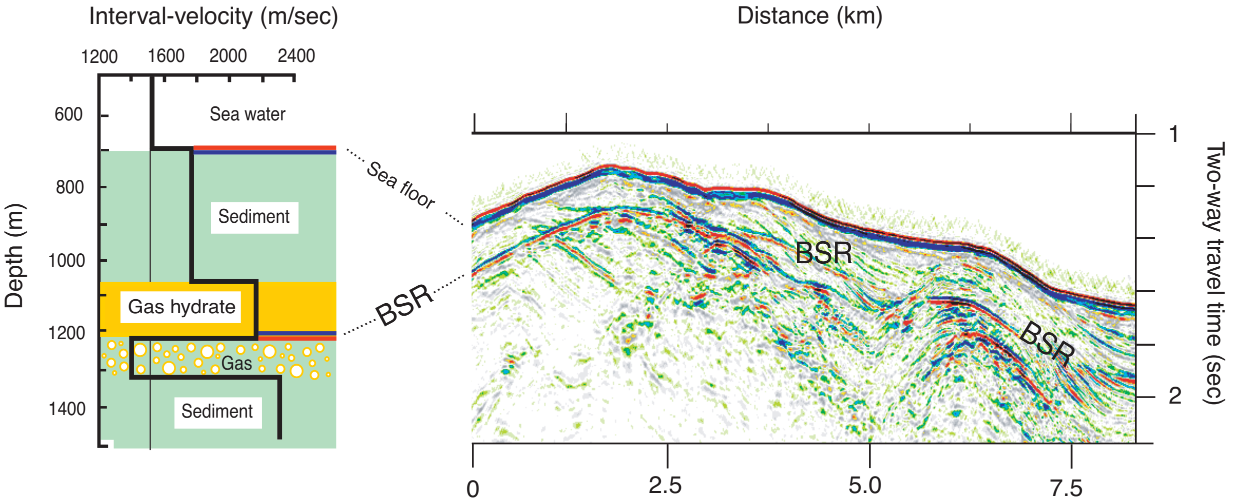
Although "freshening" of pore fluids is observed in cores, the opposite (enrichment) should occur *in situ* because the ions of sea salt and the light isotopes of water, ^{16}O and ^{1}H, are excluded and become enriched in the residual pore fluid. Over the past decade and a half of ODP drilling, convincing evidence for "excess salt" as well as "light isotopes" has remained elusive. On the contrary, as discussed previously, dissociation of hydrate during core retrieval tends to mask and even reverse any "salt and light isotope" exclusion.

Leg 146 (Kastner et al., 1998) and Leg 164 (Matsumoto, 2000) pore fluid data were used to derive an O isotope fractionation factor, $\alpha = 1.003$, for *in situ* hydrate formation (Fig. 4). This factor agrees with the value estimated from hydrate water analyses and with experimentally derived values (Maekawa and Imai, 2000). Figure 4 illustrates how the fractionation of ^{18}O to ^{16}O between pore water and hydrate water derived from dissociation is related to the fractionation under *in situ* conditions, assuming a closed system. Only the latter case represents the "real world". No field data have yet been discovered from that situation. Ocean drilling and recovery of hydrated sediment under *in situ* conditions are the only means with which to verify this process.

ANAEROBIC METHANE OXIDATION AND THE GAS HYDRATE CONNECTION

Methane from gas hydrates greatly stimulates microbial activity not only at the seafloor but much deeper than previously believed. High levels of microbial methane oxidation and high cell counts from sediments

Figure 3. *Schematic seismic velocity distribution of subseafloor strata (left) and seismic profile across hydrate and gas-containing strata showing layered and folded structures with crosscutting bottom simulating reflection (BSR; right). Red = large positive amplitude p-waves, and blue = large negative amplitude p-waves. BSR with negative polarity comes from the contrast between high acoustic impedance of hydrate-filled sediment (>2000 m/sec) and free gas-containing sediment (<1500 m/sec). Sea floor reflection shows positive polarity from contrast between sea water seismic velocity (1500 m/sec) and sediment velocity (about 1800 m/sec).*



of the gas hydrate stability zone and underlying free gas zone were among the outstanding results of ODP data collected during Legs 146 and 164. These data suggest that microbes extensively oxidize methane, apparently utilizing sulfate in the absence of oxygen. Such a process has long been suspected by geochemists, based on reaction-transport models of interstitial sulfate and methane (Borowski et al., 2000). The recent first identification of a microbial consortium of methanotrophic archeabacteria and sulfate-reducing bacteria from gas hydrate-bearing sediments (Boetius et al., 2000), has opened the door for anaerobic methane oxidation (AMO) research. The increasing library of biomarkers, combined with C isotopes information on the molecular level, promise an enormous leap in the basic knowledge of these processes (Elvert et al., 1999).

The significance of this ongoing research, and the essential role of ODP, is dealt with in the chapter on The Deep Biosphere (D'Hondt, this volume). In the context of this article, emphasis is placed on the importance of AMO for the formation of authigenic hydrate-carbonates, limestone buildups at the seafloor known as "chemoherms" (Bohrmann et al., 1998). Other AMO-related features are crusts, concretions, cement, and massive limestone beds in deep continental margin sediments, often referred to as "organic carbonates". The biogeochemical process underlying this carbonate formation and its intimate association with gas hydrates can be gleaned from the set of reactions shown in Table 1. Gas hydrates provide an almost inexhaustible supply of isotopically "light" methane (shown in red as $^{13}C/^{12}C$) which is transformed by the microbial consortium into bicarbonate. The bicarbonate then equilibrates with pore water containing ^{18}O-enriched hydrate water (shown in blue as $^{18}O/^{16}O$). This process is unique for the recognition of gas-hydrate involvement because the oxygen isotope signal is "heavier" than expected from normal pore water. This "heavy" water signal originates from hydrate water via dissociation and is recorded by the precipitating $CaCO_3$ phases along with isotopically "light" calcium carbonate (shown in blue and red). The mineral phases formed are low- and high-Mg calcites with a highly enriched ^{12}C isotope signal of up to -60‰ PDB. Aragonite and dolomite have been reported with similar C isotope signals.

The hydrate-associated carbonates also faithfully preserve biomarker evidence for the individual microbial reactions involved in methane oxidation from gas hydrates. These are shown in red in Table 1 as two types of "lipid biomarker". One group is synthesized by sulfate-reducing bacteria (SRBs), the other by archaebacteria (Boetius et al., 2000). Biomarkers of archaebacteria consist of irregular saturated and unsaturated isoprenoids known as crocetane and pentamethylicosane (PMI). They are the dominant compounds obtained from gas hydrate-containing sediments and carbonate precipitates. Crocetane and PMI in such a setting are specific for known methanogenic archaebacteria, which grow on methane as their carbon source rather than forming it as a metabolic product. The sulfate-reducing bacteria of the consortium are recognized by other lipid biomarkers. The association of archeabacteria- and SRB-derived biomarkers identify the AMO consortium. Both groups of molecular compounds also contain ultra-high enrichments of ^{12}C derived from hydrate methane; $\Delta\delta^{13}C$ values of between

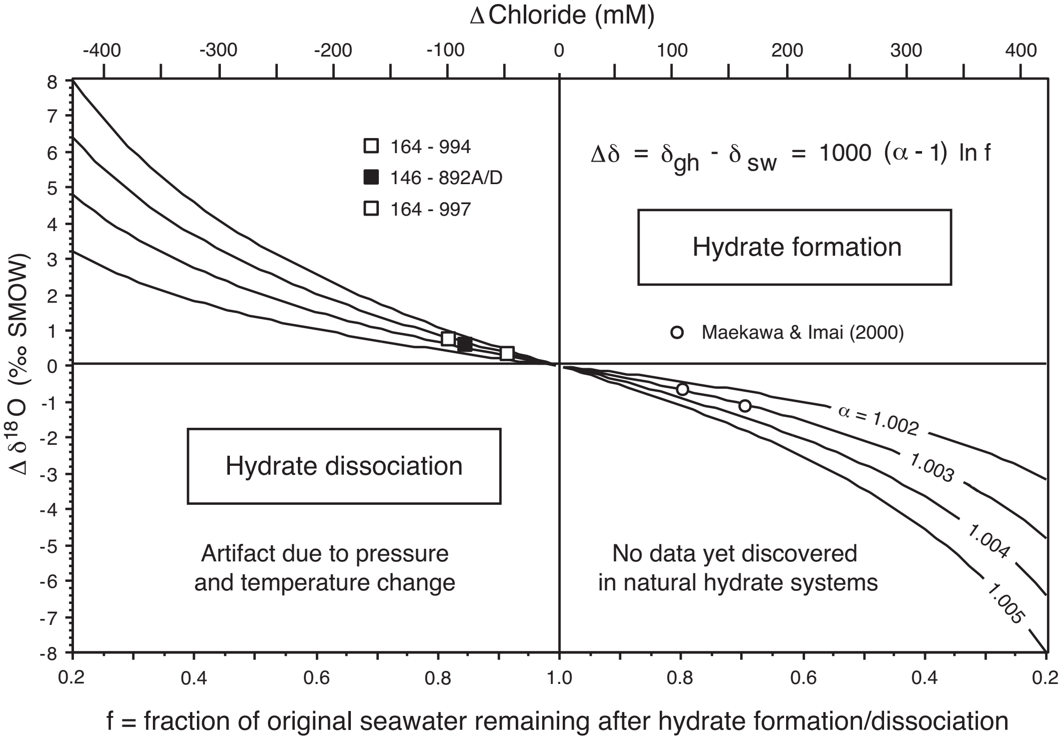


Figure 4. *Oxygen isotope fractionation ($\Delta\delta^{18}O$) between pore water and hydrate water and simultaneous Cl anomaly (ΔCl mM). Hydrate dissociation (left quadrant = artifact) causes Cl dilution and ^{18}O enrichment; hydrate formation (right quadrant = real world) causes Cl enrichment and ^{18}O depletion. The fraction factor, α = 1.003, was derived from Leg 146 and Leg 164 pore fluid data, and agrees with experimentally derived values.*

-102 and -124‰ PDB for crocetane and PMI have been reported (Elvert et al., 1999). These unambiguously document the gas hydrate connection.

FUTURE ENERGY RESOURCE AND IMPACT ON CLIMATE

Marine as well as permafrost-bound gas hydrates have come under increased worldwide attention. The large volumes of methane stored in these deposits represent a significant fraction of the global methane budget, and may be an almost inexhaustible energy resource for the future (Kvenvolden et al., 1993; Booth et al., 1998).

Massive and catastrophic release of methane hydrates from subseafloor deposits are believed to have triggered transient warm climates, and are implicated in the generation of large submarine slides with ensuing tsunamis (Dickens et al., 1997; MacDonald, 1990). One locality from which such a catastrophic release has been identified through ODP drilling is the Blake Spur in the western Atlantic. The evidence is based on chaotic and brecciated sediment fabric from disrupted strata left behind after methane eruption during the Late Paleocene Thermal Maximum (LPTM), a time of extremely warm global climate (Norris and Röhl, 1999).

Overall reaction by microbial consortium

Hydrate methane

$$^{13/12}CH_4 + SO_4^{2-} \longrightarrow H^{13/12}CO_3^- + HS^- + H_2O$$

Hydrate water

$$H_2O \longleftrightarrow H_2^{18/16}O$$

Isotope exchange equilibrium

$$H_2^{18/16}O + CO_2 \longleftrightarrow H^{13/12}C^{18/16}O_3^- + H^+$$

Carbonate equilibrium

$$H^{13/12}CO_3^- \longleftrightarrow H^+ + {}^{13/12}C^{18/16}O_3^{2-}$$

Sulfide removal

$$H^+ + HS^- \longleftrightarrow H_2S$$

Precipitation

$$^{13/12}C^{18/16}O_3^{2-} + Ca^{2+} \longleftrightarrow Ca^{13/12}C^{18/16}O_3$$

Aragonite and High-, Low-Mg calcite

Possible individual reactions

Hydrate methane

$$^{13/12}CH_4 + 2\,H_2O \longrightarrow {}^{13/12}CO_2 + 4\,H_2$$

Archeae-C Lipid biomarker

$$SO_4^{2-} + 4\,H_2 + H^+ \longrightarrow HS^- + 4\,H_2O$$

SRBs-C Lipid biomarker

Table 1. *Coupled anaerobic methane oxidation (AMO) and calcium carbonate precipitation as a unique process for gas hydrate environment. Hydrate methane =* $^{13/12}CH_4$ *and hydrate water =* $H_2^{18/16}O$ *are involved in precipitating hydrate* $CaCO_3$ *phases. Groups of lipid biomarkers from methane oxidizing consortium (sulfate-reducing bacteria = SRBs and Archeabacteria) contain ultra-high enrichments of* ^{12}C*; (*$\Delta\delta^{13}C$ *= -102 ‰ and -124‰ PDB, respectively). Biomarkers are preserved in hydrate* $CaCO_3$ *phases.*

Generally, release of large amounts of methane implies a positive climate feedback (MacDonald, 1990). Dissociation of hydrate from shelf and upper slope deposits caused by post-glacial warming may further accelerate global greenhouse warming. Conversely, sea level lowering during initiation of ice ages may have a negative feedback. This also is caused by dissociation of continental margin hydrates, but with the effect of inhibiting further cooling and lowering of sea level (Paull et al., 1991). Dissociation of hydrates in either scenario could mechanically destabilize continental margin sediments and lead to massive slides.

A third possible way for gas hydrates to affect global climate is by "hydrate floats". These chunks of porous, positively buoyant hydrate constitute an efficient mechanism for rapid transport of methane directly into the atmosphere, where it is climatically active. Large chunks of gas hydrate, newly formed from free methane gas in near-surface sediments, have been observed to detach from the seafloor and float to the surface (Suess et al., 2001). Central to the hypothesis of hydrate floats is the role of the porous hydrate fabric. It consists of macroscopic pores filled with free methane providing the buoyancy. These scenarios remain speculative, however, as the volume of gas stored in the hydrate reservoir, and its physical and chemical properties and behavior during changing environmental conditions, are currently not well understood.

OUTLOOK

Research on natural methane hydrates, in seafloor and deep subseafloor settings at active and passive continental margins, is a topic of worldwide interest. IODP is set to play a leading role in the following high prior-ity gas hydrate research topics in the coming decade:

- Recent data indicate the existence of highly specialized ecosystems in seafloor gas hydrate sites and in hydrates of deeply buried strata, where large quantities of methane carbon are efficiently converted. Characterization and quantification of turnover rates of methane from gas hydrates is indispensable to understanding the global carbon cycle.
- The quantification of hydrates and free gas is a high priority. The relationship between seismic detection and quantity, as well as phase properties of gases and

hydrates, is poorly understood. Gas hydrate thermodynamics and kinetics also affect seismic properties.

- The role of hydrate methane as a greenhouse gas has not been adequately considered in global climate models. Data from paleoclimate research suggest that gas hydrates might have played an important role in the world's climate. Gas hydrates are sensitive to the equilibrium of the natural environment. They are stable under low temperatures and/or high pressure but respond rapidly to changes, providing a modulator for the greenhouse gas budget.
- The influence of hydrate on slope stability, the mechanical behavior of sediments and their resulting hazards are not known. However, evidence from the geologic record is mounting that gas hydrate dissociation may often trigger submarine slumps and slides, possibly leading to damage of offshore structures as well as generating devastating tsunamis.
- The exploitation of gas hydrates as an efficient energy source has been unsuccessful due to the complex technical requirements for economical extraction despite existing offshore and onshore expertise. Potentially serious environmental consequences, and the continued emission of CO_2 when using hydrate as fuel, may ultimately prevent worldwide exploitation.

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EXPLORATION OF THE MARINE SUBSURFACE BIOSPHERE

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INTRODUCTION

The Ocean Drilling Program (ODP) has provided a unique glimpse of another living world - the buried biosphere of deep-sea sediments and crust. Porewater geochemical studies of sediments recovered by ODP have shown that microbial activity occurs beneath the seafloor throughout much of the world. Direct counts of microbial cells in ODP samples have shown microbes to be ubiquitous in the subsurface realm of deep-sea sediments (Cragg et al., 1990; Thierstein and Störrlein, 1991; Parkes et al., 2000). Biogeochemical and microbiological studies have pushed the estimated maximum burial depth of the subseafloor sedimentary biosphere to more than 800 meters below seafloor (mbsf).

The results of ODP studies suggest that subseafloor microbes may constitute a large and biogeochemically important portion of Earthly life. Extrapolation from direct cell counts of ODP samples suggests that the subsurface biosphere of seafloor sediments may constitute as much as one-third of the living biomass on Earth (Whitman et al., 1998). The activities of this subsurface biosphere affect long-term global biogeochemical cycles by mediating the diagenesis of marine sediments (Claypool and Kaplan, 1974) and the weathering of oceanic basalt (Fisk et al., 1998). Under certain conditions, the subsurface microbes may also occasionally affect the surface Earth on much shorter time scales. Intermittent release of methane (CH_4) from marine sedimentary hydrates may have greatly affected the global climate and/or oceans at multiple times in Earth history (Dickens, 2001).

PRE-ODP STUDIES

The subsurface biosphere has been a subject of intermittent investigation since the early 20th century. Pioneering work was undertaken by U.S. microbiologist E. Bastin and colleagues in the 1920s, and by Soviet microbiologists T.L. Ginsburg-Karagitscheva and V. Issatchenko in the 1930s and 1940s. These early studies of subsurface life were generally limited to analyses of the formation fluids of oil wells, sampled at well heads. For example, in an elegant microbiological and geochemical study, Bastin and collaborators identified and cultured sulfate-reducing bacteria from the formation fluids of 28 oil wells in Illinois and 15 oil and water wells in California (Bastin et al., 1926). The fluid-producing horizons ranged in burial depth from 400 ft to 3090 ft (122 m to 942 m), and temperatures at the wellhead of fluids from these horizons were as high as 47°C. The Illinois horizons were Ordovician to Pennsylvanian in age and the California horizons were of Miocene and Pliocene age.

These early investigations provided microbiological and geochemical evidence that subsurface oil and gas deposits support an active microbial world fueled by degradation of the buried hydrocarbons. However, the ecologic structure, environmental consequences, rates of metabolic activity and genetic composition of this world were essentially unknown, as was the existence of an active microbial world in less organic-rich sediments and the rocky crust of the continents and oceans.

Sediments recovered by the Deep Sea Drilling Project (DSDP) provided the first evidence of microbial activity in the subsurface realm of oceanic sediments. This evidence took two forms. First, downhole profiles of CH_4 and sulfate (SO_4^{-2}) concentrations, and isotopic signatures, indicated that microbial activity can occur throughout the deep-sea sediment column, even at burial depths as great as 800 m and in sediments that have been buried for tens of million years (m.y.) (Claypool and Kaplan, 1974). Second, experimental manipulation of sediment samples from DSDP cores demonstrated that methanogenic and sulfate-reducing activity can be readily induced in DSDP sediments recovered from a range of burial depths.

In the first of these experimental studies, Oremland and colleagues (1982) measured CH_4 concentrations during incubation experiments with DSDP sediments from the Gulf of California. These experiments demonstrated that methanogenic activity occurs in sediments recovered from burial depths as great as 12 mbsf. Two subsequent studies used far more sensitive radiotracer experiments to identify anaerobic microbial activity in sediments recovered at six DSDP sites along the New Jersey Margin (Tarafa and Whelan, 1987) and the Gulf of Mexico (Whelan et al., 1986).

These radiotracer studies, undertaken during the last two DSDP legs, had two objectives. The first was to test for the presence of potential microbial activity in sediments recovered from depth. The second objective was to set the stage for ODP studies of the subsurface biosphere by developing methodology for microbiological experiments on future ODP cruises (Whelan et al., 1986). DSDP scientists succeeded in both objectives. Sulfate-reducing and methanogenic activity occurred in radiolabeled samples recovered from a wide range of burial depths at all six sites, including the most deeply buried sample recovered from 167 mbsf (Whelan et al., 1986; Tarafa and Whelan, 1987).

ODP STUDIES OF THE SUBSURFACE BIOSPHERE

Porewater Traces of Subseafloor Catabolism

Prior to direct microbiological studies of the subseafloor biosphere, the DSDP began an ambitious program of studying interstitial water (porewater) and organic chemistry in deep-sea drill cores. This program was carried forward into the ODP, where it remains an integral part of every cruise. By studying the porewater chemistry and organic geochemistry of cored sediments, ODP researchers have been able to sensitively track changes in the organic and inorganic inventories of the solid and aqueous phases within sedimentary sequences.

Microbiological activity has commonly been inferred from these chemical distributions. Throughout the history of DSDP and ODP, shipboard studies have routinely identified downhole patterns of SO_4^{-2} depletion, methanogenesis, methanotrophy, alkalinity enrichment, manganese (Mn) reduction, and ammonium (NH_4^+) production and depletion. Related DSDP and ODP studies have used stable isotope analyses of CH_4, CO_2, and SO_4^{-2} in sedimentary pore waters to identify the occurrence of specific microbial processes in subsurface regimes (e.g., within the subsurface methanogenic zone).

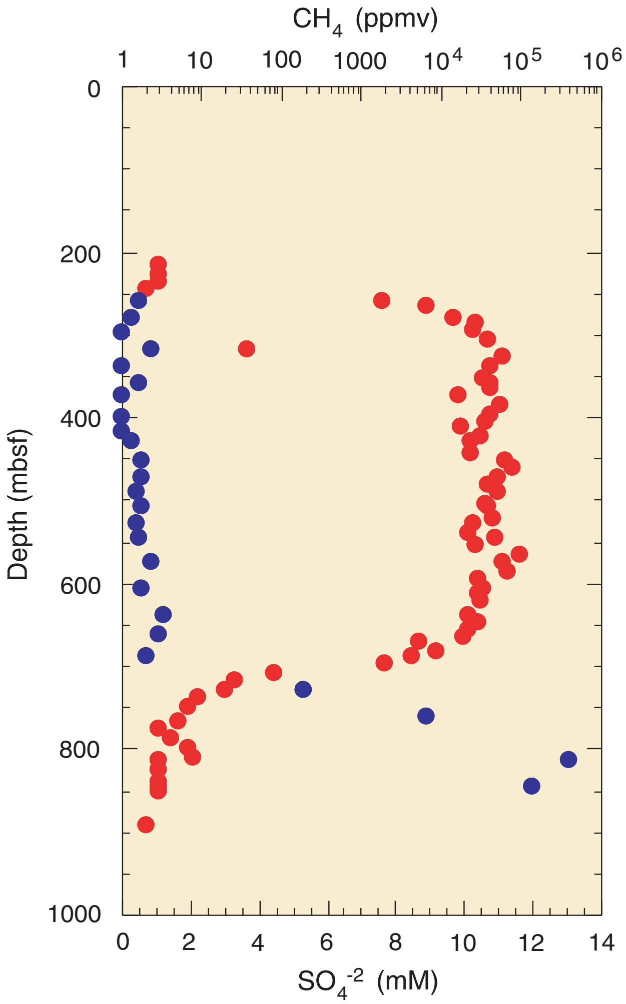

Figure 1. *Porewater concentrations of SO_4^{-2} (blue circles) and CH_4 (red circles) at ODP Site 1118 boreholes, drilled during Leg 180 in the Woodlark Basin, western Pacific Ocean.*

Cruise after cruise, ODP chemical studies have provided consistent evidence of subseafloor microbial activity throughout the world ocean (e.g., D'Hondt et al., 2002). These shipboard studies have also shown that this subsurface activity can extend hundreds of meters beneath the seafloor, particularly along ocean margins. For example, porewater chemical data show that subsurface flow introduces abundant dissolved SO_4^{-2} to deeply buried methane-rich sediments at ODP Site 1118, explored during Leg 180 in the Woodlark Basin of the western Pacific (Fig. 1). The sharply intersecting gradients of SO_4^{-2} and CH_4 concentrations at this site demonstrate that the introduction of SO_4^{-2} sustains active anaerobic methanotrophy at depths in excess of 705 mbsf. Flux estimates based on these concentration gradients indicate that microbes buried at and below this depth collectively reduce 2×10^{-7} moles SO_4^{-2}/cm²-yr, oxidizing an equivalent amount of CH_4 in the process. This rate of deeply buried catabolic activity is nearly comparable to the rate of activity in shallowly buried sediments of the same region. For example, at nearby ODP Site 1109, the downward flux of sulfate into the sediment allows subsurface microbes (microbes buried more deeply than 5 mbsf) to reduce 8×10^{-7} moles SO_4^{-2}/cm²-yr, with 85% of the downward-diffusing SO_4^{-2} going to anaerobic methanotrophy at approximately 100 mbsf.

Microbiological Studies

Several research groups have advanced our understanding of the subseafloor biosphere. However, our direct knowledge of the organisms buried in deep-sea sediments has been most greatly advanced by the dedicated effort of a single research group, led by R. J. Parkes. Parkes, B. Cragg, and colleagues participated as shore-based or shipboard scientists on nearly a third of all the ODP cruises that occurred in the 1990s. Direct counts of microbial cells stained with Acridine Orange demonstrated that microbes are ubiquitous in subsurface deep-sea sediments throughout the world ocean (Fig. 2; Parkes et al., 2000). Radiotracer studies extended the DSDP findings of Whelan, Tarafa and colleagues throughout the continental margins of the world ocean by revealing the occurrence of SO_4^{-2} reduction, methanogenesis and CH_4 oxidation in subseafloor sediments recovered from the margins of Peru, Japan, the northeast Pacific (Cascadia Margin) and the western North Atlantic (Blake Ridge) (Parkes et al., 2000). Most-probable-number (MPN) enrichment cultivations showed that culturable bacteria represent a very small proportion of the direct counts (0% to 0.6%) that is often predictably correlated with potential microbial activity and porewater chemistry. For example, the proportion of viable sulfate-reducing bacteria is correlated with sulfate-reduction rates and porewater SO_4^{-2} concentrations (Parkes et al., 2000). Polymerase-chain-reaction (PCR) amplification of high-molecular-weight DNA from subsurface sediments of the Japan Sea and the Cascadia Margin provided the first evidence of the genetic composition of subseafloor microbial communities (e.g., Rochelle et al., 1992). Isolation and genetic characterization of a barophilic sulfate-reducing bacterium from deeply buried sediments of the Japan Sea (80 mbsf and 500 mbsf) led to the identification of an entirely new species, *Desulfovibrio profundus* (Bale et al., 1997).

Other research groups have advanced evidence of microbial communities in oceanic crust. Altered surfaces of oceanic basalt display textures suggestive of individual microbes and microbial aggregates (Fisk et al., 1998). Prokaryotic DNA has been identified in some altered surfaces of deep-sea basalts sampled by ODP drilling (e.g., Torsvik et al., 1998). Along with laboratory weathering experiments (Staudigel et al., 1998), these findings suggest that microbial activity plays an important role in the weathering of oceanic crust.

Assessment of Microbial Contamination

Because microbes can be introduced from the surface Earth (and from shallower burial depths) during drilling and sample handling, interpretations of subsurface microbiology are complicated by the possibility of contamination. The potential for such contamination is exacerbated by the fact that cell concentrations, nucleic acid concentrations, potential activities, and a number of other indices of microbial activity and abundance are generally much lower in subseafloor environments than in the surface world (Parkes et al., 2000). In order to better assess the possible effects of contamination on interpretations of the subseafloor biosphere, the ODP Deep Biosphere Program Planning Group recommended that procedures be standardized for quantitatively testing the possible extent of microbial contamination during drilling of unconsolidated sediments, consolidated sediments and igneous oceanic crust.

Shipboard scientists standardized and applied such contamination protocols for the first time on western Pacific ODP Leg 185 (Smith et al., 2000). Their protocols relied on perfluoromethylcyclohexane as a fluid tracer and microbe-sized fluorescent microspherules as a particle tracer. These protocols were adapted from techniques that were originally developed and have been routinely used for studies of microbial contamination in continental drilling (e.g., Griffin et al., 1997). Based on the fluid tracer, the centers of most recovered cores contained undetectable or very small amounts of contaminants. These small concentrations correspond to potential drilling contamination of no more than a few bacteria per gram of sediment. This finding indicated that the *JOIDES Resolution* is a useful platform for clean sampling of the deep biosphere. It also suggested that the vast majority of the cells enumerated in previous studies (e.g., Parkes et al., 2000) were indigenous to the sampled sediments. The contamination protocols of Smith et al. (2000) are now routinely applied on ODP legs of special microbiological interest.

CONCLUDING REMARKS

The cruises of the ODP drillship, the *JOIDES Resolution*, have provided unique documentation of subseafloor microbial communities and microbially mediated biogeochemical processes in a wide variety of subseafloor environments. These include organic-rich sediments of continental margins, organic-poor sediments of the open ocean, mid ocean ridge hydrothermal

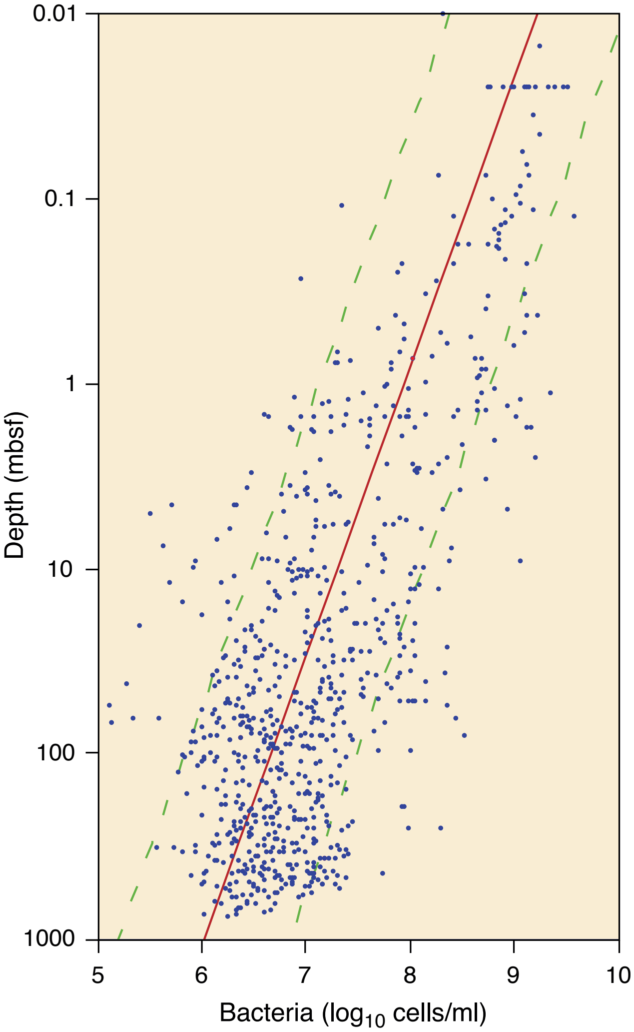

Figure 2. *Direct counts of microbial cells in ODP sediment samples. Detection limit is 104 cells/ml. Figure modified from the University of Bristol Geomicrobiology website (http://biosphere.gly.bris.ac.uk/Pops/Pops.html). Data sources listed in Parkes et al. (2000).*

systems, and the relatively cold environment of several-m.y.-old oceanic crust.

Studies of the samples and data collected during ODP cruises have documented the common occurrence of microbial activity and abundant microbial cells deep beneath the seafloor. Studies of ODP samples have led to the first genetic assays of the subseafloor biosphere and the first discovery of a new species uniquely adapted to a subseafloor environment. These results are tantalizing. However, they provide only a fragmentary glimpse of the subsurface world.

Many fundamental questions remain to be answered by future ocean drilling. At the most basic level, we need to determine whether most individual cells routinely enumerated in ODP sediment samples are active, dormant or dead. The genetic continuity of the marine subsurface biosphere from one environment to another awaits exploration, and the factors that ultimately limit the presence and activity of subsurface life remain to be proven. The possibility of a deeply buried, hot sub-seafloor biosphere that exists completely independently of the sunlit surface world is largely untested.

Some of these fundamental questions will be addressed in the closing legs of the Ocean Drilling Program. For example, Peru Margin and equatorial Pacific ODP Leg 201 will address the continuity of subsurface microbial activities and communities from organic-rich margin sediments to organic-poor open-ocean sediments. Other fundamental questions will be addressed only if ODP is succeeded by a new phase of ocean drilling, such as the Integrated Ocean Drilling Program now receiving widespread support from the international Earth and ocean science communities.

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ILLUMINATING EARTH'S MANTLE AND CORE: A NEW CHALLENGE FOR ODP

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INTRODUCTION

Scientists affiliated with the Ocean Drilling Program (ODP) have been investigating cores drilled at sedimentary and crustal depths beneath the ocean floor that covers 71% of Earth's surface. If we view the Earth as a solid, however, the mantle and core hidden beneath the crust constitute more than 99% of Earth. During the past few decades, it has become obvious that the dynamics of the Earth's deep interior control various aspects of its surface processes. The core dynamo determines the geomagnetic field. Mantle rocks rise up and produce magmatic liquids that solidify to form the crust, quickly transferring heat that can modify the climate. Oceanic plate subductions produce arc volcanisms and back-arc openings. These examples emphasize the dynamic interaction between the earth's surface and its deep interior. How the transfer of material and energy operates remains a major question. What are the key processes, and how essential are their effects to life on Earth through oceanic hydrothermal activity, sea level variations, rapid climate change, and other aspects of the ocean-atmosphere system?

Figure 1 shows that we have hypotheses for these questions but not enough evidence for verification. Why are the plates distributed the way they are, and why do they move the way they do? Are plumes connecting the bottom of the mantle and the surface in a much more effective way than normal mantle con-

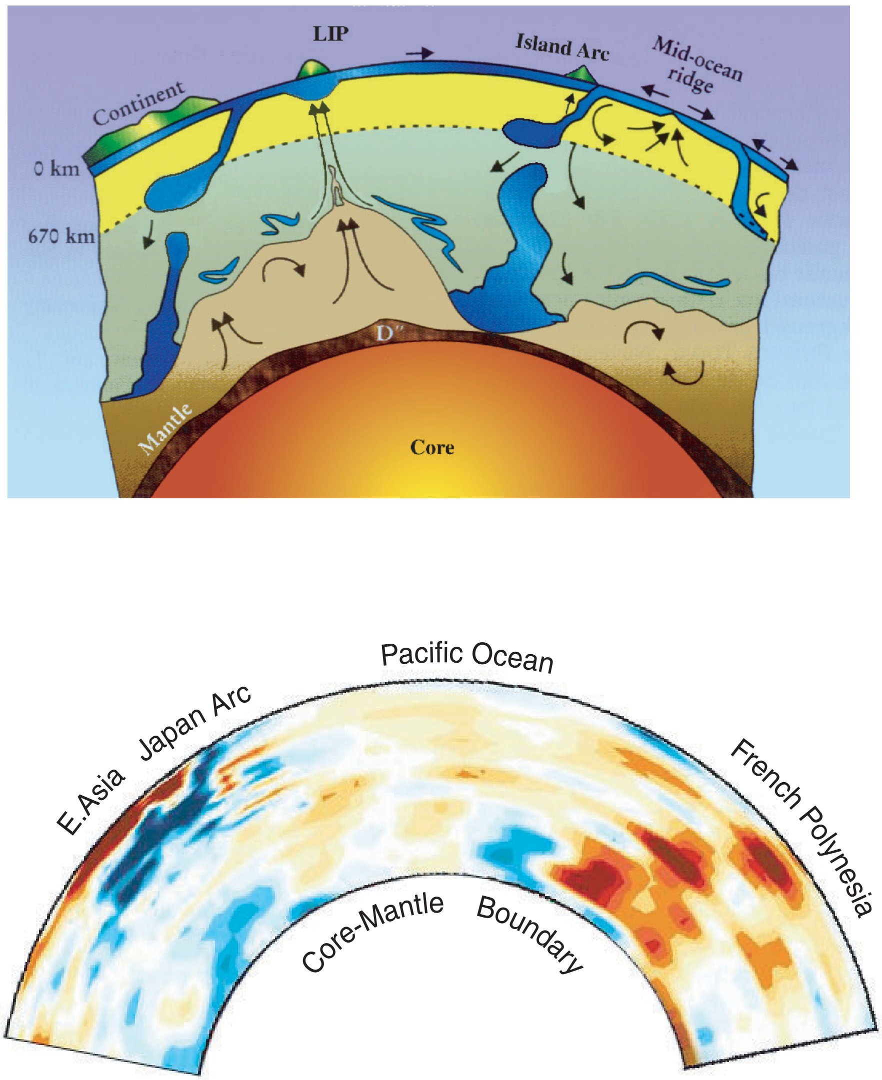

***Figure 1**. Earth's dynamism and actual tomographic view. Models similar to the upper illustration (modified after Kellogg et al., 1999) have been proposed to explain how the earth operates physically and chemically. Verification of such models will rely on the quality of seismic tomography. Resolution of the present seismic tomography of the crust and mantle, as shown in the lower illustration across the Pacific Ocean (after Fukao, pers. comm.), suffers from lack of stations in the oceans. The conspicuous red feature on the right side suggests an upwelling plume from the core-mantle boundary to surface. The dark blue feature on the left suggests stagnation of subducted plates at the boundary of upper and lower mantles.*

vection would do in terms of material and energy transfer? How well is the mantle mixed?

The traditional approach of ODP in addressing major scientific problems is to directly sample representative material from the seafloor. To understand transfers from and to the deep interior of Earth, sampling of the whole globe is needed. Remote sensing is the only way to achieve this scale of sampling. Tomographic images can help constrain convecting movements within Earth. Much of the present day understanding of the mantle and core dynamics comes from snapshots by means of seismological, geodetic, or electromagnetic observations from stations on land. However, as shown in Figure 1, present day images are incomplete and lack sufficient resolution because the coverage of Earth's surface is irregular owing to the uneven distribution of land. Seafloor stations are required to fill the gaps.

The seismology community has long suggested that ODP holes could provide excellent environments for such observatories. Borehole or vault seismic observatories on land produce data of improved quality since atmospheric and temperature disturbances are removed from the data. A comparison can be made with astronomy telescopes located at the top of Mauna Kea, Kit Peak, or even on a space-orbiting satellite to minimize disturbances. How this approach translates to seafloor observatories has been debated. ODP has definitely made the step forward toward new discoveries by scanning the earth through seafloor boreholes.

ILLUMINATING THE SOLID INTERIOR BY SCANNING

Scanning by Seismic Rays

Natural earthquakes mostly occur at plate boundaries; in particular, large events mainly occur along the Pacific Rim. These are the signal sources that emit body (P and S) waves and surface waves that can be observed worldwide if the signal can be extracted from the noise at each station. The number of occurrences per given time period increases more than tenfold as the earthquake magnitude (M) scale unit decreases by one. More than ten earthquakes of $M>7$ occur every year, on average, but only in limited areas. More than 150 events of $M>6$ occur annually. Present day seismic tomography images rely on hundreds of thousands of seismic records spanning more than thirty years of observations. Ways to obtain new constraints are to increase the number of events, particularly the larger ones, and the number of stations to scan every part of the body of Earth by seismic rays. This is why it is important to construct a network of high quality stations at as many places on Earth as possible. Presently, high resolution is about 1000 km at a horizontal scale. The upper mantle beneath major oceans remains basically unresolved.

Seismic Information: What Does It Tell Us?

Seismic tomography images as in Figure 1 show the deviation from a certain reference model that defines the distribution of P and S wave velocities with depth. What are they telling us? Velocities are directly dependent on elastic parameters and density. A more qualitative but interesting view is to see the deviations as hotter or colder than average. This can be justified if we assume that the thermal effect is stronger than the change in chemical composition. Hot (cold) volumes are lighter (denser) and thus suggest which way these volumes may be moving, since lighter (denser) material tends to rise (sink). Therefore, the tomography images can be thought of as important representations of mantle convection. Velocity values and their abrupt changes at 410 km or 660 km are important constraints for defining mineral components. Density variations can be checked against geoid anomalies, which are important for viscosity distributions. Deep mantle heterogeneity may represent thermal and mechanical coupling of the mantle and core and, perhaps, the graveyard of subducted plates and the birthplace of superplumes. This means that the entire mantle is involved in making and changing Earth's surface in a wide spectrum of time scales from earthquake to sea level change to climate change.

Noise

Noise from the sensor system itself can now be suppressed to a level less than the natural low noise level, even for the ocean borehole of limited diameter. How, then, can we remove the unwanted part of the waveforms? At sea, the ocean and atmosphere generate unwanted noise if we are targeting for distant natural earthquakes, and cause a seismometer to register noise in a variety of ways. Numerous theoretical and experimental studies have been conducted at high frequencies. Only recently, via ODP experiments, have we begun to understand noise at long periods of several seconds to 1000s of seconds in mantle and core studies.

At long periods, the three major noise sources are microseisms, sea bottom current noise, and infragravity waves. Interacting ocean surface gravity waves generate an acoustic wave that propagates into deep water as microseismic noise. Such ocean waves are due to local and distant winds. Longperiod ocean gravity waves, also known as "infragravity" waves, can directly exert pressure change on the seafloor and deform the underlying sediments and rocks. All these mechanisms suggest that noise should decrease with distance away from the source. Although that is not always strictly true, considerable noise reduction can be expected if a seismometer is emplaced in hard rock; that is, not on the seafloor which will be affected by the bottom current and not in soft sediments which will be affected by easy deformation due to infragravity waves (Fig. 2).

In boreholes, however, fluids tend to circulate and fluid motion can exert noise. Different methods such as packing off, cementing or filling the hole with glass beads have been tried to avoid this noise contamination.

ODP ACHIEVEMENTS

A number of holes have been drilled and instrumented during cruises on the *JOIDES Resolution* to test the benefit of using boreholes rather than seafloor observatories. These efforts also have led to the recording of new data at important locations in the global ocean.

Drilling Holes for Long-term Observatories

Though the COSOD II report and the two ODP Long Range Plans clearly described the importance of seafloor observatories and the role of ODP in establishing them, actual installation has only recently occurred. This new initiative is currently gaining momentum, and ODP boreholes can now be utilized to sample seismic waves that have traveled deep through the earth. A window into the workings of the earth system has been opened.

As stated before, a number of reasons exist to implant the seismic sensor into a hard rock section. However, there are also cases where such a borehole setup may be considered not cost-effective in consideration of the signal-to-noise ratio of the target waveforms. After several experiments at different locations by different groups, we have much more confidence in saying that in order to cover a broad spectrum of seismic frequencies, one needs to put sensors in boreholes in intact rocks. Even so, the ODP community should not expect as many borehole observatories as are located on land. A borehole observatory may become the center of an array network linking other seafloor sensors on a regional scale to detail structures in the mantle and core.

Selection of Sites

ODP drilled six sites specifically for establishing borehole observatories, and will occupy two more sites for broadband seismology before October 2003 (Table 1; Fig. 3). OSN1 (Site 843), south of Oahu in the Hawaiian Swell, was selected for a comprehensive assessment of the characteristics of signal and noise in the marine environment. JT1 and JT2 (Sites 1150 and 1151) were drilled off the coast of northeast Japan, immediately above the seismogenic zone, to record seismic rays from the deepest events that travel up through the subducting plate. NERO (Site 1107), on the Ninety Degree East Ridge, was instrumented to fill an important gap in seismic stations in the Indian Ocean. WP1 and WP2 (Sites 1201 and 1179) were selected in the western Pacific for similar reasons. Two more sites are to be drilled in the eastern Pacific. Each of these sites

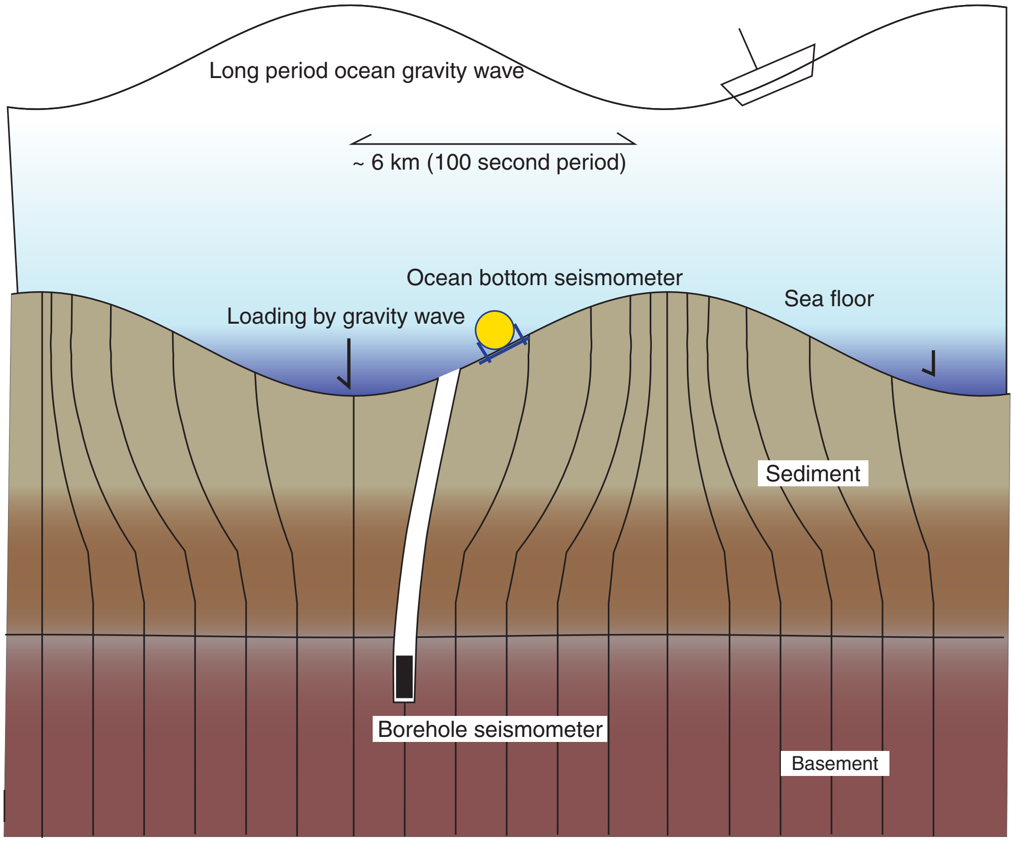

Figure 2. *Schematic drawing of noise-free environment within basement rocks. At long periods, an ocean gravity ("infragravity") wave deforms sediments but has little effect within hard rocks.*

can address problems of regional mantle processes such as where and how plumes originate or where and how subducting plates end up. At the same time, these sites, equipped with long-term high-quality sensors, will provide key data that complement the global network data and allow a much clearer image of the interior of the solid earth.

Other areas need seafloor stations in order to cover the earth more homogeneously. Logistically and technologically difficult areas, such as at high latitudes in the Southern Hemisphere, provide a challenge. Science will eventually direct us into these regions (Fig. 3).

Data Recovery

In this internet era, fast and real-time access to data seems to have become the norm. However, that is not the case for data from the seafloor. We are now in the stage of proving that the data from ODP boreholes significantly affect our understanding of mantle and core dynamics. For some years to come, we will rely on deep water ROVs (Remotely Operated Vehicles) to recover the data, to check the seafloor observing systems, and to repair and improve the systems, if necessary. We must learn as we collect and analyze the data.

Present Status

As of this writing, few observational results are in hand. The first borehole broadband seismic experiment was made at Site 794 on Leg 128 in the Japan Sea in 1989. This experiment proved the superiority of borehole data at relatively high frequencies (>0.1 Hz), but the employed sensor system noise level was higher than the ambient noise level at long periods (Kanazawa et al.,

Table 1. *ODP broadband seismic station locations and operational status. Station OFP installed at DSDP Site 396 also is included.*

Station	Latitude	Longitude	Water Depth (m)	Depth below seafloor (m)	Status	Site	Leg
OSN1	19°20.5'N	159°05.7'W	4412	242	discontinued	843	136
NERO	17°01.4'N	88°10.9'W	1648	494	awaiting installation	1107	179
JT1	39°10.9'N	143°19.9'E	2681	1045	instrumented	1150	186
JT2	38°45.1'N	143°20.1'E	2182	1113	instrumented	1151	186
WP2	41°04.8'N	159°57.8'E	5566	467	instrumented	1179	191
WP1	19°17.9'N	135°05.9'E	5710	558	instrumented	1201	195
H2O	27°53.4'N	141°58.8'W	4967	58	awaiting installation	1224	200
OSN2	5°17.6'N	110°04.6'W	3860	226	scheduled '02	TBD	205
OFP	22°59.1'N	43°30.9'W	4465	406	discontinued	396	DSDP

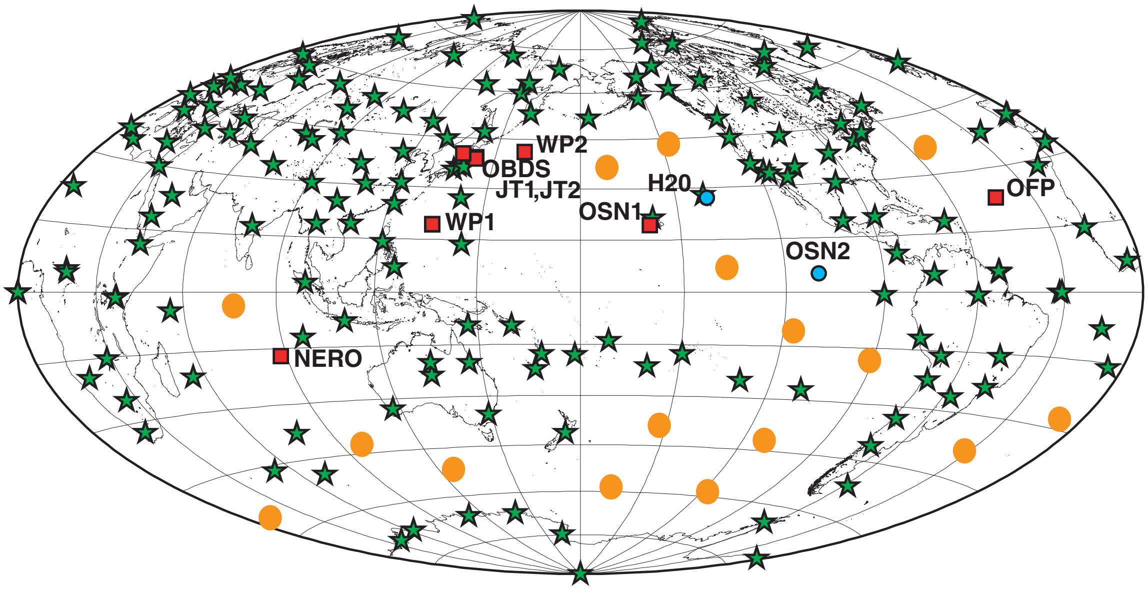

Figure 3. *Present and envisioned global seismic network. Stars are land stations of the FDSN (Federation of Digital Seismic Networks). Existing International Ocean Network (ION)/ODP boreholes are represented by squares, and locations of scheduled future boreholes are represented by blue circles (see Table 1). Orange circles indicate planned sites beneath ocean floor.*

1992). Therefore, we will look first at the U.S. experiment (OSNPE), which was the most comprehensive and has recorded the longest data record. French data (OFM-SISMOBS) and Japanese data (NEREID) will then be examined. Although each experiment was done by different groups employing different methods and different sensors leading to apparently mixed results, we believe there is a clear indication supporting the superiority of borehole observations. This indication will be tested once we retrieve more data from the borehole stations.

OSNPE: This U.S. experiment took place in 1998 at the OSN-1 Site (Table 1) in order to make a comparison of data quality for sensors deployed at the seafloor, buried in sediment, and in the borehole (Collins et al., 2001). A comparison also was made with Hawaiian island stations. Results showed that at long periods (<0.1 s) data quality was highest for the buried sensors, while at short periods (>0.1 Hz) data quality was best for the borehole sensor (Collins et al., 2001). Compared to island station data, KIP (Kipapa on Oahu) was the quietest except above about 2 Hz, and much better than other island stations.

OFM-SISMOBS: This French experiment, a comparison of noise spectra from buried and borehole sensors, took place at DSDP Hole 396B, drilled to 296 mbsf in 1992 in the North Atlantic (Montagner et al., 1994). The buried sensor was quieter than the borehole one at long periods. However, observations indicated that the borehole noise decreased during the experimental duration of about two weeks, suggesting settling of the borehole sensor.

OHP-NEREID: A series of borehole observatory installations was made during ODP Legs 186, 191, and 195 to establish the PACIFIC21 Seismic Network (Table 1). Together with land/island stations, the western Pacific region is now effectively covered by a station spacing

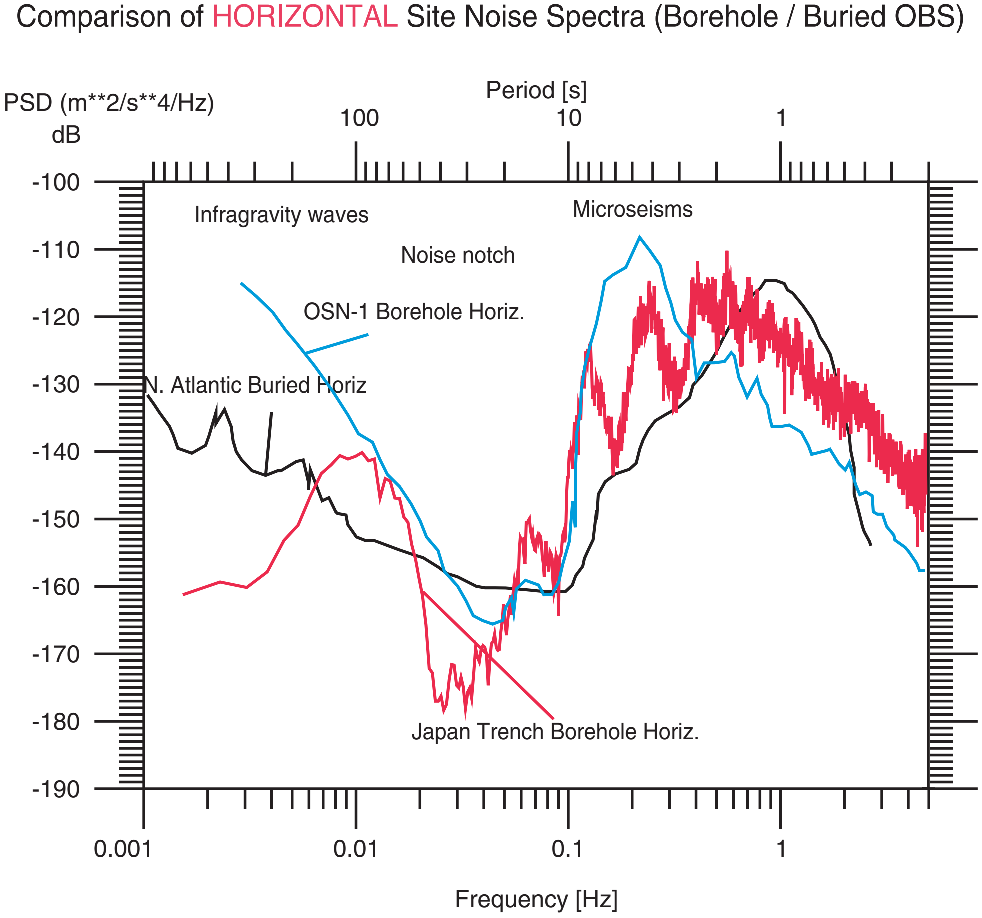

Figure 4. *Horizontal component sensor noise comparison between three different locations and installations. Two are in boreholes: JT1 is cemented but in hard sediment; OSN1 is in casing pipe near the basement. One is buried in surface sediments near Hole 396B. Different noise sources affect the noise spectra. Note the noise minima at periods >10s. JT1 data have a broad peak around 100 s affected by the ocean wave. The noise observed at the OSN1 borehole site is perhaps due to fluid motion in the borehole. The buried sensor near Hole 396B also suffers from ocean wave noise. A borehole sensor within a competent rock section would avoid fluid flow and perform better than the examples shown here. North Atlantic spectra after Beauduin et al. (1996); OSN-1 spectrum after Stephen et al. (1999).*

of less than 1000 km. Horizontal component noise spectra from one of the Japan Trench observatories are shown in Figure 4. Ocean gravity waves of very long wavelength, with a wave height of only a few mm, can affect the seismic band. Recently, a three-month record was recovered from WP2 station.

These preliminary observations indicate that the recording of high quality waveforms in three orthogonal directions is better achieved by borehole sensors than by buried sensors (Fig. 4; Araki, 2000). Buried sensors or island stations do not register good horizontal records. This result was clearly identified only recently because attempts to inhibit seawater circulation in borehole installations have not been very successful except in Japanese cemented boreholes.

International Coordination

The above pilot borehole experiments have been carried out under the various projects of OSN (Ocean Seismic Network of U.S.), SISMOBS (France), and OHP (Ocean Hemisphere Program of Japan). These and other efforts to establish long-term observatories on the seafloor are internationally coordinated by the International Ocean Network (ION). ION has been making recommendations as to how a proper borehole seismic station should perform and be maintained. For example, it must keep sufficient clock accuracy (<0.1 s/yr) and have a frequency and dynamic range window as specified by the FDSN (Federation of Digital Seismic Networks).

In a few years' time we expect to be ready for the construction of a truly global seismic network. That is, we will have learned necessary lessons from the pilot experiments made possible by ODP. Such a network is envisioned as consisting of stations with less than about 2000 km between any station pairs (Fig. 2). Real-time data links via cable or satellite will be developed by coordinated efforts. The Earth is a complex system that must be scrutinized using all available observational tools, especially in the oceans. In particular, any long-term observatory requires power and a data link. Cooperation will occur where necessary among wide-ranging disciplines to share such infrastructure.

CONCLUDING REMARKS

In a standard ODP project, it is often said that drilling is the final step by which important scientific verification is obtained by direct sampling of the earth after extensive site surveys. Installing long term borehole seismic observatories is an exciting new way of using drill holes. These sites are providing a pathway to illuminate the darkest parts of the Earth's interior which cannot be illuminated otherwise. ODP boreholes are, therefore, an important and significant global asset for probing thousands of km of Earth beyond the borehole depth.

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THE OCEANIC LITHOSPHERE

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INTRODUCTION

One of the original objectives of deep-ocean drilling was to drill through the oceanic crust into the upper mantle. This would provide valuable information on the nature, composition and genesis of the oceanic plates that form approximately two-thirds of the Earth's surface. A major achievement of the Deep Sea Drilling Project was to provide new insights into the lavas and sheeted dikes of the upper oceanic crust. An equivalent achievement of the subsequent Ocean Drilling Program (ODP) has been to extend our knowledge to the gabbros and related rocks of the lower oceanic crust and the peridotites of the uppermost part of the underlying upper mantle. This goal was achieved not by drilling through the upper crust, which proved too difficult with 1990s technology, but by developing and implementing a strategy known as offset drilling.

THE OFFSET DRILLING PROGRAM

The concept of offset drilling is to target sites where the crust is abnormally thin or where faulting has exposed the deep crust and upper mantle. The lower crust in these areas is accessible to drilling without the need to first penetrate the two or more km of overlying lavas and dikes. ODP focused on three of these "natural laboratories" for studying deep crustal processes: Hess Deep for young fast-spreading crust, the MARK area for young slow-spreading crust, and Atlantis Bank for ultra-slow-spreading crust (Fig. 1).

Hess Deep

Hess Deep, in a region of extension near the propagating tip of the Cocos-Nazca Ridge in the eastern equatorial Pacific, was drilled during ODP Leg 147. Its location provided a rare, and scientifically significant, opportunity to sample deep crust formed at the nearby fast-spreading East Pacific Rise. Approximately 150 m of gabbros were cored in boreholes at Site 894. The lack of layering in these gabbros suggested that they represented the top of the lower crustal sequence. Together with samples collected by submersible from the same area, they provided new insights into the nature and crystallization of the magma chamber at a fast-spreading ridge. Six holes were drilled at Site 895, and approximately 600 m of peridotites containing dikelets and veins of gabbro and dunite were recovered from what has been termed the "crust-mantle transition zone". The cores provided evidence for the mode of melt extraction from the mantle, the feeding of melt from the mantle to the crust, and the nature of the Moho.

The MARK Area

The MARK (Mid-Atlantic Ridge Kane) area lies south of the Kane Fracture Zone on the slow-spreading Mid-Atlantic Ridge. Periods of amagmatic extension, where plate divergence leads to detachment faulting and little magmatism and crustal growth, have exposed deep crustal sections at or near the sea floor. The two ODP drilling locations are on the western flank of the ridge axis. Approximately 450 m of gabbros of various types were recovered from boreholes at Sites 921 to 924 during Leg 153; again, little layering was observed. Further south, about 100 m of mantle peridotites were cored in holes at Site 670 during Leg 109, and Leg 153 operations recovered a further 340 m of mantle peridotite from Site 920 boreholes. The latter contain numerous dikes and dikelets of basalt, gabbro and other rocks, and are thus somewhat analogous to the crust-mantle transition zone at Hess Deep, though with fewer dunites. Together with Atlantis Bank drilling results (see below), the MARK area cores provided new insights into mantle melting, and the extraction and crystallization of that melt, at a slow-spreading ridge.

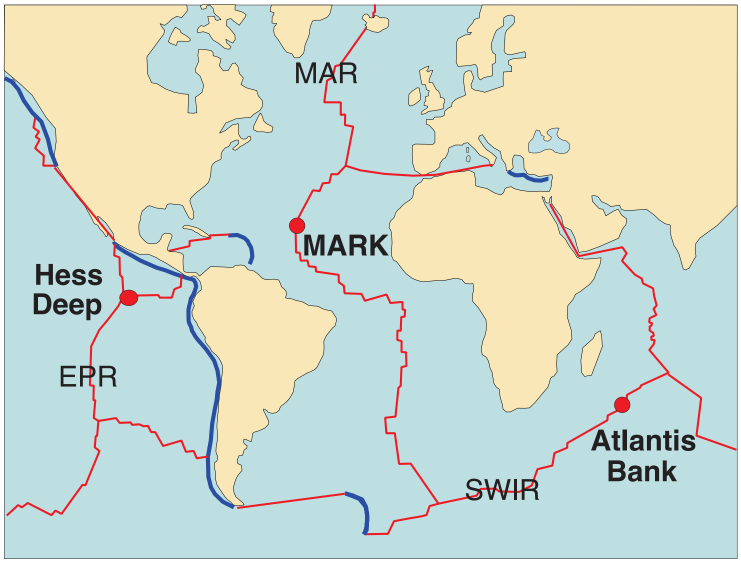


Figure 1. *Location of the three "natural laboratories" for studying the deep oceanic crust: Hess Deep of the fast-spreading East Pacific Rise (EPR); the Mid-Atlantic Ridge Kane (MARK) area of the slow-spreading Mid-Atlantic Ridge (MAR); and Atlantis Bank of the ultra-slow spreading Southwest Indian Ridge (SWIR). Ridges and transform faults are shown in red on the diagram; trenches are in blue.*

Atlantis Bank

Atlantis Bank is part of the eastern wall of the Atlantis II Fracture Zone south of the ultra-slow-spreading Southwest Indian Ridge (SWIR), where lower crust was unroofed by a large, low-angle detachment fault. A 500 m section of gabbros was recovered at Hole 735B during ODP Leg 118. ODP Leg 176 reoccupied this hole and extended it to just over 1500 meters below seafloor (mbsf). A second adjacent Hole 1105A was drilled during Leg 179, and an additional 158 m of gabbros were recovered. The remarkable 86% core recovery from Hole 735B makes it a superb reference section for the upper part of the plutonic section at slow-spreading ridges. The dominant rock type is olivine gabbro, but other rock types are present, notably ferrogabbro in the upper 500 m and troctolite (a rock dominated by olivine and plagioclase feldspar) in the lower 200 m. The olivine gabbro is commonly veined by microgabbros and melts representing the final stages of crystallization. Layering is rare; a weak foliation is common and a high intensity of plastic deformation is evident, especially in the upper part of the section.

MAGMA CHAMBER PROCESSES

Drilling of the plutonic sequence of off-axis oceanic crust provides the optimum method of ground-truthing seismic tomographic images and testing ophiolite models. Tomographic images have indicated that much of the lower oceanic crust beneath ridges is a mixture of crystals and melt, known as a crystal mush (Sinton and Detrick, 1992), and that pure melt occupies a lens-like body tens of meters thick near the top of the lower crust (Fig. 2). Such melt lenses are believed to be present for long periods at fast-spreading ridges, but transient at slow-spreading ridges. This concept is now broadly accepted, but the processes of magma plumbing and the growth of the lower oceanic crust are still debated. It is not yet clear whether melt reaches the melt lens by upward porous flow through the crystal mush or along discrete channels. It is also unclear whether the lower oceanic crust grows mainly by crystallization in a single melt lens followed by the flow of crystal mush down and away from the ridge (the "gabbro glacier" model), or whether it grows from a series of sill-like bodies throughout the crust (the "Christmas tree" model).

Interpreting gabbros is a complex procedure. Viewed simply, cumulate crystals grow in magma and accumulate. The accumulated crystals will have melt in their pores; this is the intercumulus melt. The latter can crystallize *in situ*, or it can be expelled by compaction much as pore water is driven out of compacting sediment. Crystallization may be aided by rapid cooling, and expulsion by rapid crystal accumulation and deformation. To complicate matters further, the intercumulus melt can advect within the crystal mush, elements can diffuse along compositional gradients, and melt can migrate into the mush from outside. Understanding the relative importance of these various processes will enable us to better understand magma chamber processes in general, and mid-ocean ridge processes in particular.

Inferences made from direct microscopic study of the gabbros at Hess Deep provide a rough guide to the proportion of cumulus minerals and the products of crystallization of intercumulus melt (Fig 2A). The

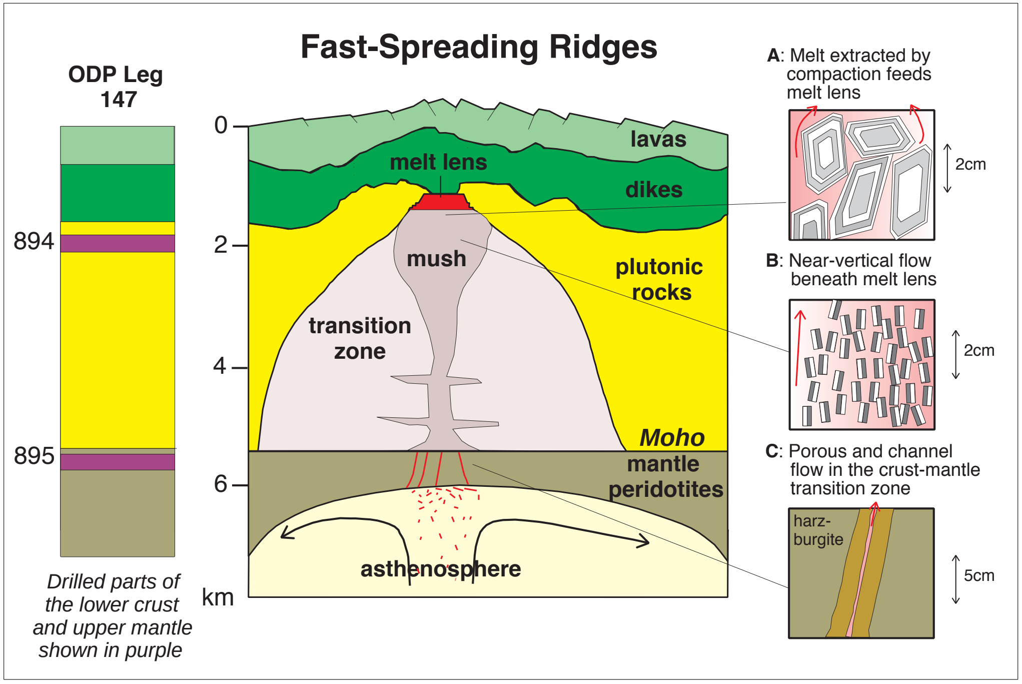


Figure 2. Center: *A section through a fast-spreading ridge, based on seismic data of Sinton and Detrick (1992), shows melt extracted from rising asthenosphere feeding a mush zone and melt lens beneath the ridge axis.* ***Left:*** *Two parts of this fast-spreading section sampled during ODP drilling at Hess Deep are shown in purple.* ***Right:*** *Three boxes depict several textures used to infer the details of some of the processes taking place along a fast-spreading ridge:* ***(A)*** *extraction of trapped melt from the mush;* ***(B)*** *upward flow of melt within the mush; and* ***(C)*** *reactions and crystallization during passage of melt from asthenosphere to crust. The crystals in boxes A and B represent plagioclase feldspars and the pink areas represent interstitial melt.*

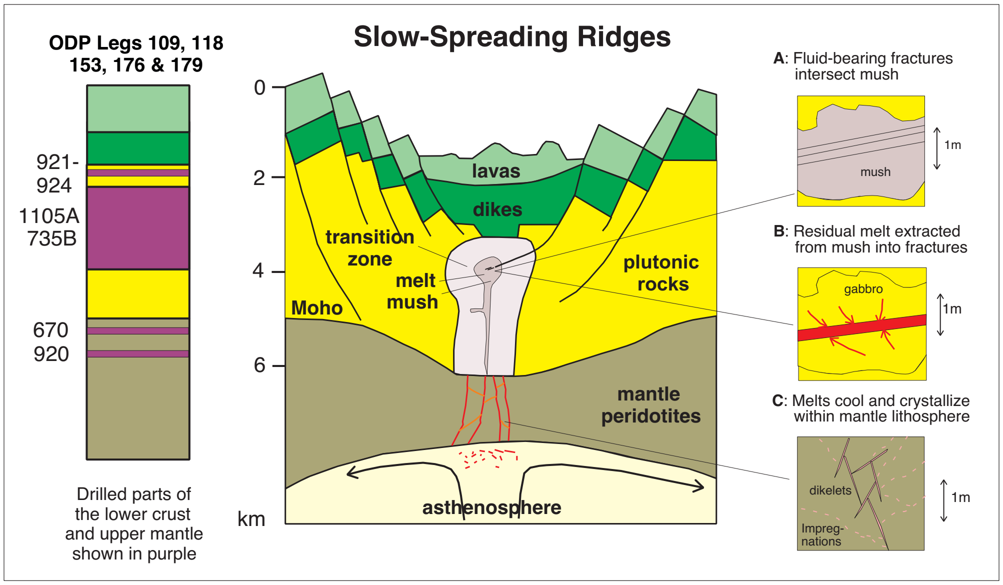
gabbros demonstrate a wide range of textures indicative of a wide variation in the proportion of cumulus minerals, but the microscopic method is not very precise. Therefore, scientists working on cores from ODP Site 894 boreholes also used a number of geochemical fingerprinting techniques to interpret the processes taking place (Natland and Dick, 1996; Pederson et al., 1996). For example, the incompatible elements such as Zr are present in high concentrations in interstitial melt compared with cumulate crystals. Gabbros with high incompatible element contents were inferred, therefore, to have retained their intercumulus melt, or have had it replenished. Conversely, those with low incompatible element contents were inferred to comprise mainly cumulus crystals. This approach demonstrated that the proportion of Hess Deep gabbros that can be attributed to crystallization of intercumulus melt varies from 30% to 100% and suggested that, overall, some 25% of the trapped liquid has been expelled from the original crystal mush. These estimates, coupled with the absence of layering, confirmed that these gabbros represent the uppermost part of the lower crust.

Although debate continues over the details, scientists studying the Hess Deep cores have provided good evidence to support the presence of a melt lens which crystallizes to produce a crystal mush at the base of the lens. According to their model, the mush undergoes compaction as it accumulates, and interstitial melts are squeezed upwards through the mush. The resulting gabbros have highly variable amounts of trapped interstitial melt, but there also is a net loss of melt which can refertilize the melt lens or penetrate already crystallised rocks along faults and fractures. Structural studies have also played an important part in interpreting these rocks. Although Hess Deep gabbros are not layered, they exhibit a marked and steeply-dipping foliation (Fig. 2B), which could be explained by crystal growth linked to the upward flux of the interstitial melts and downward flux of crystals (MacLeod et al. 1996). The many vertical contacts between different types of gabbro also are powerful evidence for the importance of near-vertical flow beneath the melt lens.

The drilling of gabbros from the Mid-Atlantic and Southwest Indian Ridges supports the concept that slow-spreading ridges have, at best, ephemeral melt lenses (Fig. 3). Mid-ocean ridge lavas and dikes evolve during crystallization from basic rocks (basalts) through iron-rich basic rocks (ferrobasalts) to acid rocks (rhyolites). The plutonic rocks follow a similar trend from troctolite and gabbro through ferrogabbro to plagiogranite. In many of the famous large igneous complexes now exposed on land, the most basic compositions lie at their bases, and the most evolved are found at their tops. At Atlantis Bank, the best interpretation is that the drilled section comprises five gabbro cycles - each 250 to 450 m thick and each becoming more evolved upwards. This supports a scenario in which the crust is constructed from numerous small intrusions and not from a single, steady-state magma chamber. In addition, gabbros, ferrogabbros and plagiogranites typically form cross-cutting bodies, indicating that late-crystallizing magma from one chamber commonly cuts the crystallized products of its own, or another, chamber (Dick et al., 2000).

An important outcome of the Atlantis Bank drilling was the realization that magma chamber evolution involves an interrelationship of *in situ* crystallization, syntectonic deformation and hydrothermal processes. In particular, the cores emphasize the potential importance of the intersection of faults with a partially

*Figure 3. **Center:** A section through a slow-spreading ridge, based on seismic data of Sinton and Detrick (1992), shows melt extracted from rising asthenosphere feeding a mush zone beneath the ridge axis. **Left:** Three parts of this slow-spreading section sampled during drilling at Atlantis Bank (ODP Sites 735, 1105) and the MARK area (ODP Sites 670, 920 through 924) are shown in purple. **Right:** Three boxes depict several of the textures used to infer the details of some of the processes taking place along a slow-spreading ridge: **(A)** faults penetrating the still partially molten gabbro; **(B)** melt entering the fractures to form gabbro veins; and **(C)** extensive crystallization of magma as dikelets and impregnations within the mantle lithosphere.*



molten intrusion (Fig. 3A). In such a situation, the accompanying deformation enhances the permeability and generates the pressure gradients that help to drive the flow of interstitial melts. This enables residual melt to move into the zones of deformation, a process also aided by compaction of the partially molten body (Fig. 3B). Geochemical studies comparable to those conducted on cores from Hess Deep have shown extreme variations (0% to 100%) in the proportion of intercumulus melt contributing to given samples. These studies also demonstrated that this intercumulus melt was not trapped *in situ* but must have flowed through the compacting matrix (Coogan et al., 2000). The flow of melt also may explain the observed marked foliation in the rocks. This residual melt was quite evolved, allowing oxides to crystallize in and around ductile shear zones. After still more crystallization, the residual melt became granitic. Hart et al. (1999) used oxygen, strontium and osmium isotope tracers to raise the possibility that hydrothermal fluids entered the system before it was fully crystallized. This would have had the effect of increasing the volume and lowering the viscosity of the residual melts, making them easier to inject into gabbro that already crystallized.

Dick et al. (2000) made the important observation that the common presence of ferrogabbro in the drill core is in marked contrast to the absence of ferrobasalt lavas in dredge hauls from the region. Their inference is that the drilled gabbro sequence formed essentially by closed system fractional crystallization and redistribution of melt. In other words, a significant volume of late-stage melt was compacted out of an olivine gabbro matrix and intruded into the cooler parts of the intrusion without eruption. This is the reverse of fast-spreading ridges where the ferrobasalts are common, and the ferrogabbros relatively rare. The implication is that, at fast-spreading ridges, melt extracted from the underlying mush feeds the overlying melt lens, assisting its evolution to a ferrobasalt composition and contributing to magmatic eruptions. At ultra-slow-spreading ridges, the other end of the spectrum, much of this melt stays in the crust where it crystallizes as ferrogabbro.

PROCESSES AT THE MANTLE-CRUST TRANSITION ZONE

The mantle rocks at both Hess Deep and MARK are harzburgites with a marked tectonic fabric. Harzburgites are rocks dominated by olivine and orthopyroxene. Because they contain little (<5%) clinopyroxene, they cannot represent unmelted mantle, and must be residues from melting. Although many such rocks have been dredged from the ocean basins and sampled by submersible, textures not apparent in isolated dredge samples were observed in ODP cores. The melting history of these rocks can be deduced by a number of geochemical techniques; the likely most effective utilize the chrome spinels, which are accessory minerals in the harzburgites. These are usefully resistant to all but the most intense alteration and have compositions that change in response to increasing degrees of partial melting. Low degrees of melting leave aluminous spinels; increased melting leaves more chrome-rich compositions. The results show that the Hess Deep peridotites contain more chrome-rich spinels than peridotites from the MARK area, indicative of a greater degree of partial melting, 20% to 25% in the former case and 12% to 20% in the latter (e.g., Ross and Elthon, 1997). This lends support to theoretical inferences that the degree of melting is greater beneath fast spreading ridges, where more rapid upwelling gives the mantle less opportunity to cool, than beneath slow-spreading ridges. Other geochemical indicators show how melting takes place. The samples recovered are consistent with near-fractional melting, whereby melt does not equilibrate with the mantle as it rises beneath the ridge, but is continually extracted and only subsequently mixes to form mid-ocean ridge basalts.

The origin of the dunites is well understood from studies of ophiolite complexes. Melt ascending through mantle at shallow pressures has the capability to dissolve pyroxenes and precipitate olivine, converting harzburgite into dunite. The dunites thus represent reaction zones around melt channels. Dick and Natland (1996) argue that the dunite dikes in the Hess Deep core point to ‘an episodic tapping and transport of melt out of the shallow mantle by repeated fracture events’. They also infer that the host harzburgites belong to a lid of conductively-cooled mantle lithosphere that overlies the hot, melting asthenosphere and is capable of sustaining this brittle fracture (Fig. 2). The gabbro dikes and veins also indicate that the mantle host had cooled sufficiently below normal mantle temperature to allow crystallization of melt. Detailed studies of mantle fabrics enabled Boudier and coworkers (1996) to identify a near-horizontal fabric within the dunite and so provide evidence for the subhorizontal flow in the underlying mantle that would be expected beneath a mantle-crust transition zone.

The detailed model of the crust-mantle transition zone that emerges from this work provides a new perspective on the nature of the Moho at fast-spreading ridges. The Dick and Natland (1996) model provides a good explanation for the observations, though the precise process can still be debated. In their model, magma first passes through the hot, plastic mantle by diffuse flow. As cooling proceeds, and fractures from the ridge intersect the uppermost mantle, melt becomes focused into channels. The principal consequence is that the melt reacts with the surrounding and still hot mantle to produce bands of dunite around the melt channels. With continued cooling and extension, magma crystallizes as gabbro and impregnates the surrounding dunite and harzburgite (Fig. 2C).

The equivalent section from the MARK area has a greater abundance of gabbro dikelets and a lower abundance of dunites compared with Hess Deep, and the gabbros themselves contain minerals with a wider range of compositions. Of the latter, some are comparable to those from Hess Deep but others require much more extensive crystallization and, hence, a lower temperature mantle host (Cannat et al., 1997). This might happen if the magma feeding the slow-spreading ridge at the MARK area flowed through a relatively thick zone of conductively cooled mantle before reaching the crust, as depicted schematically in Figure 3C. However, Cannat et al. (1995; 1997) and Karson and Lawrence (1997) argue that layered crust of the type depicted in Figure 3 only forms at those parts of the ridge system where there is plentiful magma supply; i.e., at fast-spreading ridges and in the centers of slow-spreading ridge segments. At the edges of slow-spreading ridge segments, and perhaps more pervasively at ultra-slow spreading ridges, the ridge is starved of magma. In consequence, the crust is thin and much of the extension is taken up by tectonic processes similar to those operating at non-volcanic rifted continental margins. This may tectonically expose mantle lithosphere at the seafloor so that any magma generated from mantle asthenosphere at depth cannot contribute to the construction of a gabbro layer. The magma must instead ascend through a column of mantle toward the surface.

Cannat et al. (1997) demonstrated how the ODP peridotite cores from the MARK area could provide critical information on processes at such magma-starved ridges. They used the mineral chemistry of the gabbro veins to support the idea that, in these settings, magma can crystallize entirely within the mantle lithosphere in small chambers, lenses, dikes and dikelets. The crystallization history is related to the temperature of the mantle host and, hence, to the rate of tectonic uplift and cooling. Cannat et al. (1997) also presented structural data to support the concept that large extensional (detachment) faults, together with smaller shear zones, can decapitate and deform these gabbro bodies as well as convey them toward the seafloor. The overall effect should be to give the lithosphere a "plum pudding" structure, shown schematically on the left-hand side of Figure 4, as opposed to a layered structure.

SUMMARY

The ODP has made fundamental advances in our understanding of the deep oceanic crust and uppermost mantle. We now better understand the "magma plumbing" beneath ridge axes, particularly in the upper plutonic crust and the mantle just beneath the beneath the Moho. In particular, we now have a much better appreciation of the importance of spreading rate and, hence, the thermal regime and magma budget.

Fast-spreading ridges, with their long-lived melt lenses, produce more continuous gabbro sections with the classic ophiolite stratigraphy. Evolved melts extracted from the cooling and compacting crystal mush can help feed the melt lens and so contribute to volcanic eruptions. The layer of conductively-cooled mantle lithosphere beneath the Moho is typically hot and thin. Thus, magma passing through this layer en route to the crust

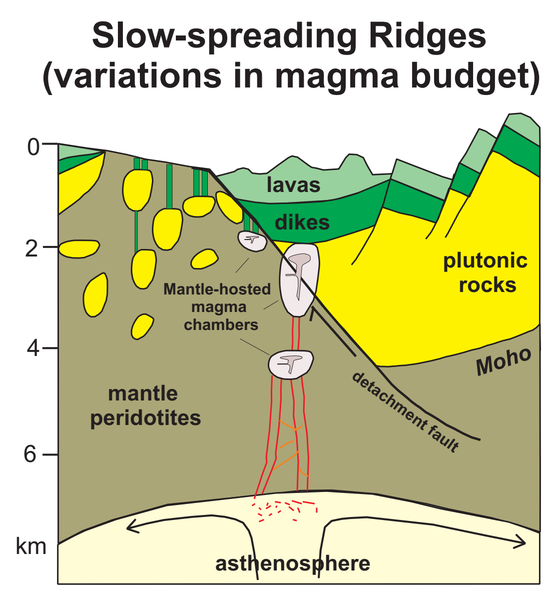


Figure 4. *Illustration of the importance of magma supply at slow-spreading ridges (adapted from Tartarotti et al., 1995). The layered crustal section on the right formed during a period of high magma budget. The plum pudding-like crustal section on the left formed during a subsequent period of magma starvation. In the latter case, extensional (detachment) faulting has uplifted mantle lithosphere toward the seafloor. Much of the magma rising through this mantle section has ponded within it, and progressively cooled and crystallized without forming a normal crustal section. The crystallizing magma bodies and their feeder dikes may be deformed, cut, and displaced by detachment faults and shear zones. Rocks recovered from Site 670 and 920 borehole along the MARK area of the Mid-Atlantic Ridge are better represented by this model than by the high magma budget section illustrated in Figure 3. These cores likely provided some of the best evidence for magma crystallization and rock deformation at the magma-starved edges of slow-spreading ridge segments.*

undergoes little cooling but mostly reacts with wall rock to form zones of dunite.

Slow-spreading ridges, in contrast, are characterized by ephemeral melt lenses and produce composite sections built up by multiple small intrusions. Deformation and fluid circulation have played significant roles in the crystallization process. Evolved melts are more likely to solidify at depth than contribute to volcanic eruptions. The layer of conductively-cooled lithosphere also is cooler and thicker, and magma traversing this layer undergoes more crystallization than reaction. In some parts of slow-spreading ridge systems, the ridge may be starved of magma and extensional faulting may dominate. This may produce a completely different type of oceanic crustal structure that is not layered but composed of pockets and veins of gabbro encased in mantle peridotite.

These advances show that there is much work still to be done. Drilling the layered cumulate sequence at fast-spreading ridges to test crustal growth models remains a major objective, and the Moho itself still has not been drilled. Moreover, offset drilling remains a necessary substitute at present for drilling to the Moho though crust of normal thickness. Most scientists working in ocean ridges still believe that only a true "Mohole"-type endeavor will enable them to fully understand ridge-crest processes and ridge contributions to global fluxes. Nonetheless, ODP has made a major step in this direction through offset drilling.

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ALTERED ROCKS AND SEAFLOOR MASSIVE SULFIDE DEPOSITS: THE RECORD OF HYDROTHERMAL PROCESSES

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INTRODUCTION

Hydrothermal circulation of seawater through the crust and upper mantle is an integral component of crustal construction at oceanic spreading centers, and is an important process in the transport of heat and mass. Complex reactions between rocks and the circulating fluids result in chemical exchange that dramatically affects the physical properties of the lithosphere, and alters the composition of the crustal material that is returned to the mantle by subduction. Upflow zones of active hydrothermal systems are manifest on the seafloor as vents discharging high-temperature fluids that mix with seawater leading to the formation of massive sulfide deposits and influencing the composition of the world's oceans. Much has been learned about conditions within hydrothermal systems from studies of vent fluid chemistry and the composition of seafloor mineral deposits at active sites along mid-ocean ridge and back arc spreading centers. In addition, investigations of altered oceanic rocks collected by dredge or submersible have elucidated the variability in subsurface water-rock reactions and the associated elemental exchanges. However, a full characterization of hydrothermal systems and their influence on crustal properties and global geochemical budgets requires a scale of sampling that can be achieved only by drilling.

Remarkable advances in our understanding of the subsurface structure of hydrothermal systems and the mechanisms of formation of massive sulfide deposits can be attributed to the Ocean Drilling Program (ODP). Detailed geochemical and isotopic studies of core material have documented subseafloor water-rock reactions during circulation, the transport and redistribution of elements, and subsurface fluid temperatures. In addition, key observations that result directly from drilling into active sulfide deposits of the impact of shallow subseafloor processes, such as fluid mixing, entrainment of seawater, and the deposition of secondary phases, have been used to reinterpret the origin of several important ore types found in ancient deposits, and have revised models of the genesis of ophiolite-hosted massive sulfide deposits.

The goal of this paper is to highlight some of the key contributions of ODP to our understanding of seafloor hydrothermal systems and crustal alteration. The focus is on the geological aspects of these systems; a complete discussion of the impact of water-rock reactions on biological activity (and vice versa) is beyond the scope of this paper.

Upflow Zones and the Formation of Massive Sulfide Deposits

There is wide recognition that active seafloor hydrothermal systems and their associated mineral deposits are modern analogs of massive sulfide deposits in ophiolites. Prior to ocean drilling, however, comparisons between modern and ancient deposits were limited by the lack of documentation of the subsurface structure of active seafloor hydrothermal systems. Significant revisions to models of genesis of massive sulfide deposits are now being made based on the results of ODP drilling at two active hydrothermal sites. In addition, a felsic-hosted system in a convergent margin setting (the PACMANUS Hydrothermal Field, Eastern Manus Basin) was recently drilled during ODP Leg 193; its study is still in progress.

A Volcanic-Hosted System on a Slow Spreading Ridge: the TAG Active Hydrothermal Mound (26°N, Mid-Atlantic Ridge)

The TAG (Trans-Atlantic Geotraverse) hydrothermal field located at the base of the eastern median valley wall of the Mid-Atlantic Ridge (Fig. 1; inset) is one of the largest and best studied sites of high-temperature hydrothermal activity and mineralization yet found on the seafloor. In 1994, a series of holes into the high-temperature active mound in the TAG hydrothermal field were drilled during ODP Leg 158 (Humphris et al., 1995). Although recovery was poor due to the brecciated nature of the rocks and difficulty in removing heavy sulfide cuttings from the drillholes, the cores revealed for the first time the nature, size and geometry of the shallow upflow zone down to 125 meters below seafloor (mbsf).

A significant finding of Leg 158 was the dominance of breccias throughout the mound and underlying upflow zone (Fig. 1). The bulk of the massive sulfide deposit consists of massive pyrite, pyrite-anhydrite, and pyrite-silica-anhydrite breccias; within the underlying stockwork, pyrite-silica breccias grade downward into silicified wallrock breccias and chloritized basalt breccias. This mineralogical zonation bears a striking resemblance to deposits in Cyprus (Fig. 1). Prior to seafloor drilling, the abundance of breccia ores and sulfide conglomerates in the Cyprus deposits was explained by post-depositional weathering (Constantinou, 1980). However, by analogy with the TAG mineral deposit, it is likely that the Cyprus breccias were formed during initial construction of the deposit. The complex and brecciated structure implies that the TAG active mound has undergone multiple stages of development. Its construction is interpreted to be a combination of accumulation of sulfides at the seafloor, and hydrothermal replacement and mineralization in the upflow zone during periods of activity, followed by collapse, mass wasting and brecciation during periods of inactivity.

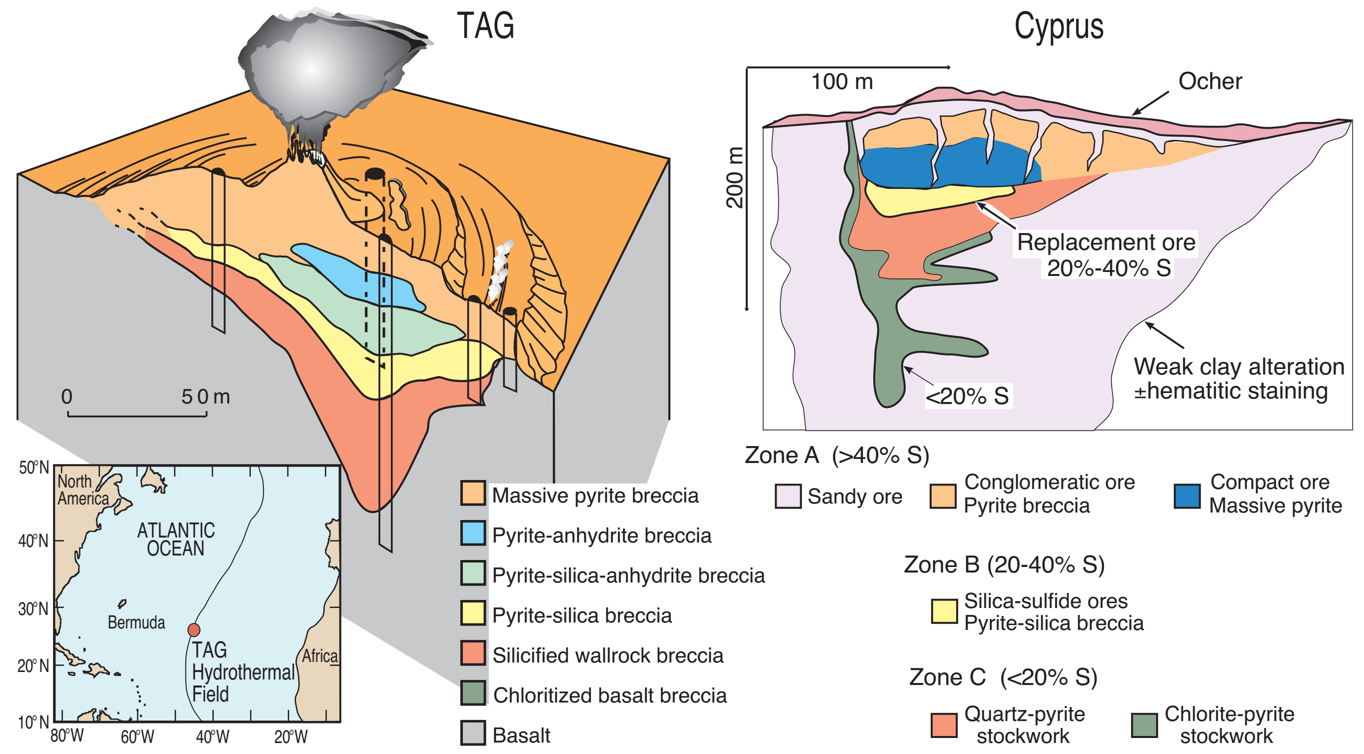
The second significant finding was the abundance of anhydrite. Anhydrite is uncommon in ancient massive sulfide deposits due to its retrograde solubility (it is saturated in seawater at temperatures >150°C, but undersaturated below 150°C). The abundance of anhydrite within the TAG active mound and stockwork provides evidence for considerable entrainment and heating of seawater into the subsurface (Humphris et al., 1995; Humphris and Tivey, 2000; Mills and Tivey, 1999). This process plays a previously unrecognized role in the construction of a large seafloor deposit. During periods of high temperature activity, anhydrite is precipitated thereby forming a framework for construction of the deposit; during periods of inactivity, anhydrite dissolves causing collapse of the structure. Such a key observation was possible only through drilling into an active hydrothermal system.

A Hydrothermal System on a Sediment-Covered Intermediate Spreading Ridge: Middle Valley Hydrothermal Sites (Juan de Fuca Ridge)

In contrast to the TAG volcanic-hosted hydrothermal system, hydrothermal deposits at Middle Valley, the northern extension of the Endeavour segment of the intermediate-spreading Juan de Fuca Ridge, occur in continentally-derived turbidites that bury the spreading center (Fig. 2; inset). The presence of a relatively impermeable sediment blanket over the volcanic basement changes the style of hydrothermal circulation, influences the associated fluid and heat fluxes, and results in the formation of a seafloor mineral deposit similar in size and grade to ore deposits mined on land. ODP Leg 169 was the second ODP leg designed to investigate geological and geochemical processes at the sediment-covered Juan de Fuca Ridge (Zierenberg et al., 1998). It built on the results obtained from ODP Leg 139 by conducting a more detailed drilling program to investigate the genesis of two large mounds of massive sulfide: the Bent Hill Massive Sulfide (BHMS) deposit and the younger ODP Mound. A 500 m-deep drillhole through the summit of the BHMS deposit penetrated the feeder zone through which the metal-rich fluids reached the seafloor, and into the underlying sediment and the uppermost oceanic crust (Fig. 2) (Zierenberg et al., 1998).

Similar to the TAG active mound, mineralization at the Middle Valley site is the result of a structurally focused, long-lived hydrothermal system. This has resulted in deposition of at least 100 m of massive sulfide (domi-

Figure 1. *Comparison of composite schematic sections of the TAG active hydrothermal mound and Cyprus massive sulfide deposits showing the vertical distribution of ore types. (Modified from Humphris et al., 1995). Inset: Location of the TAG hydrothermal field on the Mid-Atlantic Ridge.*



nantly pyrrhotite with less abundant isocubanite, sphalerite and wurtzite) on the seafloor at Bent Hill during one episode of hydrothermal activity. In contrast, three stratigraphically stacked massive sulfide lenses at the ODP Mound, each underlain by sediment-hosted feeder mineralization, indicate several episodes of activity (Fig. 2). An important accomplishment of Leg 169 was the recovery of a section through the feeder zone mineralization. Feeder zones in ancient massive sulfide deposits commonly account for a significant portion of the economic reserves of a deposit. Leg 169 demonstrated that the style of feeder zone mineralization changes with depth in response to changes in the pore pressure of the hydrothermal fluids. The upper part of the feeder zone is dominated by abundant subvertical crack-seal veins, but transitions into subhorizontal mineralization that is controlled by sedimentary texture at the base of the feeder zone.

An unexpected finding was the presence of a stratified zone of high-grade Cu-rich replacement mineralization (16.1 wt. % Cu) at the base of the feeder zone (~200 mbsf) of both deposits. A highly silicified mudstone horizon at the top of the Deep Copper Zone is thought to have formed a relatively impermeable horizon that exerted hydrologic control on fluid flow. During times when the subvertical veins were sealed, the hydrothermal fluid was forced to flow laterally into permeable sandy horizons where high-grade copper ore formed by replacement of sediment (Zierenberg et al., 1998). The Deep Copper Zone represents a type of mineralization not previously observed below seafloor mineral deposits, and has implications for land-based mineral exploration.

Subsurface Water-Rock Reactions Within the Hydrothermal Convection Cell

Studies of hydrothermally altered samples dredged, drilled or collected by submersible from the global mid-ocean ridge system, and of crustal sections within ophiolites, have documented the wide range of water-rock reactions and geochemical changes. These studies have resulted in a conceptual model for the alteration reactions that occur within different portions of the hydrothermal system near the ridge axis (Alt, 1995). There are two sites at which long sections of the oceanic crust have been recovered. Studies of these cores have allowed water-rock reactions and the elemental exchanges to be put in the context of hydrothermal convection cells at mid-ocean ridges. Hole 504B provided a ~2 km-long section of volcanics and

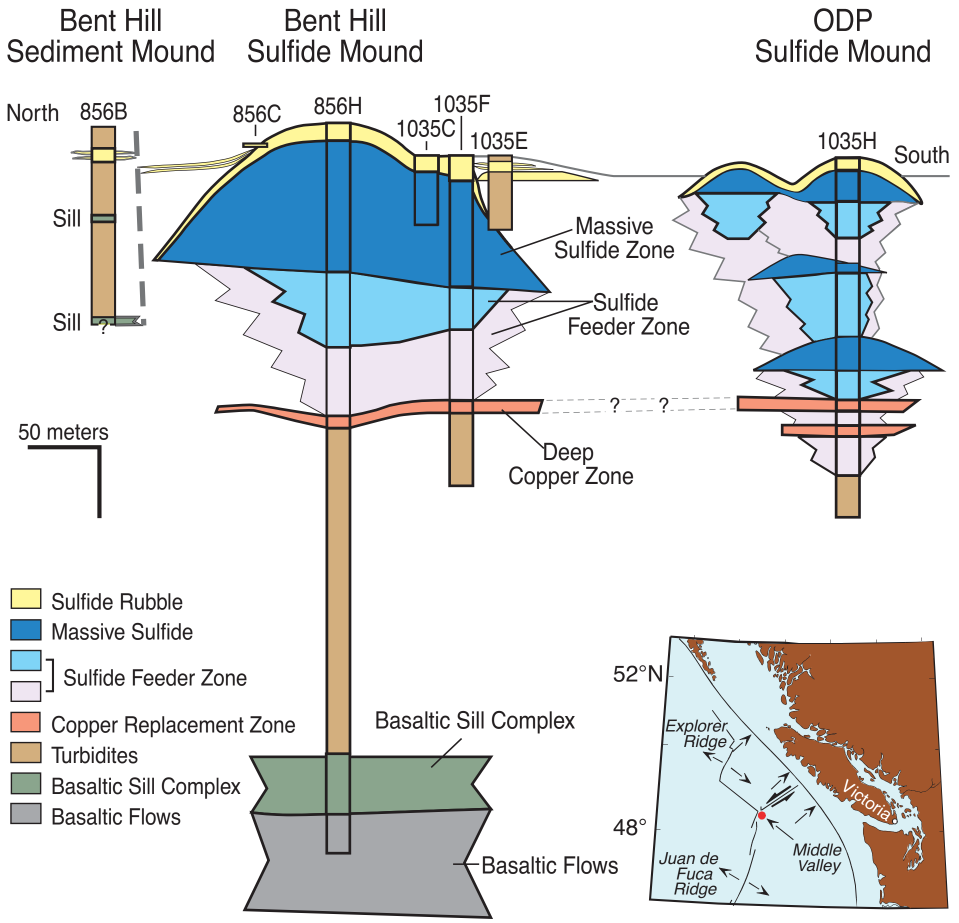


Figure 2. *North-south interpreted cross section of the distribution of mineralized zones at the Bent Hill Massive Sulfide Mound and the ODP Mound drilled during ODP Legs 139 and 169. Inset: Location of Middle Valley on the Juan de Fuca Ridge.*

the sheeted dike complex, and Hole 735B recovered a ~1.5 km-long section within the gabbros. Both have become reference sections for the upper and lower oceanic crust, respectively.

Alteration in the Upper Crustal Section and Nature of the Reaction Zone: Hole 504B (Eastern Equatorial Pacific)

Hole 504B was drilled over the course of seven Deep Sea Drilling Project (DSDP) and ODP legs on 6 million year old (Ma) crust, about 200 km south of the Costa Rica Rift in the eastern equatorial Pacific (Fig. 3; inset). It is the deepest scientific drill hole in the oceans at 2111 mbsf, and provides the most complete picture of hydrothermal circulation and water-rock reactions within the upper crust.

Detailed mineralogical, geochemical and isotopic studies have allowed reconstruction of the conditions and progression of alteration within different portions of the crust as it moves away from the spreading axis (Fig. 3; Alt et al., 1996), and have demonstrated the important role of permeability in determining the extent of water-rock reactions. Seawater-rock reactions at low temperatures within the volcanic section began at the axis, and evolved through time from open and oxidizing conditions to more restricted seawater circulation. The highly permeable nature of the upper 100 to 200 m of volcanics allowed larger volumes of seawater to freely circulate, supporting more oxidizing conditions, than in the volcanics below. The transition zone and upper dikes were initially altered in a mixing zone where upwelling hydrothermal fluids mixed with cold seawater circulating in the overlying, more permeable volcanic section, giving rise to a stockwork-like mineralization zone. As the crust moved off-axis into a recharge zone, fracturing and faulting allowed penetration of seawater into the rocks, and conductive heating resulted in precipitation of anhydrite in the cracks.

Within the lower dikes at Hole 504B, the alteration mineralogy and conditions, and the observed depletion in Cu and Zn, are consistent with this being the reaction zone of a hydrothermal system, where high temperature reactions transform seawater into hot, acidic, metal-rich and sulfide-rich hydrothermal fluids. Alteration in the lower dikes at Hole 504B occurred under conditions of low water/rock ratios and very limited fluid access. There is no evidence for a zone of penetrative alteration of the dikes to epidosites, as is observed in ophiolites, where large volumes of fluids are focused and flow upwards. This and other differences in the styles of hydrothermal alteration between ophiolites and Hole 504B still remain to be resolved.

Alteration in the Plutonic Section: Hole 735B (Southwest Indian Ridge)

Hole 735B was drilled during ODP Legs 118 and 176. It penetrates 1508 m into gabbroic ocean crust that was generated at the ultra-slow spreading Southwest Indian Ridge and later formed a 5 km-high transverse ridge that constitutes the eastern wall of the Atlantis II Fracture Zone (Fig. 4; inset). Results from this borehole have dramatically changed our perceptions of the nature of the lower ocean crust at slow-spreading ridges by documenting variations in structure and alteration different from those observed in ophiolites.

The gabbros recovered from Hole 735B preserve a complex record of high-temperature metamorphism, brittle failure, and hydrothermal alteration that began at near-solidus temperatures and continued down to

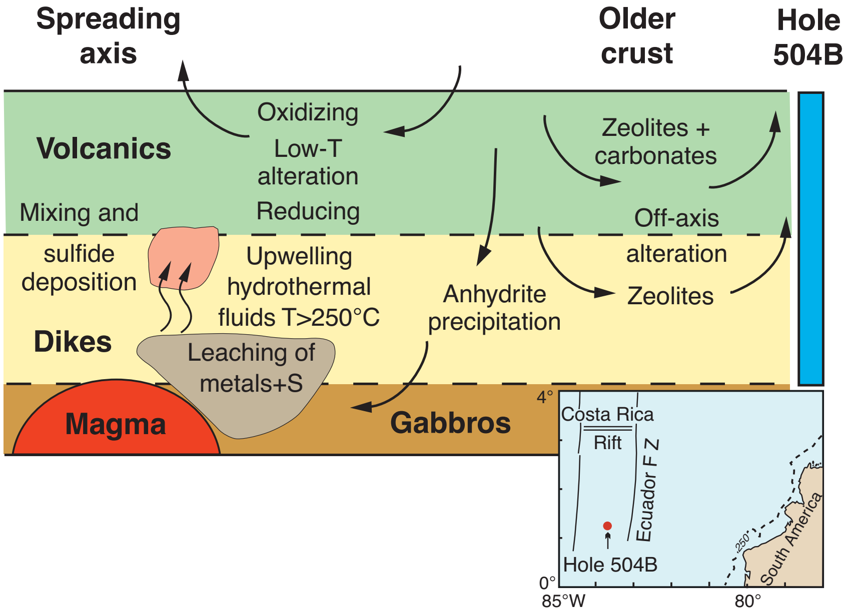


Figure 3. *Schematic illustration of the alteration of the upper crustal section at Hole 504B as it moved away from the spreading axis (From Alt et al., 1996). Inset: Location of Hole 504B south of the Costa Rica Rift.*

zeolite facies metamorphic conditions (Dick et al., 2000). The intensity of deformation and hydrothermal alteration decrease downhole (Fig. 4), and there is a close relationship between ductile deformation and fluid penetration.

The alteration history of the basement consists of several high temperature events that likely occurred at or very near the spreading axis. Granulite facies metamorphism (800° to 1000°C) is clearly indicated by localized, narrow zones of crystal-plastic deformation that cut igneous fabrics. Felsic veins also formed that show the effects of magmatic hydrous fluids, and later served as pathways for hydrothermal fluids. High-temperature static (i.e., not related to ductile deformation) background alteration by hydrothermal fluids over a range of temperature, from 600° to 700°C to much lower temperatures, is patchy. Development of subvertical amphibole veins probably related to cooling and cracking of the rocks in the subaxial environment resulted in the ingress of moderately high temperature (400° to 550°C) fluids. Microcracks filled with greenschist facies mineral assemblages throughout the section are indicative of smaller scale fracturing and fluid penetration. Later, low temperature (smectite) hydrothermal alteration observed throughout the core is likely related to cooling during uplift to form the transverse ridge.

A striking feature of the alteration is that high-temperature assemblages are prevalent near the top of the section whereas low-temperature assemblages dominate at the base of the section. This unusual cooling history is the reverse of the sequence observed at Hole 504B, and may reflect the role of major fault zones responsible for unroofing of the gabbros.

FUTURE DIRECTIONS

Ocean drilling has played a major role in the development of a first-order, generalized model that predicts the types of alteration reactions and resulting elemental exchanges between fluids and rocks from the time seawater enters the crustal section until it discharges at high-temperature hydrothermal vents. In addition, drilling directly into modern seafloor hydrothermal systems has resulted in revised models of the genesis and evolution of massive sulfide deposits that may have implications for mineral exploration. However, we are only at the beginning of investigating the full range of seafloor hydrothermal systems, and quantifying elemental exchange and its role in global geochemical budgets.

Definition of the full spectrum of seafloor hydrothermal systems requires that we continue to drill into upflow zones beneath hydrothermal mineral deposits.

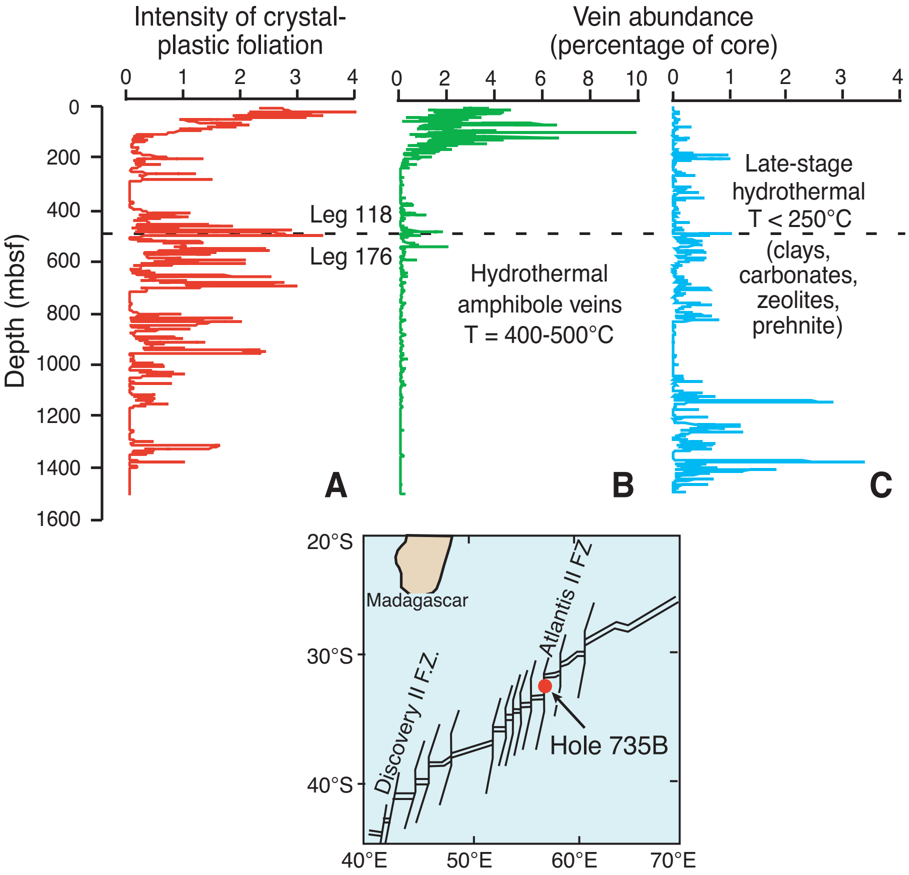


Figure 4. *Downhole variations in intensive of ductile deformation **(A)** and abundances of amphibole veins **(B)** and low-grade metamorphic veins **(C)** in the gabbro section recovered at Hole 735B. (From Bach et al., 2001). Inset: Location of Hole 735B at the Atlantis II Fracture Zone on the Southwest Indian Ridge.*

We have yet to sample an ultramafic-hosted hydrothermal system, or penetrate the deepest parts of an upflow zone to reach the reaction zone. We have no data on the geometry, longevity or extent of water-rock reactions within the reaction zones underpinning large ore bodies. We do not know how differences in spreading regime influence the distribution of permeability and hence the nature of fluid-rock interactions. Addressing these problems requires advances in technology that will allow deep drilling and high temperature logging in these hostile environments, and improved hole stability and core recovery.

An exciting new future direction in studying hydrothermal circulation will be to couple drilling with long term *in situ* measurements at seafloor and downhole observatories. Data and sample collection at different vertical and horizontal scales will enable investigation of hydrothermal circulation as an integrated system to better understand the linkages between physical, chemical and biological characteristics, and their spatial and temporal variability. This will be essential in furthering our understanding of the genesis of mineral deposits, and in quantifying elemental transport and hydrothermal fluxes and their role in global geochemical cycles.

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SUBDUCTION FACTORY INPUT AND OUTPUT

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INTRODUCTION

The Subduction Factory is the dynamic site of mass and energy exchange between the solid earth and its surface (Fig. 1). Raw materials - seafloor sediments, oceanic crust, mantle lithosphere, and fluids - are carried with the down-going plate and fed into the Subduction Factory at deep sea trenches. Inside the Subduction Factory, these raw materials are mixed with mantle and processed into various output products that eventually emerge on the upper plate as magmas, aqueous fluids, metalliferous deposits, serpentine diapirs, volcanoes, continental crust, gases and back-arc seafloor. The waste products - residual slab and associated mantle - sink into the deep mantle and possibly even to the core, to be resurrected as mantle plumes. The functioning of the Subduction Factory through time has fundamentally affected the growth of the continental crust, the chemical evolution of the mantle, and the composition of the atmosphere and oceans.

Despite its central role in Earth functions, the Subduction Factory is largely hidden from view. Thus, aside from probing its modern state with seismic waves and simulating its function in the laboratory and on the computer, the primary mode of study of the Subduction Factory is by examining its inputs and outputs. The Ocean Drilling Program (ODP) and its predecessor, the Deep Sea Drilling Program (DSDP), have been essential in this pursuit. Drilling has provided our only samples of input to the subduction zone, in the form of marine sediments and oceanic crust outboard of deep sea trenches. ODP has enabled comparisons between subducting input and volcanic arc output, demonstrating the cycling of material through the Subduction Factory. ODP has also provided unique samples of subduction output, in the form of serpentine mud volcanoes in forearcs and arc ash records. These different output products constrain the active devolatilization reactions occurring in subducting slabs, as well as the evolution of volcanic arc systems.

SUBDUCTION INPUT: TRACERS AND FLUXES

The distinctive composition of marine sediments and altered oceanic crust make it possible to conduct a giant tracer experiment to follow the cycling of material from the downgoing plate, through the subduction zone, to the upper plate. ODP provides samples of the subducted material, and analysis of nearby arc volcanics

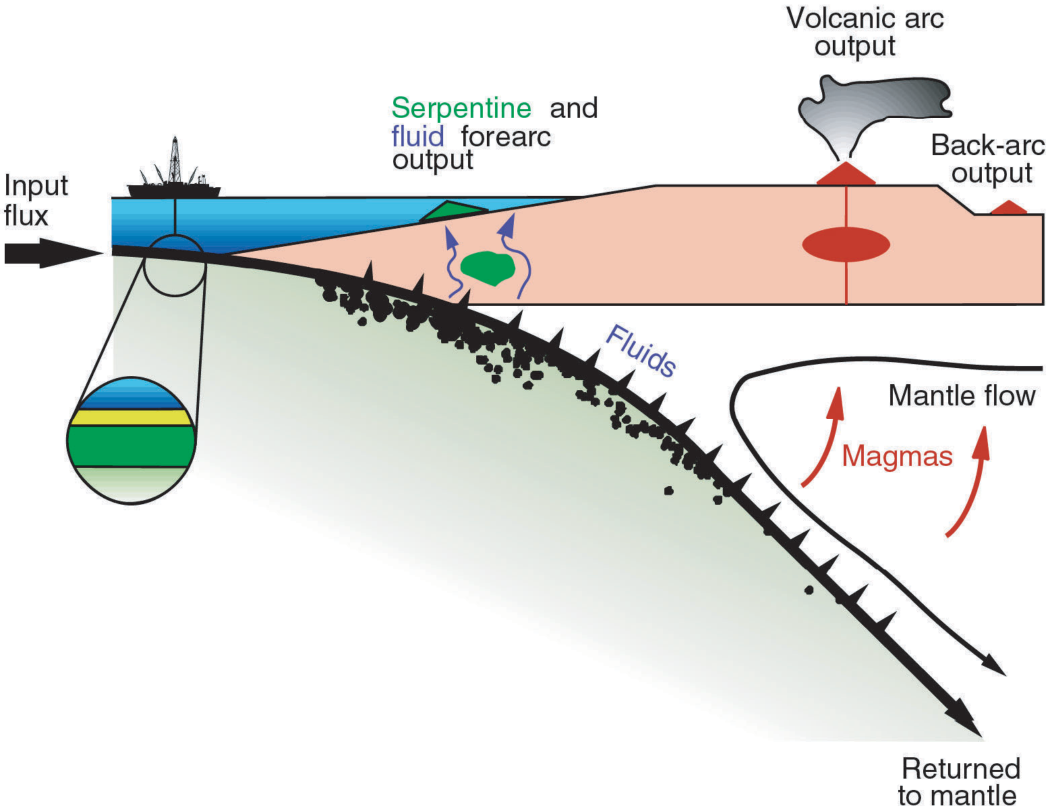

Figure 1. *Inputs and outputs through the Subduction Factory.*

documents the return of slab tracers to the upper plate. This field of study has progressed from identifying the tracers, to comparing the efficiency of different tracers to infer processes deep in the subduction zone, to ultimately mass balancing the inputs and outputs across the subduction zone.

The combined efforts of DSDP and ODP have resulted in drill holes to basement outboard of most trenches. It was not until a significant number of these holes had been analyzed chemically that wholesale element recycling was discovered. The list of elements that can be traced through the subduction zone via their mass flux or isotopic composition has grown markedly over the past fifteen years (e.g., Be, B, Li, K, Rb, Cs, Sr, Ba, U, Th, Pb, REE). For example, where the sedimentary section is high in Ba, so to is the corresponding volcanic arc (Plank and Langmuir, 1998; Fig. 2). Where the sedimentary section contains elevated Th/Rb, so too does the arc (Fig. 2). Thus, the sedimentological and oceanographic processes that control elemental abundance on the seafloor can ultimately affect the composition of arc volcanism.

Just as important, however, is the lack of sediment recycling at some margins. The complete sedimentary section to the Eocene recovered during Leg 145 drilling was used to estimate the bulk composition of sediment subducting at the Kamchatka trench. The Pb isotopic composition of the sediments is much more radiogenic than that of Kamchatka arc igneous rocks, which are indistinguishable from Mid-Ocean Ridge Basalt, or MORB (Kersting and Arculus, 1995). This study demonstrated that the subducting sedimentary column at the Kamchatka trench must be accreted or underplated, and that recycled sediment components from the slab are not a requirement of arc volcanism. At other margins, where the effects of sediment recycling have not been observed, efforts are underway to mass balance the inputs and outputs. A recent study used Li isotopes from ODP Site 1039 to demonstrate that 50% of the Li from the downgoing plate is recycled to the Costa Rica arc, 25% is returned to the ocean via the décollement, and 25% is lost to the deep mantle (Chan and Kastner, 2000).

ODP and DSDP drilling also has enabled a number of global studies of the flux of material into trenches. von Huene and Scholl (1991), Rea and Ruff (1996), and Plank and Langmuir (1988) have estimated the mass flux of sediment subducting at each convergent margin, its lithological make-up, and its chemical composition, respectively. These studies have made extensive use of DSDP and ODP results and databases, and together represent a distillation of most DSDP and ODP drilling relevant to subduction fluxes. Perhaps the largest-scale discovery resulting from these works is how the flux of continental material into trenches is roughly comparable to continental growth rates. It is possible that the continental mass is currently in steady-state, shrinking by sediment subduction as fast as it grows by igneous additions. The full impact of these studies is larger than the continental growth implications, with contributions to science in areas as varied as CO$_2$ cycling, element partitioning, the Archean, and mantle plumes.

Subduction Output: Mud from the Slab and Mantle

The Mariana forearc contains unusual mud volcanoes that are actively extruding serpentine mud, blueschist clasts and freshened fluids (e.g., Fryer et al., 1999; Maekawa et al., 1993; Fig. 2). These materials appear to derive from the subducting plate and overlying mantle

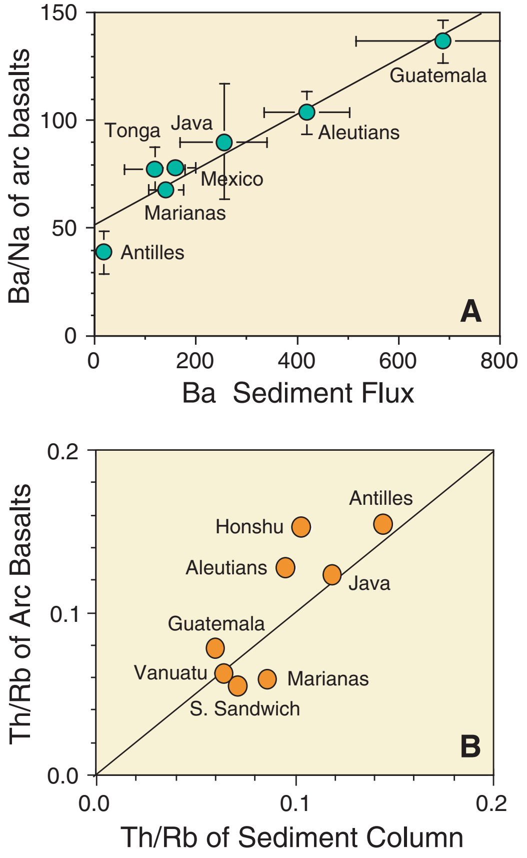

***Figure 2.** Correlations between marine sediment input and volcanic arc output provide strong evidence for the cycling of material from the subducting slab to arc magmas. **A.** Ba sediment flux (in g/yr/cm arc length, calculated from in DSDP and ODP sites drilled near trenches) vs. Ba/Na$_2$O in arc basalts (Ba is normalized to Na to correct for partial melting and crystallization). From Plank and Langmuir (1993). **B.** Th/Rb in each arc appears to be inherited from the subducting sediment column. Only margins with high Rb flux (>3 g/yr/cm arc length) are plotted as low sediment flux margins are dominated by oceanic crust and mantle contributions. From Johnson and Plank (1999).*

wedge. Drilling during ODP Leg 125 (and more recently during Leg 195) recovered samples of the serpentine mud and fluids. Subsequent analysis has revealed that 1) the only measured *in situ* pressures, temperatures and reactions from intermediate depths in an active subduction zone, and 2) a modern analog to sedimentary serpentine accretionary complexes worldwide.

The variety of minerals and fluids contained within the serpentine mud volcanoes record the conditions within the active Mariana subduction zone. The initial discovery of winchite, a blue amphibole, along with other clasts that contain aragonite, lawsonite + quartz, and jadeite, require blueschist facies metamorphism (Maekawa et al., 1993). No other sources of blueschist facies rocks exist near the Marianas islands, aside from the active subduction zone itself. Thus, the serpentine mud volcanoes appear to be extruding material that has risen from the subducting plate. The blueschist assemblages require 5 kbar to 6 kbar pressure (16 km to 20 km) and 150° to 250°C (Maekawa et al., 1993), and provide a unique constraint for numerical models of slab thermal structure. Some mud volcanoes also vent freshened fluids that appear to be derived from the slab. Brucite and carbonate chimney structures, along with pore fluid compositions from the serpentine mud, indicate active decarbonation reactions occurring at 15 km to 25 km depth in the Marianas slab (Fryer et al., 1999). Blueschist mud with a rich mineral assemblage was recovered during recent Leg 195 drilling (Fig. 3), and a long-term geochemical observatory was installed in a borehole drilled into the central conduit of one of the serpentine seamounts. After the hole has rebounded from drilling disturbances, this observatory may provide samples of fluids that are minimally altered from those expelled from the subducting slab, and may be our most direct samples of the recycling elixir.

The discovery of serpentine mud volcanoes has also led to a better understanding of "sedimentary" serpentines in accretionary complexes such as in the Franciscan complex of California or the Kamuikotan terranes in Japan. Sedimentary serpentine deposits are common to many of these accretionary melanges, and thus far have had an equivocal origin. The Marianas forearc serpentine structures appear to reflect a combination of emplacement mechanisms, from diapirism, to fluidization of fault gouge, to *in situ* hydration and uplift of forearc mantle (Fryer et al., 1995). All of these mechanisms may occur during subduction, and are quite different from the syn- or post-obduction mechanisms proposed for many serpentine deposits exposed on land. The modern Marianas serpentine mud volcanoes may help to interpret ancient serpentine deposits, and thus develop of better understanding of subduction processes in the past.

Subduction Output: The Arc Ash Record

Drilling near subduction zones has recovered, sometimes unexpectedly, remarkable sections of ash derived from nearby volcanic arcs. Volcanoes on land typically

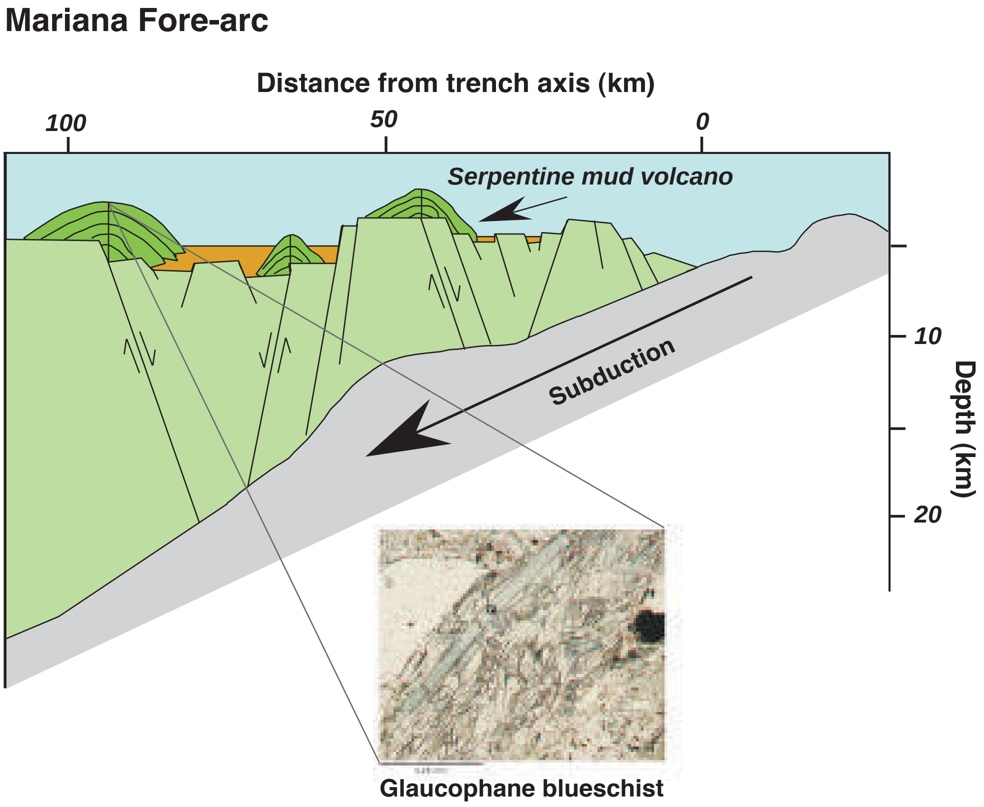

Figure 3. Mud volcanoes in the Mariana fore-arc emit serpentine and blueschist that derive from from the mantle wedge and subducting plate, respectively. Mineral equilibria in blueschist clasts recovered during Leg 125 constrain the slab to be 150° to 250°C at 16 km to 20 km (Maekawa, et al., 1993). A borehole observatory was installed in one of the serpentine mud volcanoes during ODP Leg 195 to provide fluid samples that derive from the subducting slab. From Fryer et al. (1999).

bury their own eruptive products, or where sections are exposed, they may be poorly preserved and difficult to date precisely. Alternatively, marine ash layers may be well preserved and dated biostratigraphically. The conventional microprobe, coupled with more recent advances in the ion microprobe and laser ablation inductively-coupled plasma mass spectrometry (ICPMS), now enable large geochemical data sets (including major, trace and some isotopic compositions) to be collected on single ~100 micron volcanic glass shards or phenocrysts. Single crystal laser-fusion ^{40}Ar/^{39}Ar dating also has improved the precision of dating tiny amounts of material. The combination of recent ODP drilling of ash-rich sections near volcanic arcs, along with the development of the microbeam techniques, has led to several new high resolution tephra records. These geochemical and geochronological records are providing new views into arc evolution and the episodicity of explosive volcanism.

Several studies have been carried out over the past ten years on the ash record of the Mariana-Izu arcs (see review in Arculus et al., 1995). The ash layers preserved in cores drilled during Legs 125 and 126, as well as during previous DSDP legs, record almost the entire 45 million year (m.y.) history of arc volcanism in this area. The chemical composition of the ash layers, turbidites and individual shards reveal several new observations about this arc system (Fig. 4). First, the Mariana and Izu arc systems were similar chemically from 30 to 15 million years ago (Ma), when back-arc spreading ceased behind both arcs (e.g., Bryant et al., 1999). Since 15 Ma, the two arc systems have diverged chemically, with the Izu arc possessing remarkably uniform and depleted compositions over the past 10 m.y. On the other hand, the Mariana arc experienced a peak in recycling sediment flux (Th/Yb) from the slab to the arc 6 to 12 Ma. The cause of these variations still is not well understood, but these discoveries have proved false the previous hypothesis of arc evolution that predicted a monotonic increase in alkalinity as the arcs mature. Instead, these ash records have demonstrated that some subduction factories may be near steady state with respect to slab and mantle fluxes over time scales of 10 m.y.

In contrast to the Mariana-Izu studies, which focused on the geochemical evolution of arc systems, studies of the prodigious ash record cored on the Caribbean plate during Leg 165 focused on the episodicity of explosive volcanism from the source region in Central America (Fig. 4). The marine tephra record shows two major peaks in volcanism, one in the Miocene, and one in the Eocene (e.g., Sigurdsson et al., 2000). The magnitude of the source eruptions is as large as some of the largest recorded eruptions on earth (e.g., Toba, at ~1000 km^3). The two peaks in volcanism correspond well to two major episodes of ignimbrite formation in both the Mexican and Central American arcs. The cause

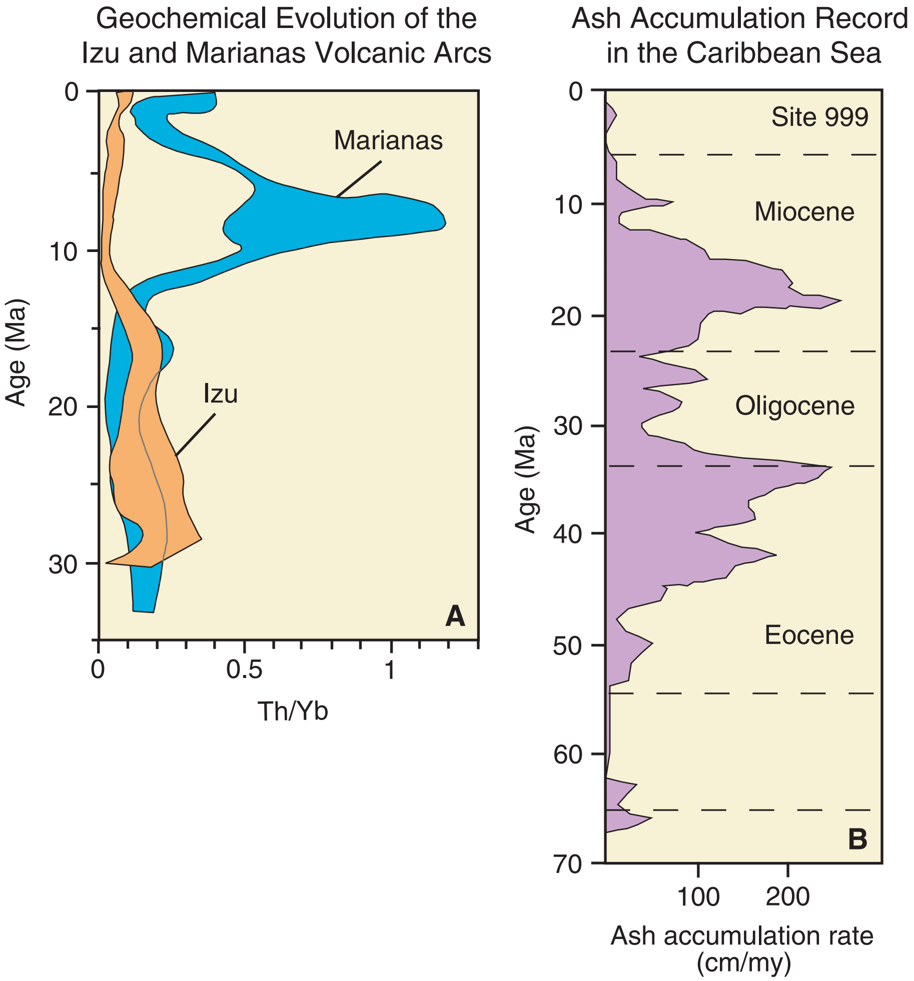

Figure 4. *Ash records from ODP sites near volcanic arcs.* ***A.*** *Geochemical evolution of the Mariana and Izu arcs, as revealed from laser-ablation ICPMS analyses of volcanic glass shards. Th/Yb is a measure of subducted sediment input to the arcs. From Bryant et al. (1999).* ***B.*** *The ash record in the Caribbean reflects two large pulses of explosive volcanism in Central America and Mexico: one in the Miocene and one in the Eocene. From Sigurdsson et al. (2000).*

of such large ignimbrite flare-ups, their possible global synchroneity, and their effect on climate, remain topics of debate. The peaks in Central American eruption volume appear to coincide with major plate reorganizations, and the late Eocene event may relate to a period of global cooling. The ODP ash records may thus demonstrate a link between plate tectonic control on the magnitude of arc volcanism and the effect of volcanic eruptions on climate change.

Few ODP boreholes have been drilled specifically to study the Subduction Factory. The legacy of ODP in Subduction Factory studies is, therefore, one example of what can be done largely by using holes of opportunity. The future holds many exciting opportunities, as joint science planning between the NSF MARGINS Program, Inter-MARGINs and IODP guide further multidisciplinary studies of the Subduction Factory. While the sedimentary input and ash output records have been well sampled by ODP, processes of oceanic crust input and fluid output present greater challenges. The challenges can be met with dedicated drilling efforts and technological advances in the form of riser drilling, improved recovery in fractured rock, and borehole sampling of fluids.

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OCEANIC PLATEAUS AS WINDOWS TO THE EARTH'S INTERIOR: AN ODP SUCCESS STORY

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WHAT ARE OCEANIC PLATEAUS?

Oceanic plateaus were virtually unknown twenty years ago. Now, thanks largely to Ocean Drilling Program (ODP) activities, they are recognized as a major component of the oceanic crust. Plateaus provide a record of a phenomenon that has occurred episodically throughout Earth history and very probably represent a style of mantle dynamics quite distinct from normal plate tectonics.

An oceanic plateau is a large region of anomalously thick oceanic crust. Well-known examples include the giant Ontong Java Plateau in the southeast Pacific, and the slightly smaller Caribbean Plateau (Fig. 1). Smaller plateaus (Manihiki Plateau, Hess Rise and the Shatsky Rise) are distributed throughout the Pacific Ocean Basin. These examples are composed predominantly of mafic to ultramafic rocks, and erupted in an oceanic setting. In contrast, parts of the Kerguelen Plateau in the Indian Ocean consist of subaerial rocks and overlie continental lithosphere (e.g., Frey et al., 2000).

We focus here on the petrological and geochemical characteristics of three plateaus chosen to illustrate both the general features of these enormous but enigmatic structures, and the scientific questions that surround their formation. Information from ocean drilling has been essential in the investigation of these submarine, sediment-covered structures.

Ontong Java: The Type Example of an Oceanic Plateau

The Alaska-sized Ontong Java Plateau covers 1.6 x 10^6 km^2 of the Pacific Ocean floor and is more than 35 km thick. It is almost entirely submerged, and what little is known about the main plateau comes from Deep Sea Drilling Program (DSDP) and ODP geophysical surveys and drilling (e.g., Coffin and Eldholm, 1994). Beneath a thick layer of sediments, the plateau consists of four layers of materials with distinct seismic velocities. The uppermost magmatic rocks consist entirely of basaltic flows whose ubiquitous pillow structures indicate submarine eruption. The lower layers of the plateau are

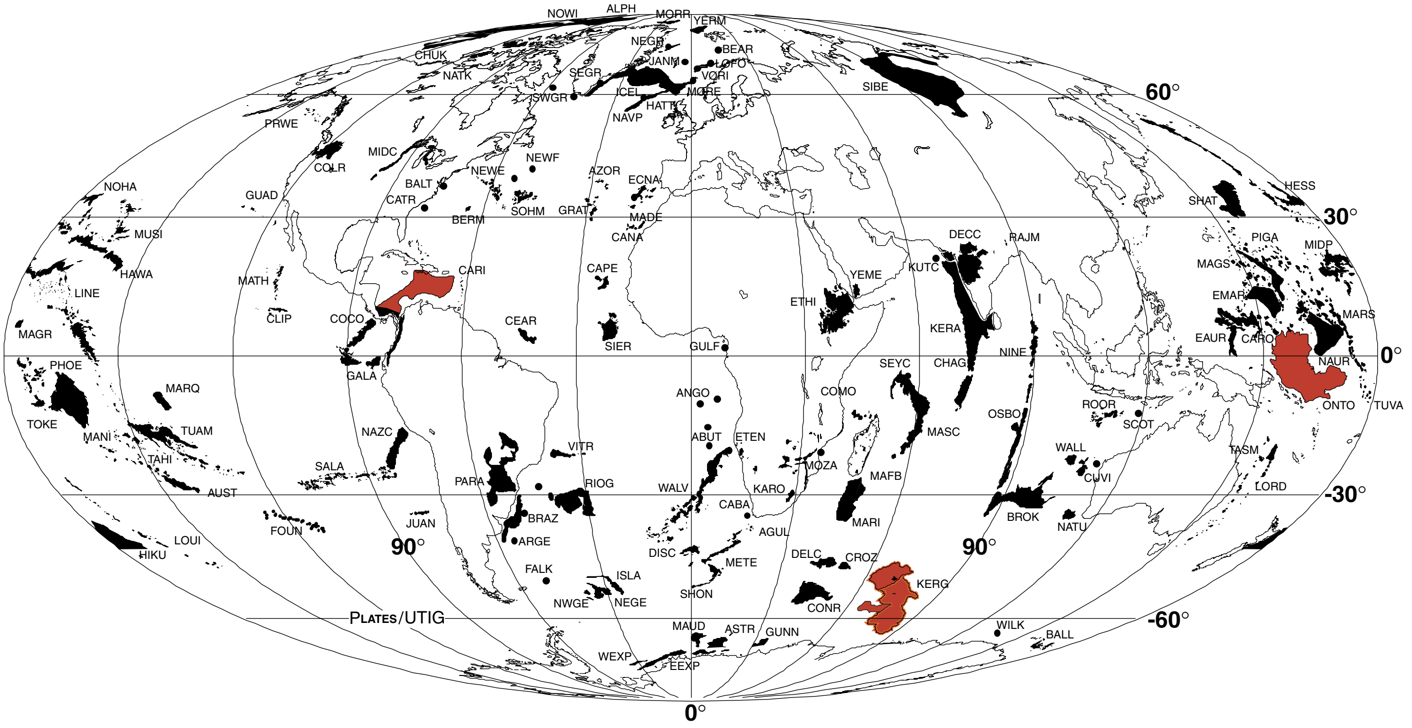

Figure 1. Map showing locations of oceanic plateaus (from Coffin and Eldholm, 1994). Red areas indicate the three oceanic plateaus targeted by ODP and discussed in this paper - Ontong Java (ONTO), Caribbean (CARI), and Kerguelen (KERG).

inferred to consist of intrusive rocks with mafic to ultramafic compositions, partly converted to high-pressure metamorphic assemblages. The plateau erupted during two major pulses, one around 122 million years ago (Ma) and the second around 90 Ma (e.g., Mahoney et al., 1993). Even though over 30 km of mafic to ultramafic rock was added to the oceanic lithosphere, it seems that almost the entire plateau erupted and remained below sea level.

The upper volcanic layers are composed almost entirely of tholeiitic basalts. Despite their huge volume and relatively large age span, basalts throughout the plateau have remarkably uniform chemical and isotopic compositions, with near-constant SiO_2 and MgO and near-chondritic proportions of rare earth elements (REE) (Fig. 2). Sr, Nd and Pb isotope ratios all plot near the centers of fields for oceanic island basalts (Fig. 3).

Caribbean: An Oceanic Plateau Partially Accreted to Continental Crust

The Caribbean oceanic plateau originally may have been almost as large as Ontong Java, but major portions have been lost through accretion to Central and South American continental crust. This plateau originally formed in the Pacific Ocean and then migrated to its present position in the Caribbean basin (Burke et al., 1984). Obduction has exposed a diverse suite of rocks exposed from the deeper parts of the plateau. Homogeneous evolved tholeiitic basalts with near-chondritic ratios of incompatible trace elements are dominant. Geochemically enriched basalts, various types of highly extremely depleted picrites and komatiites, and the intrusive equivalents of these rocks are scattered through the plateau (Fig. 2). Isotopic compositions of the dominant basalts plot together with Ontong Java basalts (Fig. 3), but the more extreme magma types have diverse compositions. The enriched rocks have $\varepsilon Nd_{(T)}$ around +4 while rocks with flat to depleted element patterns have higher $\varepsilon Nd_{(T)}$ around +6. Pb isotopic compositions cover a large range of values, from 18.3 to 19.8, extending towards higher $^{206}Pb/^{204}Pb$ values than the field of Pacific MORB.

Reported ages parallel those from Ontong Java. Most fall in the range of 87 to 90 million years (m.y.), but an older portion accreted to Colombia and Ecuador has ages of 120 to 123 Ma.

Kerguelen: A Hybrid Plateau

Although Kerguelen and Ontong Java have long been considered type examples of an oceanic plateau, recent ODP-related research has shown that parts of Kerguelen erupted in a continental setting (e.g., Frey et al., 2000). The plateau started to form at the edges of Gondwana during breakup of the supercontinent, and then evolved within the expanding Indian Ocean basin as the continents drifted apart. Unlike other oceanic

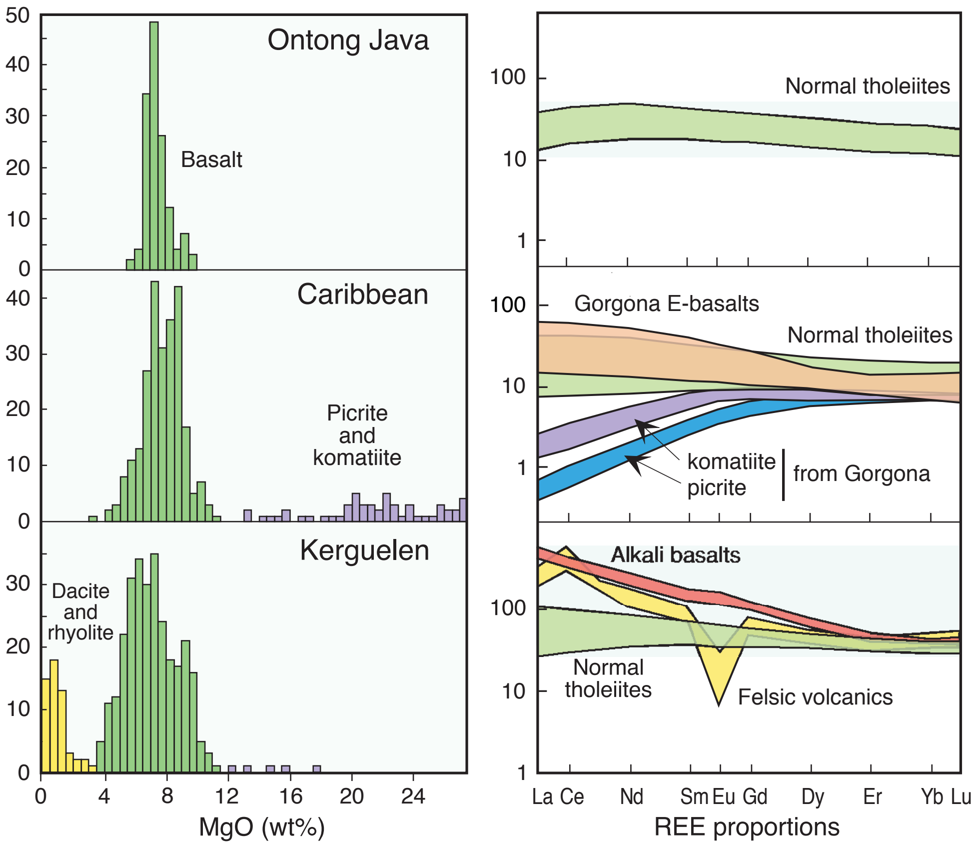

Figure 2. Histogram of MgO contents and REE patterns of lavas from three oceanic plateaus: Ontong Java, Caribbean and Kerguelen. The basalts have remarkably similar patterns despite large dispersion of the compositions for other types of lavas in the Caribbean and Kerguelen Plateau.

plateaus, which seem to have erupted during one to two peaks of intense activity, the Kerguelen Plateau had a protracted, 120 m.y.-long magmatic history punctuated by enhanced activity at 115 and 85 Ma.

The oldest activity was the subaerial eruption of flood basalts about 120 Ma ago, on the Indian and Australian continents. Similar rocks are preserved in now-submerged southern and central parts of the Kerguelen plateau. More magma erupted 85 to 90 Ma ago onto segments of continental lithosphere that had become isolated in the growing Indian Ocean basin. The ~5000 km-long Ninetyeast Ridge, the longest linear feature on Earth, formed between 82 and 38 Ma during rapid northward migration of the Indian plate over the Kerguelen plume. At 40 Ma, the plume was located on the mid-ocean ridge; it then migrated to its present intraplate location on the Kerguelen Archipelago.

These diverse tectonic settings yielded a wide variation of rock types and chemical compositions (Figs. 2 and 3). Flood basalts in parts of the southern and central Plateau are thick massive subaerial flows with evolved tholeiitic basaltic compositions and a "continental" geochemical signature - relatively high SiO$_2$, enriched incompatible elements, a Nb-Ta deficit, and high ^{87}Sr/^{86}Sr and low ^{143}Nd/^{144}Nd ratios. On Elan Bank, the location of ODP Leg 183's Site 1137, bimodal mafic-felsic volcanic rocks overlie fluviatile sediments. Clasts of garnet-bearing gneiss in a conglomerate, and geochemical evidence of crustal contamination in felsic and mafic lavas, indicate emplacement on or near continental lithosphere (Weis et al., 2001). Submarine basalts of the Northern Plateau and Broken Ridge have compositions similar to basalts from other oceanic plateaus and lack a geochemical continental component.

Late-stage volcanism on the Kerguelen Archipelago and some submerged parts of the plateau (e.g., Skiff Bank, Site 1139 of ODP Leg 183) formed bimodal tholeiitic and alkali sequences. The alkali basalts are moderately to extremely enriched in incompatible trace elements (Fig. 2) but lack the geochemical characteristics that indicate interaction with continental crust. They formed as shield volcanoes upon the main volcanic plateau in an entirely oceanic setting.

The early stages of the hybrid Kerguelen Plateau resemble the North Atlantic Magmatic Province; the younger parts are more like other oceanic plateaus. The situation 40 Ma was directly comparable with that of present day Iceland. A puzzling aspect is why so much of the crust-contaminated flood basalt sequence and underlying continental lithosphere now lie submerged under 1 to 3000 km of seawater.

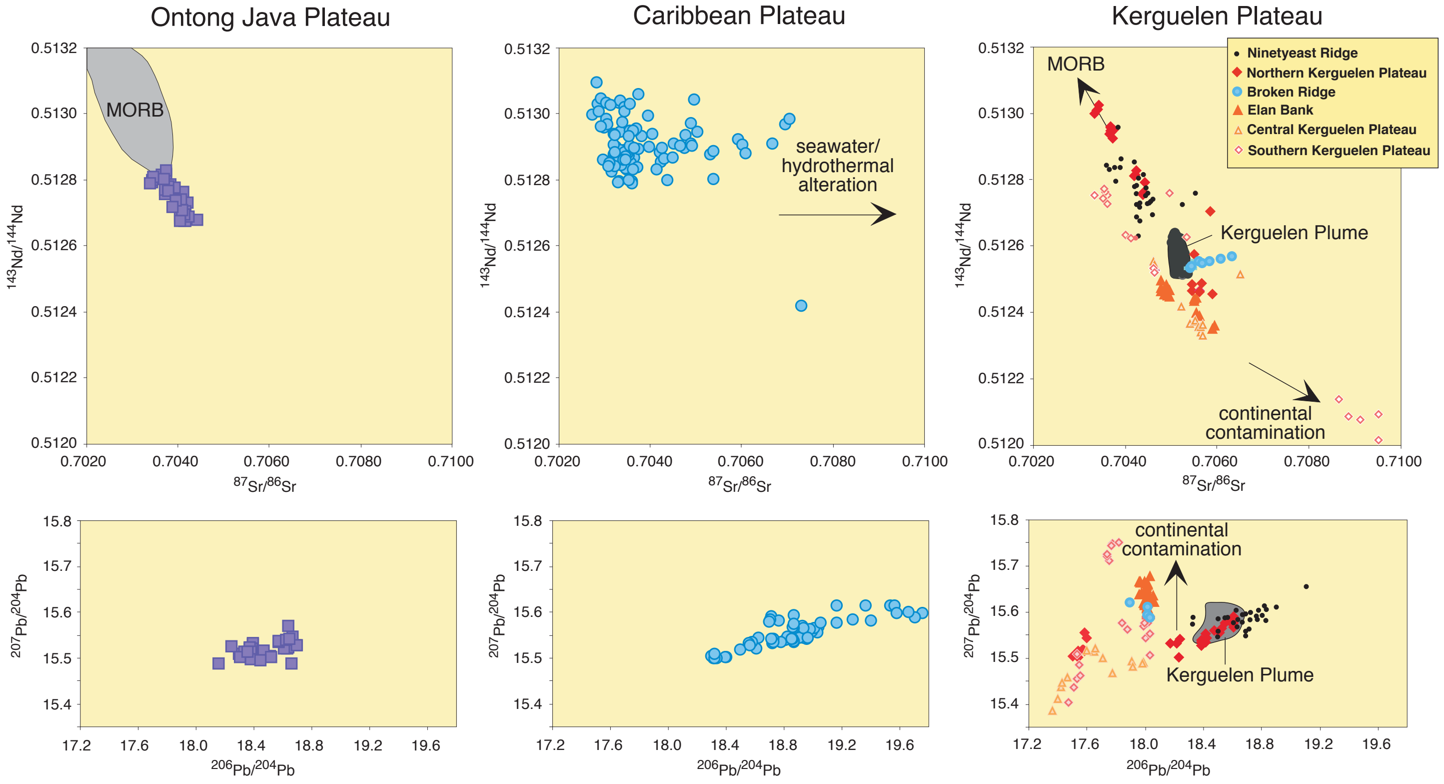

Figure 3. *Sr, Nd and Pb isotopic ratios. The anomalously high Sr isotope ratios of some samples from the Caribbean Plateau are due to alteration. For the Kerguelen Plateau, the high ^{87}Sr/^{86}Sr and ^{207}Pb/^{204}Pb ratios reflect continental contamination. Note the striking homogeneity of Ontong Java basalts.*

THE ROLE OF MANTLE PLUMES IN THE FORMATION OF OCEANIC PLATEAUS

Similarities in structure, rock types and eruption histories of oceanic and continental plateaus suggest that both are manifestations of the same mantle process. Both consist mainly of enormous volumes of mafic volcanic and intrusive rocks. Although some have complex histories, most formed during one or two short, massive bursts of magmatic activity.

Formation of a huge volume of mafic magma requires that an enormous volume of hot mantle ascended from deeper in the mantle to the base of the lithosphere. Most authors attribute both continental and oceanic plateaus to melting in the large head of a starting mantle plume (Fig. 4; e.g., White and McKenzie, 1995; Campbell and Griffiths, 1990). Continued melting in the plume conduit leads to the formation of trails of oceanic islands like the Ninetyeast Ridge and the Kerguelen Archipelago.

MAGMA FLUX AND EPISODICITY DURING THE FORMATION OF OCEANIC PLATEAUS

A major achievement of ocean drilling was to constrain the age and the flux of magmatic activity during formation of oceanic plateaus. There are two main issues. The first involves the contrasting magmatic histories recorded in different oceanic plateaus - the emplacement of virtually the entire Ontong Java Plateau in two short bursts of activity, as opposed to the more continuous and protracted activity of the Kerguelen Plateau. The persistence of magmatism in the Kerguelen Plateau in part can be attributed to melting of the plume as it welled up between rifting portions of continental lithosphere. Such a process explains the thick volcanic sequences at both margins of the North Atlantic (Saunders et al., 1997) and may account for the earlier ~120 Ma period of Kerguelen magmatism (Weis et al., 2001). This process cannot, however, explain the second pulse of magmatism around 90 Ma, which is recorded in central and northern parts of the Plateau. It seems instead that the Kerguelen magmatism resulted from pulsed activity of a plume that continued to produce large volumes of magma over a 100 m.y. period after its arrival near the Earth's surface.

The second issue concerns striking similarities of the age patterns of oceanic plateaus - the ~120 Ma peak of the Ontong Java plateau also is registered in the Manihiki Plateau and in parts of the Kerguelen and Caribbean Plateaus. The younger ~90 Ma peak is repeated in the Kerguelen and Caribbean Plateaus, and in continental flood volcanism on Madagascar. Similar age clusters are recorded in other parts of the world and earlier in Earth history. Archean greenstone belts on all continents have been interpreted as relicts of oceanic plateaus, and the largest of these all formed within a remarkably short period about 2.7 billion years ago (Ga). It appears that the episodicity recorded worldwide, in Archean as well as Cretaceous oceanic plateaus (Arndt et al., 1997), results from a mantle process that operates at a global scale. The tasks facing

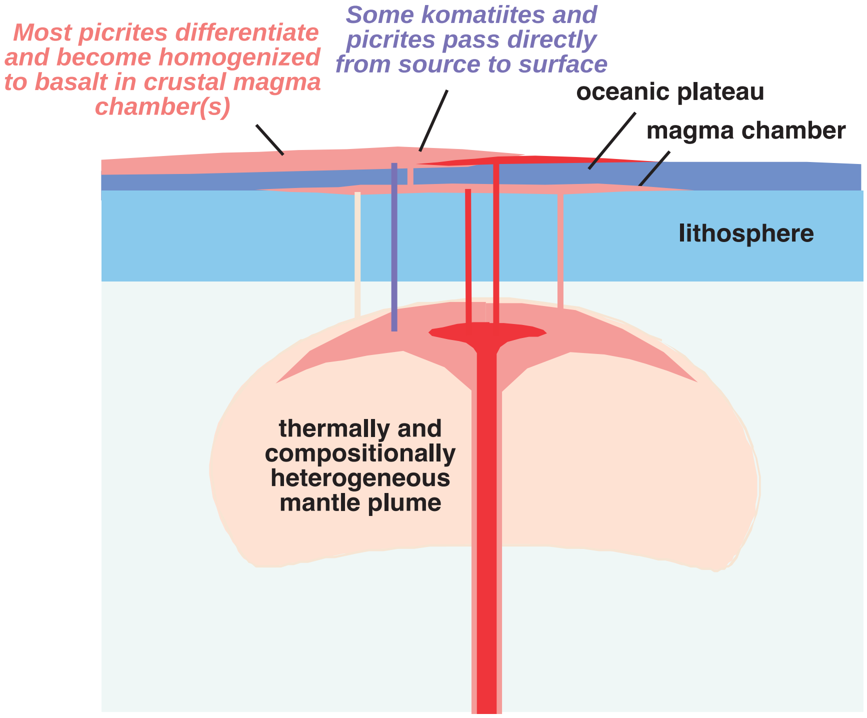

Figure 4. Sketch of a mantle plume feeding an oceanic plateau. The temperature of the plume varies from its hot interior to its cool margins, and its composition also changes. It partially melts to give picritic magmas of variable compositions. Some of these erupt directly; others are processed in large magma chambers and erupt as homogeneous, evolved basalt.

geologists and geophysicists are to verify the episodicity of this process and to explain it in terms of mantle dynamics.

MAGMATIC EVOLUTION OF AN OCEANIC PLATEAU

Experimental petrology tells us that deep-seated primary melts have highly magnesian, picritic to komatiitic compositions. In continental regions, where thick lithosphere limits melting to great depth and pressure, even low-degree melts have high MgO contents; in an oceanic setting where the plume melts at shallower depth, a high degree of melting leads to picritic compositions.

The evolved compositions of the basalts that dominate oceanic plateaus arise from fractional crystallization of parental picritic magmas, probably in magma chambers near the crust-mantle boundary. The evolved liquids erupt at the surface while large volumes of mafic to ultramafic rock accumulate in the crust or uppermost mantle (Fig. 4).

The volcanic and intrusive rocks of Gorgona Island, part of the Caribbean Plateau, illustrate the complex magmatic plumbing of an oceanic plateau. Komatiites and picrites first formed through high-degree fractional melting of the mantle plume, then ascended directly to the surface. Other primary magmas became trapped in crustal magma chambers where they mixed with other magmas and fractionally crystallized to form the homogenized, evolved basalt that dominates all oceanic plateaus. Intrusive gabbros and peridotites are interpreted as portions of high-level magma chambers that were fed by magmas that evolved deeper in the crust (Révillon et al., 2000).

THE HOMOGENEITY OF BASALT COMPOSITIONS

The outstanding petrological characteristic of oceanic plateau basalts is their remarkably uniform composition. Recent ODP drilling has demonstrated minimal variation from one end of the Ontong Java plateau to the other, and the composition is reproduced in the two principal age groups (120 and 90 Ma). Leg 192 scientists attributed this similarity to generation of the basalts from a large, long-lived homogeneous mantle source, but is this correct?

Figure 2 emphasizes the similarity of basalt compositions in the three plateaus. The data set includes basalts from the Caribbean Plateau where homogeneous basalts alternate with compositionally diverse picrites. The situation parallels that of continental flood basalts, which also show remarkable homogeneity. In both cases, the composition of the erupted basalt probably results from processes operating during passage through the lithosphere, particularly the pooling, fractionation and homogenization of magmas in crustal chambers. These processes are repeated in different ocean basins and at different times. The eruption of homogenous magma does not require a homogeneous mantle source; instead, it is explained in terms of reproducible conditions during mantle melting and magma migration, and, above all, through efficient homogenization in large magma chambers.

SOME UNRESOLVED ISSUES

Emergence/Submersion of Plateaus

Why did the Ontong Java Plateau remain submerged throughout its evolution, despite the arrival of a huge volume of hot, low-density mantle at the base of the lithosphere, and the addition of 35 km of new material to the crust? Why did large parts of the Kerguelen Plateau, which formed as subaerial flood volcanics upon continental lithosphere, subsequently sink beneath the ocean? What does this tell us about the extent of thinning of the lithosphere and the persistence of low-density sub-plateau roots?

What is the Nature, and Fate, of Mantle Roots of Oceanic Plateaus?

The extraction of large volumes of high-degree melt leaves a mantle root with distinctive physical and chemical characteristics. Its density is low because of its initially high temperature and because it has lost the high-density mantle components (Fe-rich mafic minerals and garnet). How do these roots influence the magmatic and tectonic evolution of the plateau?

The Environmental Impact of the Emplacement of an Oceanic Plateau

Eruptions of continental flood basalts have been linked to mass extinctions such as those at the Permian-Triassic and Cretaceous-Tertiary boundaries (e.g. Courtillot et al., 1999). The effect of submarine eruption of basalt is probably less, but may be manifested in anoxic conditions and changes in the temperature and composition of ocean waters. The key to understanding these effects is the nature and vigor of hydrothermal circulation within the volcanic pile. If interaction between seawater and basalt is limited to the uppermost layer of the volcanic pile, the effects will be minor. Only if large-scale circulation is achieved will the effect be significant.

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INVESTIGATIONS OF RIFTED MARGINS

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INTRODUCTION AND BACKGROUND

The formation of rifted margins during continental breakup and subsequent formation of new ocean basins are fundamental components of the plate tectonic cycle. Rifted margins host hydrocarbon deposits and their stratigraphy reflects the history of sea level change. Ocean Drilling Program (ODP) drilling in rift settings included objectives related to sequence stratigraphy (see Miller, this volume), back-arc rifting (e.g., Legs 125 through 128, Leg 135) and active rifting (Leg 180). This review focuses on ODP investigations of continental breakup during Legs 103, 104, 149, 152, 163, and 173 in the North Atlantic. Results from these legs, combined with geophysical studies, have shown that continental breakup can lead to the formation of very different margins: volcanic rifted margins with thick igneous crust, and non-volcanic, or magma-poor, margins with, apparently, virtually no igneous crust formed during breakup.

This extreme variation in margin structure contrasts with the idea of a homogenized upper mantle responding to breakup and removal of the continental lithosphere by decompression melting and formation of new igneous (oceanic) crust 6 to 7 km thick. Hot spots arising from a mantle plume may explain the anomalous magmatism along volcanic rifted margins, and suggest a close link between mantle plumes and breakup (e.g., White and McKenzie, 1989; Campbell and Griffiths, 1990). An alternate mechanism may be forced initial upwelling of ambient mantle during rifting (Mutter et al., 1988). However, no accepted mechanism exists to form 'cold spots' that could explain the highly amagmatic nature of non-volcanic margins. Instead, low strain rates and/or decoupling of crustal extension and lithospheric thinning may control the amount and distribution of rift-related magmatism (e.g., Latin and White, 1990; Bown and White, 1995).

Following initial discoveries on Legs 103 and 104, a JOIDES North Atlantic Rifted Margins Detailed Planning Group (DPG) designed drilling transects across North Atlantic margins of both types to further explore this profound diversity in margin development. DPG planning led directly to the Leg 149, 152, 163, and 173 outcomes reviewed herein, as well as to the final ODP Leg 210 scheduled for Summer 2003.

VOLCANIC RIFTED MARGIN DRILLING

North Atlantic volcanic rifted margins (Fig. 1) are comprised of wedges of seaward-dipping sub-basement reflections, more than 5 km thick and 100 km wide, known as seaward-dipping reflector sequences (SDRS). Their stratigraphic pattern is consistent with basaltic lavas extruded from an Icelandic-type rift zone.

The landward portion of the SDRS off mid-Norway was the target of ODP Leg 104 drilling (Fig. 1). At Site 642 on the Voering Plateau, a ~700-m-thick Upper Series of basaltic lava flows was found to overlie more developed lavas, in part derived by melting of the continental crust; the entire section was deposited subaerially. The basaltic Upper Series was emplaced within magnetic chron C24r (ca. 53 to 56 Ma (million years ago)) and, unlike the underlying volcanic series, shows little

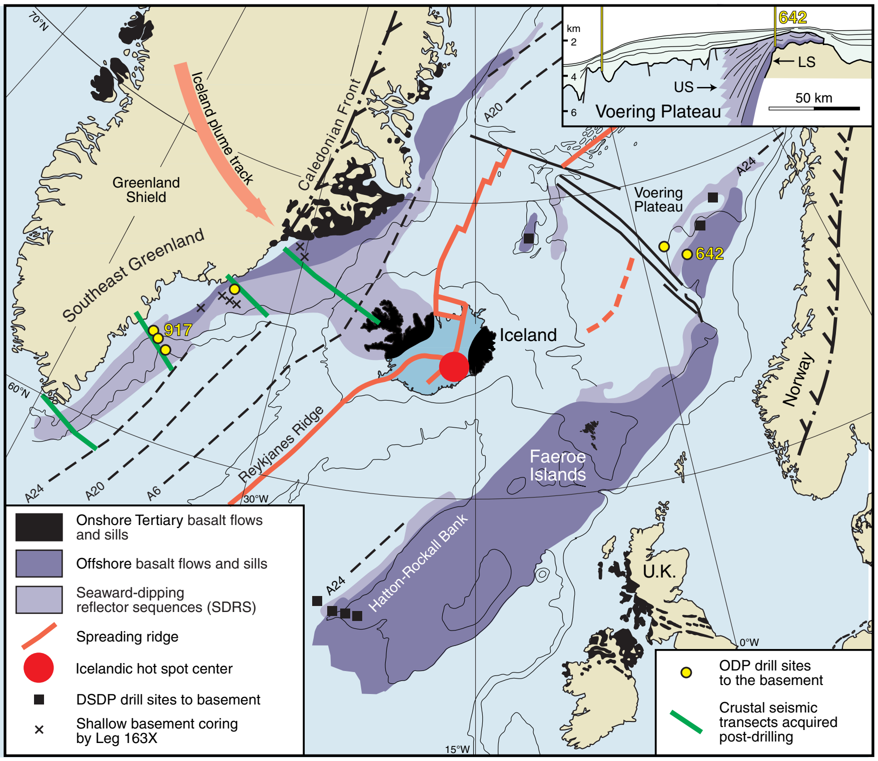

Figure 1. *North Atlantic volcanic rifted margin drilling locations of ODP Leg 104, 152 and 163 basement sites (yellow circles), DSDP basement sites (black squares) and Leg 163X shallow holes (crosses). Insert: depth cross-section of deep basement investigated by ODP at Voering Plateau Site 642. Upper Series (US) and Lower Series (LS) basalts are described in the text. The pre-breakup LS was encountered below the thick US belonging to the main seaward-dipping reflector sequence (SDRS). Details of East Greenland Site 917 and adjacent sites are given in Figure 2. Green lines indicate four offshore crustal seismic transects collected by Holbrook et al. (2001).*

evidence for continental crustal contamination (Eldholm et al., 2002). Thus, while the Lower Series of Site 642 clearly was erupted through a continental basement, the overlying upper series suggests that the SDRS crust, typically 15 to 20 km thick (White and McKenzie, 1989; Holbrook et al., 2001), is Icelandic-type crust. However, extrapolation of Leg 104 findings along the entire extent of SDRS crust (Fig. 1) suggests that during breakup igneous crust up to ~30 km thick formed below the Iceland-Greenland Ridge along an Icelandic-type rift zone more than 2000 km long. The total implied igneous productivity is an order of magnitude larger than the present productivity of the Iceland hot-spot, and suggests either the presence of a very large plume head during breakup or some other process causing increased magmatism along the entire margin (e.g., Mutter et al., 1988).

Important questions raised by Leg 104 include whether volcanic rifted margin formation is an inherent process of continental breakup. If so, is the Iceland plume only a local overprint on a different, margin-wide process? Or, if large (>2000 km) margin-wide plume heads exist, what is their role in breakup and when were the SDRS emplaced? Subsequent drilling investigated (1) mantle temperature anomalies and possible geochemical relations to Icelandic plume mantle; (2) relative timing of plume emplacement and breakup; and (3) temporal and spatial variability of SDRS formation. Legs 152 and 163 off Southeast Greenland included one margin transect distal (>500 km), and one more proximal (~200 km), to the Iceland hot-spot track (Fig. 1). Shallow coring was conducted later as Leg 163X.

Hole 917A (Fig. 1) off Southeast Greenland located the transition from rift to drift at an unconformity between a lower, ~700-m-thick continental and seaward dipping succession of 61- to 59-million year (m.y.)-old pre-breakup lavas and overlying, primitive and picritic lavas. This section is overlain by a 56- to 53-m.y.-old oceanic succession of basalts (Fig. 2) that are similar in age and composition to the Voering Upper Series (Site 642). The continental

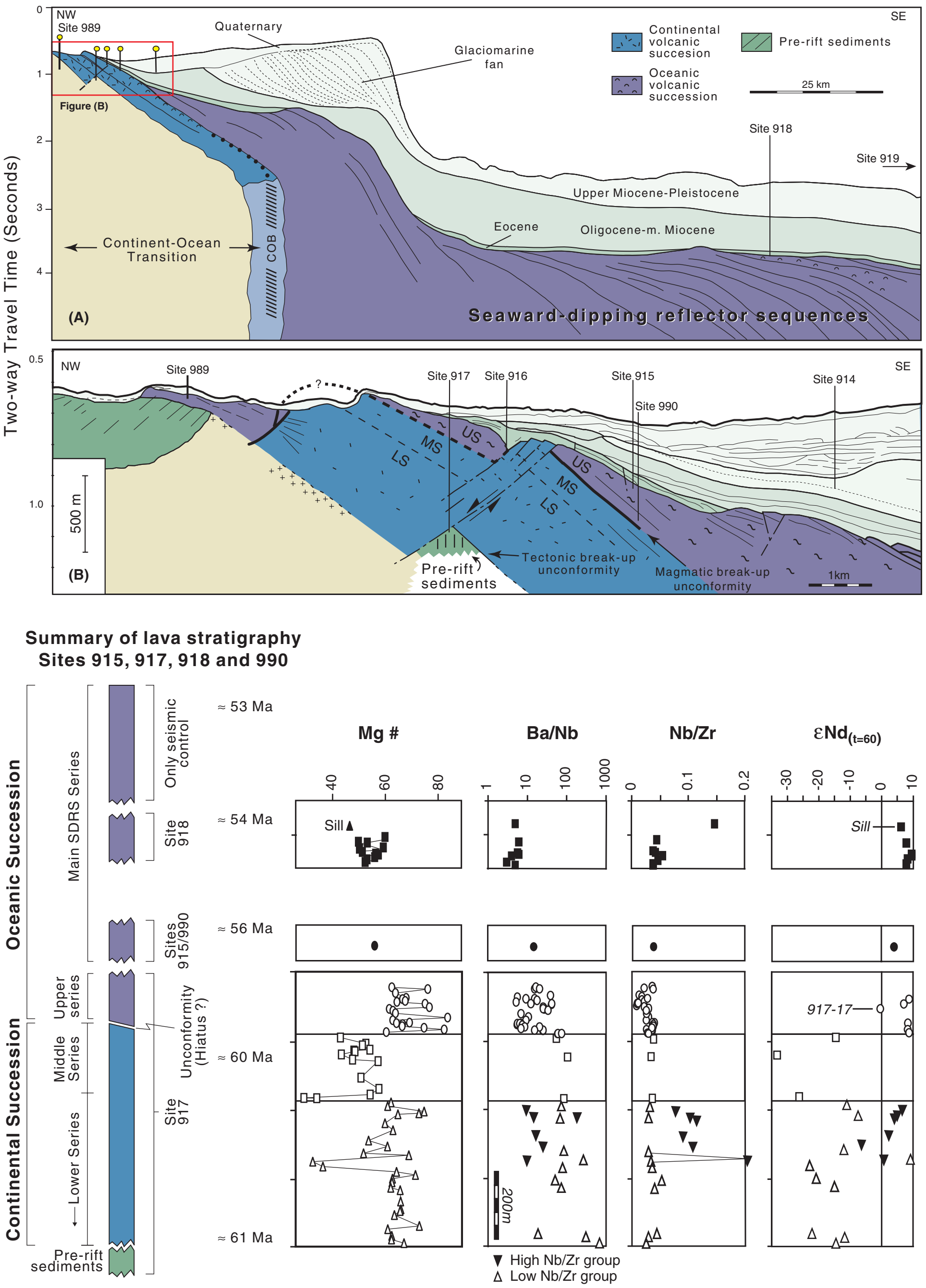

Figure 2. Cross sections and summary of lava stratigraphy off Southeast Greenland from ODP Site 917 (Leg 163) and adjacent sites. A lower Continental Succession of pre-breakup age (Lower and Middle Series, Site 917) is located below the landward feather-edge of the main SDRS (Oceanic Succession). The Oceanic Succession begins with the picritic Upper Series of Site 917, but quickly translates into Icelandic depleted basalts (Sites 915/990, Site 918). The SDRS terminates seaward around 53 Ma, when the volcanic rift zone is interpreted to have subsided below sea level. The igneous crust is close to 20 km thick just seaward of the continent-ocean boundary (COB), and thins to ~15 km prior to subsidence of the spreading center at ca. 53 Ma (Holbrook et al., 2001). Note the trend towards developed magmas (i.e., decreasing Mg number) within the Continental Succession before magmatism is reinvigorated during final breakup (~56 Ma). High Ba/Nb and negative εNd values indicate continental contamination. Note the generally low Nb/Zr indicating a depleted source (e.g., Fitton et al., 2000).

succession in Hole 917A rests unconformably on steeply dipping pre-rift sediments and ranges in composition from picrites and basalts to dacitic lavas and rhyolitic tuff (Lower and Middle Series of Site 917).

Extrusion of the picritic series (Upper Series of Site 917) followed a small hiatus in volcanism (Fig. 2). Tracers of continental contamination largely disappear within the picritic series, and shifts in trace element ratios sensitive to depth of mantle melting show rapid (~1 m.y.) thinning and removal of a continental lithosphere originally ~100 km thick. Slightly younger rocks at Sites 915 and 990 (~55.8 Ma) record the final transition into quite uniform, depleted Icelandic basalts, extending seaward into Site 918 lavas. Their subaerial emplacement proves persistent subaerial deposition of SDRS lavas until ca. 3 m.y. after breakup.

Deep crustal seismic data show that ~30-km-thick continental crust is replaced seaward by ~20-km-thick igneous crust over a zone only ca. 40 km wide (Fig. 2). Landbased studies show this transition zone experienced intense magmatic dilation through dyke emplacement and probable less vigorous tectonic extension and crustal thinning (Klausen and Larsen, 2002).

The picritic Upper Series (Site 917, Fig. 2) ranges in composition up to 23% MgO and may include cumulates. The lower MgO (15% to 18%) picrites are interpreted to represent primary melt compositions formed from asthenospheric mantle ca. 100°C hotter than normal, in agreement with temperature estimates made for East Greenland flood basalts (Tegner et al., 1998). Crustal fractionation of the primary mantle melts during later steady-state formation of SDRS crust prevented picritic magmas from reaching the surface (Fig. 2). However, the presence of higher MgO rocks at depth and a continued temperature anomaly is inferred from high-velocity lower crust (>7 km/s; Holbrook et al., 2001). Thus, drill cores and crustal seismic data both suggest margin-wide increased mantle temperatures and support the notion of a large plume head during breakup.

The lower age bound (~61 Ma) of the continental succession at Site 917 is similar to the initial age of early Tertiary volcanism in West Greenland and the British Tertiary province (Fig. 1), suggesting a widespread, sudden arrival of the Iceland plume below the North Atlantic. However, the discovery of the 56-m.y.-old final ("magmatic") breakup unconformity at Site 917 (Fig. 2) shows that breakup followed ca. 5 m.y. after this plume impact. The nature of pre-breakup volcanism at Sites 642 and 917 suggests that considerable interaction took place between the plume and the continental lithosphere along the line of rifting during these 5 m.y. Rapid lithospheric thinning related to final breakup caused massive (decompression) melting of the mantle and coeval (~56 to 53 Ma) formation of continental flood basalts (e.g., East Greenland, Faeroe Islands) and SDRS crust. This exhausted the plume head reservoir outside the area of the central plume track within ca. 3 m.y.

A compositional trend is observed from dominantly enriched Fe-Ti basalts along the plume-proximal parts of the margin to more depleted, MORB-type compositions at larger offsets (Fig. 2). This poorly understood geochemical zonation is not easily compatible with one single reservoir source of hot plume mantle. Mixing

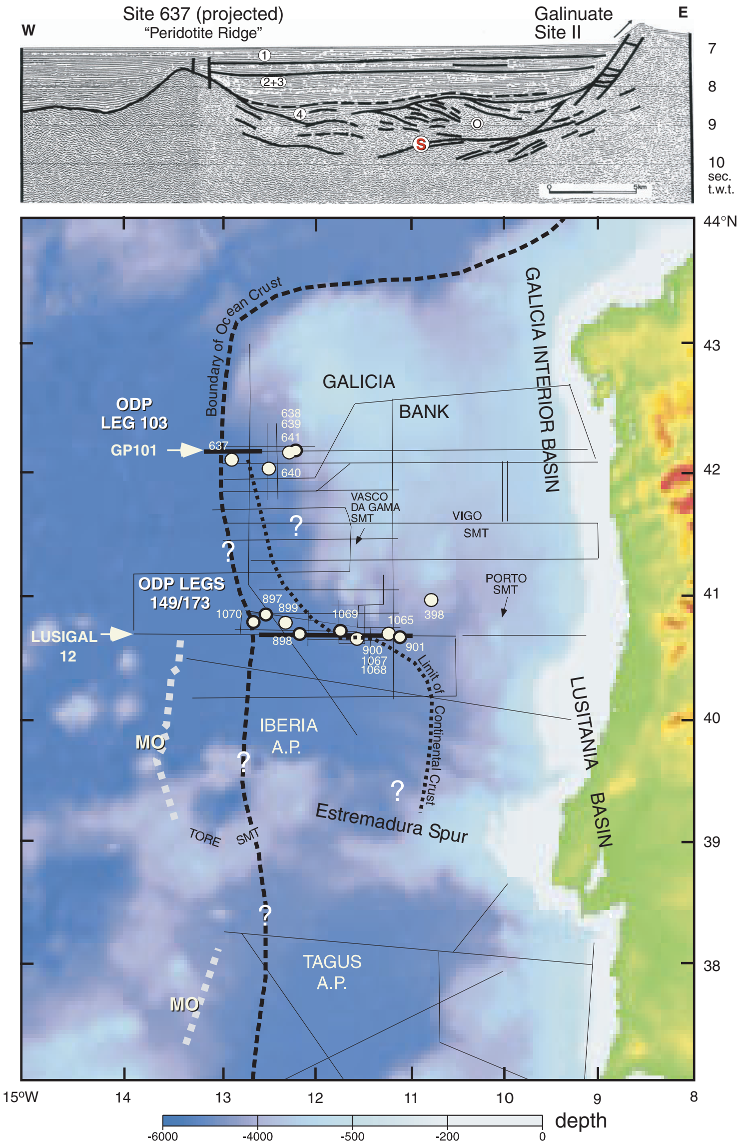

Figure 3. Top: *Cross-section of Galicia margin with Site 637 of ODP Leg 103 projected onto the marginal peridotite ridge. Note complex basement faulting, mid-crustal S-reflector, post-rift sediment sequences 1 through 3, syn-rift fill (4), continental basement, pre-rift sediments recovered at Sites 638 through 641, and Galinuate Site II dive location.* ***Bottom:*** *Location map, courtesy of K. Louden, shows Galicia Bank, Iberia Abyssal Plain, and Tagus Abyssal Plain segments, all ODP Leg 103, 149 and 173 sites, DSDP Site 398, and regional bathymetry. Mo: Seafloor magnetic chron of Aptian age. Note northward narrowing of transitional crust between continental crust to the east and interpreted oceanic (igneous) crust to the west.*

with a heated ambient asthenospheric mantle and/or a depleted component within the Iceland plume has been suggested (e.g., Fitton et al., 2000).

NON-VOLCANIC OR MAGMA-POOR RIFTED MARGINS

Leg 103 targeted the transition from normal-faulted, thinned continental crust into thin transitional or oceanic crust along the Galicia Bank rifted margin (Fig. 3). Deformed and serpentinized mantle peridotite was recovered at Site 637 from a margin-parallel basement ridge seaward of proven continental basement (Fig. 3), along with a prominent intra-basement reflection, the so-called S-reflector. A breakup model involving crustal scale simple shear extension evolved from this fundamental discovery (e.g., Reston et al., 1996). This model is consistent with several common features of mantle rocks recovered from the Iberia margin: (1) sub-continental origin; (2) strong (brittle) deformation at top of section; and (3) association with tectono-sedimentary breccias.

The Iberia margin and its conjugate, the Newfoundland margin, are comprised of three segments. The Galicia Bank-Flemish Cap segment, drilled during Leg 103, is the northernmost component. ODP Leg 149 and 173 operations targeted a transect across the southern Iberia Abyssal Plain conjugate to the Newfoundland Basin margin (Fig. 3). Despite margin segmentation, seismic data along the Iberia rift margin suggest continuity of serpentinized basement highs (Fig. 3) and, possibly, complex S-reflector type structures. Off Iberia, the width of the transitional lithosphere between landward-rotated fault blocks of (upper) continental crust and oceanic crust of perceived igneous origin narrows northward, from over 100 km at the Leg 149/173 transect to around 30 km at Galicia Bank (Fig. 3). A roughly similar-shaped zone of thin crust has been seismically imaged recently on the conjugate margin off Newfoundland (unpublished data). Buried basement ridges within the landward, eastern part of the southern Iberia Abyssal Plain connect northward into the continental crust of Galicia Bank. The faults bounding these landward-rotated fault blocks adjacent to the

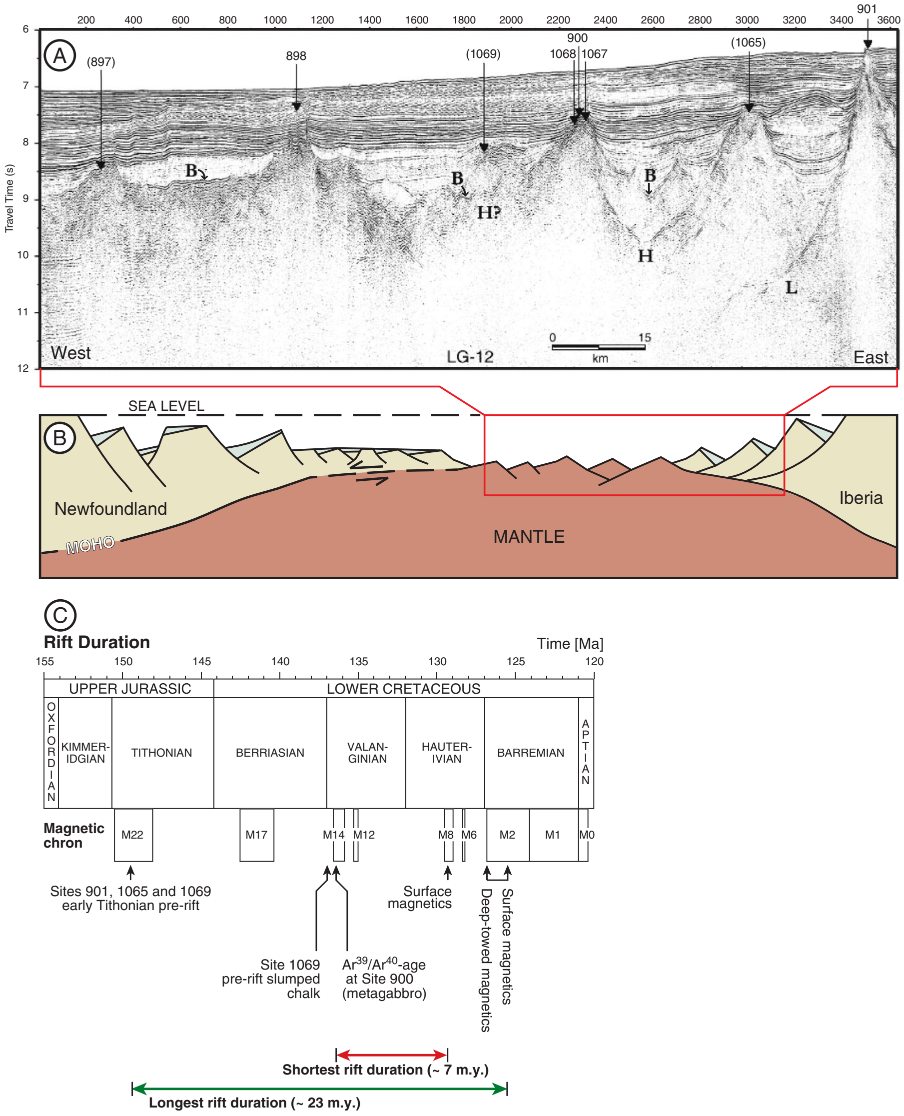

Figure 4. A. *ODP Iberia margin drill sites along seismic profile Lusigal-12 (LG-12; see Fig. 3 for location) showing basement (B) and shallowing of interpreted detachment fault (H) near Sites 900, 1067 and 1068. Continental basement (with pre-rift sediments) is present landward of these sites; serpentinized and tectonized mantle peridotite is present at all sites seaward of the basement high. Reflection H may reappear below Site 1069, suggesting a tectonic offset of H seaward of Site 1068. Multiple detachment faulting also is indicated by reflector L, interpreted to represent the upper crustal breakaway by a different generation detachment fault. The presence of some lava fill between the basement highs cannot be excluded, but no* in situ *volcanic rocks were recovered at any of the drill sites.* ***B.*** *Tectonic model for the Iberia-Newfoundland conjugate margin pair at a stage near magnetic chron M3, after tectonic unroofing of the mantle but before generation of new igneous crust. Approximate location of the Iberia margin transect in this generic model is indicated. Highly asymmetric margin development through low-angle detachment faulting is envisaged toward later stages of breakup. Structure of the Newfoundland margin remains a high priority for model testing and will be investigated during the final ODP Leg 210.* ***C.*** *Chronology constraining the rate of extension and mantle unroofing along the Iberia margin.(Original figures courtesy of K. Louden and B. Tucholke).*

continental slope verge downwards onto low-angle, intra-basement reflectors (e.g., the L- and H-reflectors; Fig. 4). These, like the S-reflector on the Galicia Bank, indicate the presence of low-angle detachment faults (Reston et al., 1996).

The southern Iberia margin was targeted to constrain (1) along-margin continuity of major basement lithologies; (2) detachment zones and across-margin variation in basement exposure (i.e., permissible models of tectonic deformation); (3) timing of rifting, and (4) rift environment (i.e., margin subsidence). Drilling into the fault-bounded (continental) basement blocks at landward Site 901, 1065 and 1069 boreholes recovered pre-rift (Tithonian) continental shelf sediments (Fig. 4). Possible lower continental crust (including gabbro) and serpentinized peridotite were sampled in boreholes of seaward Sites 900, 1067 and 1068, all within 2 km of one another. Further seaward, Sites 899 and 897 recovered breccia of serpentinite and serpentinized peridotite, respectively. Finally, Site 1070 targeted the sampling of igneous oceanic crust ca. 30 km landward of seafloor of approximately M0 age (Figs. 3, 4), but, surprisingly, recovered more serpentinized peridotite, presumably also of subcontinental origin. However, the Site 1070 serpentinite hosts veins of 119-m.y.-old gabbro of enriched Mid-Ocean Ridge Basalt (E-MORB) composition, suggesting that igneous (oceanic) crustal accretion was developing. Most surprisingly, along the entire transect no volcanic rocks were recovered *in situ* or within the tectonic breccias carrying gabbro clasts; a few basalt clasts were recovered at Site 899 within mass flow deposits overlying the basement. While it cannot be excluded that syn-rift volcanics exist between the basement highs, limited melt generation is consistent with the modest degree of mantle melting shown by recovered mantle lithologies. Furthermore, most magmas might have been trapped within a low density serpentinite crust (Whitmarsh et al., 2002).

Seismic velocity models suggest that Sites 900, 1067 and 1068 are located at the transition from thin, extended continental crust to a basement consisting mainly of serpentinized peridotite that extends for close to 100 km to near Site 1070 (Figs. 3, 4; Louden and Chian, 1999; Dean et al., 2000). Zircon dating of the gabbro cored at Site 900 suggests that it was emplaced at 270 Ma and therefore does not represent Cretaceous rift magmatism. However, it was exhumed during rifting and cooled below the 200° to 250°C isotherm at 136 Ma, shortly before breakup (Fig. 4). The H-reflector is interpreted to represent a major late-stage detachment strongly contributing to this unroofing of the lower crust and upper mantle. Landward it has a breakaway within the upper continental crust and then shallows seaward and appears truncated, perhaps tectonically, by the basement-sediment interface (i.e., tectono-sedimentary breccias) near Sites 1067 and 1068 (Fig. 4). Multiple stages of separate concave downward detachment fault generation are thought to have contributed to mantle unroofing and formation of "extensional allochthons" (Whitmarsh et al., 2001).

Comparative studies of ancient margins of the Tethys Ocean exposed within the Alps show striking similarities to lithologies and deformation of the Iberia margin, and support the notion that crustal- to lithospheric-scale simple shear deformation during breakup may have led to extensive mantle unroofing. According to Manatschal and Bernoulli (1999), initial symmetric extension was followed during advanced rifting by simple shear along low-angle detachment faults with a top-to-the-ocean sense of movement. Breakaways forming in the continental crust cut into mantle rocks, implying that initial decoupling of the upper crust from the upper mantle was no longer active. Detachment faulting propagated toward the future ocean. Tectono-sedimentary breccias, similar to those cored offshore of Iberia, accumulated on the exhumed footwall and were intruded by syn-kinematic gabbro bodies similar to those observed at Site 1070. Finally, pillow basalts (not recovered off Iberia), heralding the transition into more normal seafloor spreading, were deposited on the tectonically exhumed sub-continental mantle along ancient Tethys margins.

Significant margin asymmetry can be expected from such a model (Fig. 4) that awaits future testing by drilling on conjugate margin pairs by ODP Leg 210 and the Integrated Ocean Drilling Program (IODP). A fundamental question is why so little igneous activity apparently is associated with formation of the Iberia margin despite complete unroofing of the mantle. Did highly asymmetric rifting focus magmatism on the conjugate Newfoundland margin? Or were strain rates so slow that mantle melting was suppressed by conductive cooling of the rising mantle (e.g., Bown and White, 1995)? However, simple modeling for a longer rift duration of 23 m.y (Fig. 4) predicts a minimum of 1 km of melt thickness by decompression melting. It is hypothesized that such basaltic magma volumes largely could have been trapped within a low density serpentinite crust (Whitmarsh et al., 2002).

CONCLUDING REMARKS

Zones of transitional crust up to 100 km wide exist along both volcanic and non-volcanic rifted margins. The transitional zone along volcanic margins consists of as little as 40 km of Icelandic-type, thick igneous crust between continental crust of approximately normal thickness and full igneous crust. This width was likely significantly less prior to dilation by magma emplacement. Tectonic thinning of the continental crust required for breakup along this type of margin seems relatively modest. In strong contrast, non-volcanic rifted margins show extreme tectonic thinning of the crust and lithosphere via unroofing of the subcontinental lithospheric mantle over many 10s to perhaps 100s of km, and, apparently, with a surprising lack of significant magmatism. The result is a wide transitional zone of primarily serpentinized and tectonized mantle peridotite, possibly with subordinate gabbro bodies.

Current hypotheses explain excess magmatism along the North Atlantic volcanic margins by hotter (~100°C) than normal mantle associated with rapid emplacement of a mantle plume head shortly before breakup. However, the geochemical zonation along North Atlantic margins suggests that different mantle reservoirs and/or differences in melting dynamics along the margin are involved. This less well understood aspect of margin development should be a subject of future IODP investigations in the North Atlantic and other settings.

The hypothesis of asymmetric breakup at non-volcanic rifted margins through lithospheric-scale simple shear needs verification by sampling across a full rift system on a conjugate margin pair. Leg 210, scheduled for Newfoundland margin drilling in 2003, will address this issue. Ultimately, deep crustal drilling into S-reflector-type structures is needed to examine their true nature and setting. Improved sampling of the rift fill can constrain the igneous productivity, rift setting, vertical crustal movements and strain rates operating during breakup. Regions hosting both types of margins in close spatial and temporal proximity, as well as actively rifting environments and land-sea transects, are other prospects for future IODP investigations.

ODP drilling has fostered this new paradigm for rifted margin formation. As the petroleum industry moves into the deep-water regions of rift margins, it will gradually adapt to these new concepts which are highly relevant to exploration. The IODP, including its deep-water riser technology, will allow for important new scientific achievements to be made on rifted margins in collaboration with industry.

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FLUID FLOW IN ACCRETING AND ERODING CONVERGENT MARGINS

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INTRODUCTION

Convergent plate boundaries or subduction zones are loci of lithospheric recycling to Earth's interior. Subduction zones spawn the world's largest earthquakes and most destructive volcanoes, and the negatively buoyant subducting slabs dominate the driving mechanisms for plate tectonics. Sediments and rocks may be scraped off the incoming plate at various depths to compose accretionary prisms, mountain belts, and ultimately collision zones. Other materials are carried deep into the subduction system to be underplated at great depths, melted in volcanic arcs, or returned to the mantle. About half of Earth's subduction zones underthrust virtually all incoming sediment; a significant fraction remove forearc material through subduction erosion and carry these materials into the mantle. Study of this convergent plate system is essential to understanding how Earth's plate motions are translated into geologic processes (e.g., earthquakes) and products (e.g., fold mountain belts and volcanoes).

The Ocean Drilling Program (ODP) has probed the upper surface of convergent plate margins, directly observed inputs and shallow features, and interpreted deeper level processes. Convergent margin drilling has determined the nature of the initial deformation of accreted sediment, established accretion history or lack thereof, defined the processes operating along the plate boundary thrust or décollement zone, and established the nature of fluids and solids migrating out of the subduction system. ODP results have built on Deep Sea Drilling Program (DSDP) contributions to provide an overview of how subduction systems function.

Advances in the study of convergent margins during ODP include documenting fluid migration and clarifying processes of non-accretion and subduction erosion. Both of these advances bear on subduction processes operating at deeper levels, including seismogenesis and magma generation. These processes are central to the Seismogenic Zone and Subduction Factory initiatives of the MARGINS program that will be important in the next phase of international deep-sea drilling, the Integrated Ocean Drilling Program (IODP).

FLUID MIGRATION AND CONVERGENT PLATE MARGINS

Thick sediment accumulations at convergent margins are rapidly buried due to the high rates of plate motions. The rapid burial creates fluid overpressures that drives porewater out; burial also causes dehydration of minerals and maturation of organic matter that produce chemically distinct fluids at depth. ODP has made a major contribution in documenting this fluid outflux that has major implications for monitoring seismogenic processes and related geologic hazards, and for understanding basic processes of fluid migration of interest to the oil industry.

Evidence for Fluid Flow at Convergent Margins

DSDP Legs recognized the importance of high fluid pressures at convergent margins. ODP has shown that flow is ubiquitous in this environment as a local process along individual conduits, and as a regional process that both raises and lowers thermal gradients over large areas (Figs. 1 and 2). This fluid transfer process can strongly affect the geology and seismology of subduction zones since fluids can transport solutes and significantly modify the temperature regime.

Localized Flow in Conduits: Flow along specific conduits was first recognized during Northern Barbados Ridge drilling (Leg 110) when porewater geochemists measured anomalies that could only be explained by fluid flow along high permeability faults and sand layers. Temperature anomalies supported this interpretation. Similar porewater chemistry anomalies have been recognized primarily along faults at convergent margins off Peru (Leg 112) Marianas (Leg 125), Southwest Japan (Legs 131, 190), Vanuatu (Leg 134), Cascadia (146), Barbados (Leg 156), and Costa Rica (Leg 170) (Fig. 1).

Typically, the porewater shows negative anomalies in chloride concentration that are ascribed to mineral (commonly smectite) dehydration at depth. Carbon isotopic ratios of dissolved methane indicate thermal cracking of organic matter that must have occurred at greater depths and temperatures than those of sampling (Vrolijk et al., 1991). Negative chlorine isotope ratios suggest that the anomalous waters were derived from diagenetic to metamorphic dehydration reactions (Ransom et al., 1995). Modeling studies suggest that these non-equilibrium chemical and thermal anomalies would be erased by diffusion if the fluids were not continuously replenished by flow events occurring on a 10^4 to 10^5 year basis (Saffer and Bekins, 1998). Thus, the fluids apparently carry information about processes operating at substantial depths in the subduction zone and indicate long-distance (10s of km) lateral migration that is of interest to the oil industry, and perhaps provide clues to earthquake processes at depth.

The localized conduits are mostly faults. Where they emerge at the surface, some faults raise thermal gradients and provide chemical constituents that support chemosynthetic biological communities and precipitate carbonates (Fig. 3). The high permeability conduits are sometimes cryptic. For example, flow of fluids through the underthrust sediments off Costa Rica has been shown to require localized high permeability conduits. The incoming sediment section is reduced in thickness by 25% to 30% within 1 km of the toe (Fig. 2). Drilling documents no offscraping of the incoming section so this reduction implies massive dewatering. The implied rates of dewatering exceed the measured permeability of the bulk sediment (Saffer et al., 2000), which implicates localized high permeability zones (perhaps microfractures or thin ash layers) as conduits for flow.

Regional Thermal Anomalies Ascribed to Fluid Flow: Localized flow occurs in conduits tens of m thick producing flow related anomalies observed over larger areas. Above and up to 6 km seaward of the Northern Barbados Accretionary Prism, both borehole temperature measurements and traditional marine heatflow measurements demonstrated thermal gradients roughly double that expected for the age of the subducting crust (Fisher and Hounslow, 1990). Thus, the outflux of fluids along specific conduits has warmed the sedimentary section much above the heat flow expected for the normal conductive cooling of the oceanic crust.

Heat flow values lower than conductive have also been reported offshore Peru (Leg 112) and Costa Rica (Langseth and Silver, 1996). The low heat flow (<40 mW/m^2) offshore Peru was thought to be a combination of hydrothermal fluid flux within the uppermost oceanic crust and local, rapidly deposited trench sediment, preventing equilibrium values to develop. Heat flow in the lower plate approaching the trench axis off Costa Rica is measured at 5 mW/m^2 to 8 mW/m^2, based on surface (Langseth and Silver, 1996) and borehole (Leg 170) observations (Fig. 3). Geochemical evidence from Leg 170 documents the seawater flow at the base of the sediment section of the incoming plate, and flow can be modeled as thermally driven (Silver et al., 2000). Thus, fluid flow through the oceanic crust is substantially cooling the subducting plate and could affect metamorphic and seismogenic processes at depth.

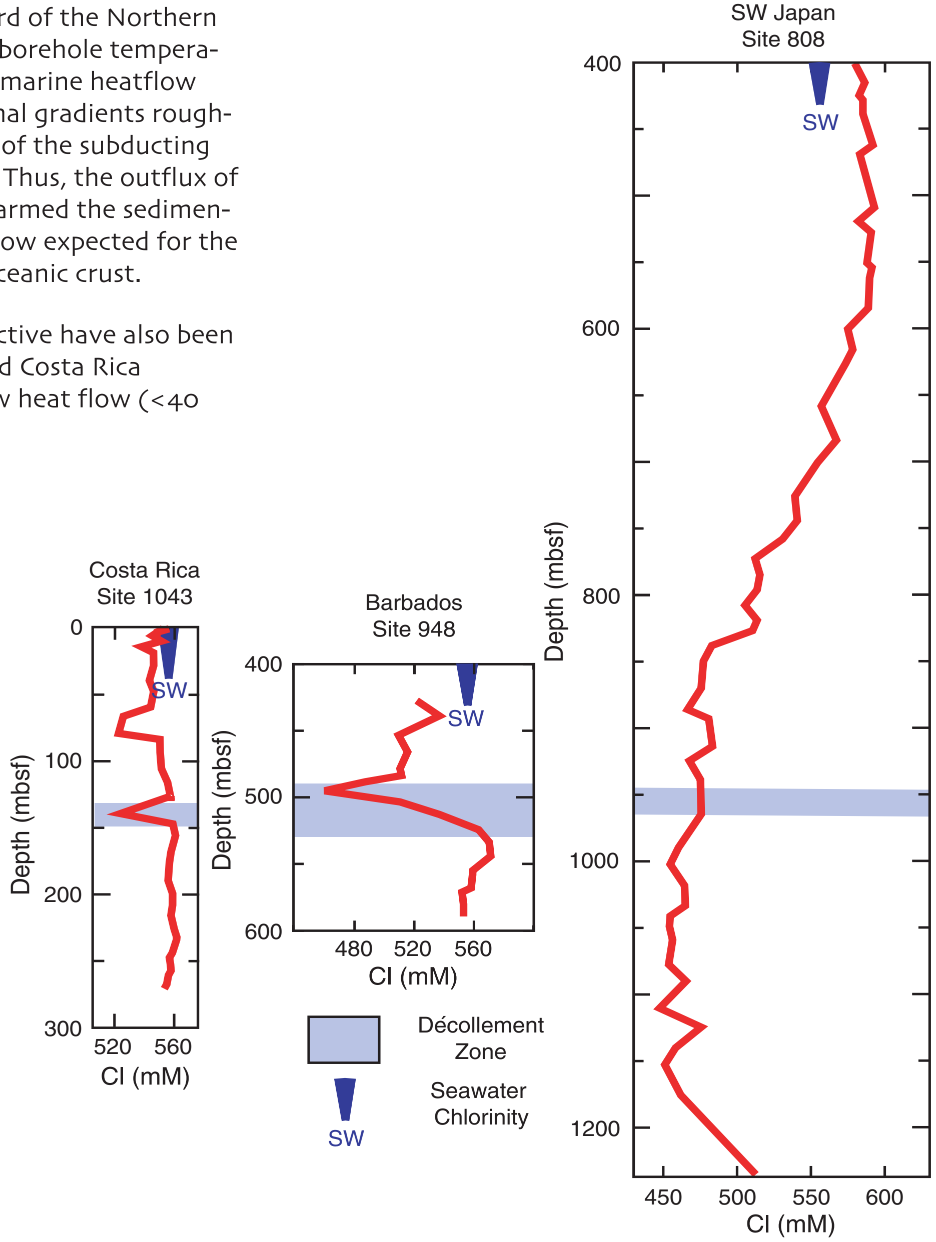

Figure 1. *Chloride compositions of pore waters from Costa Rica (Leg 170), Barbados (Leg 156), and SW Japan (Leg 131). Note that well-defined negative anomalies are associated with the décollement, or plate boundary fault zone, in each case in Barbados and Costa Rica. This consistent correlation with the plate boundary fault zone occurs at the non-accretionary Costa Rican margin, the Barbados subduction zone involving primarily pelagic and hemipelagic sediments. In both cases the anomaly is explained by focused flow from depth along the décollement zone. The subduction zone of SW Japan, dominated by terrigenous sediment and with a high thermal gradient, shows a much broader and deeper geochemical anomaly. This anomaly may result largely from* in situ *dehydration of clays with a secondary contribution of fluid flow along the décollement zone.*

Seismic Imaging of Fluids

A priority of ODP drilling has been creation of calibration holes coincident with seismic images that allow these images to be used to broadly interpret the geology and physical properties of the rocks that they penetrate. In the case of convergent margins geophysicists have attempted to image fluid accumulations.

The plate boundary fault at subduction zones typically thrusts higher velocity and density over lower velocity and density sediments and thus creates a decrease in acoustic impedance and a negative polarity seismic reflection. A negative polarity seismic reflection fault plane reflection characterizes part of the plate boundary thrust or décollement of the Barbados accretionary prism (Fig. 4). Here ODP coring and Logging While Drilling (Legs 110, 156, and 171A) show that the plate boundary thrust typically is localized along a transition from lower velocity and density sediments to higher velocity and density deposits. However, one ODP hole shows a 10 to 15 m-thick zone of low-density material in the plate-boundary fault zone that correlates with a negative polarity reflection (Bangs et al., 1999). Thus, the seismic image maps a zone of low density and high porosity in the fault zone that is interpreted as underconsolidated, overpressured fluid conduit.

The high porosity portion of the fault zone beneath the Barbados accretionary prism is similar to a “bright spot”, an accumulation of oil and gas identified on seismic images by the oil industry. The Barbados décollement polarity map is the best documented example of imaging fluid concentration along a fault surface, including unpublished examples from industry sources (P. Vrolijk, Exxon-Mobil Upstream Research, pers. comm., 2001). Because fluid pressure affects fault strength, mapping zones of high fluid pressure (and low strength) is of great interest to those studying faults as earthquake hazards.

NON-ACCRETIONARY CONVERGENT MARGINS AND SUBDUCTION EROSION

In addition to being accreted, the incoming sediment may be completely underthrust at convergent margins. Moreover, the lower plate may remove parts of the upper plate causing subduction erosion. ODP drilling has been instrumental in proving the hypotheses of non-accretion and subduction erosion (von Huene and Scholl, 1991). Documenting these processes requires establishing the removal of material from the forearc. Because of the difficulty in obtaining definitive geophysical images of subduction erosion, drilling remains the primary tool for its documentation. Vertical subsid-

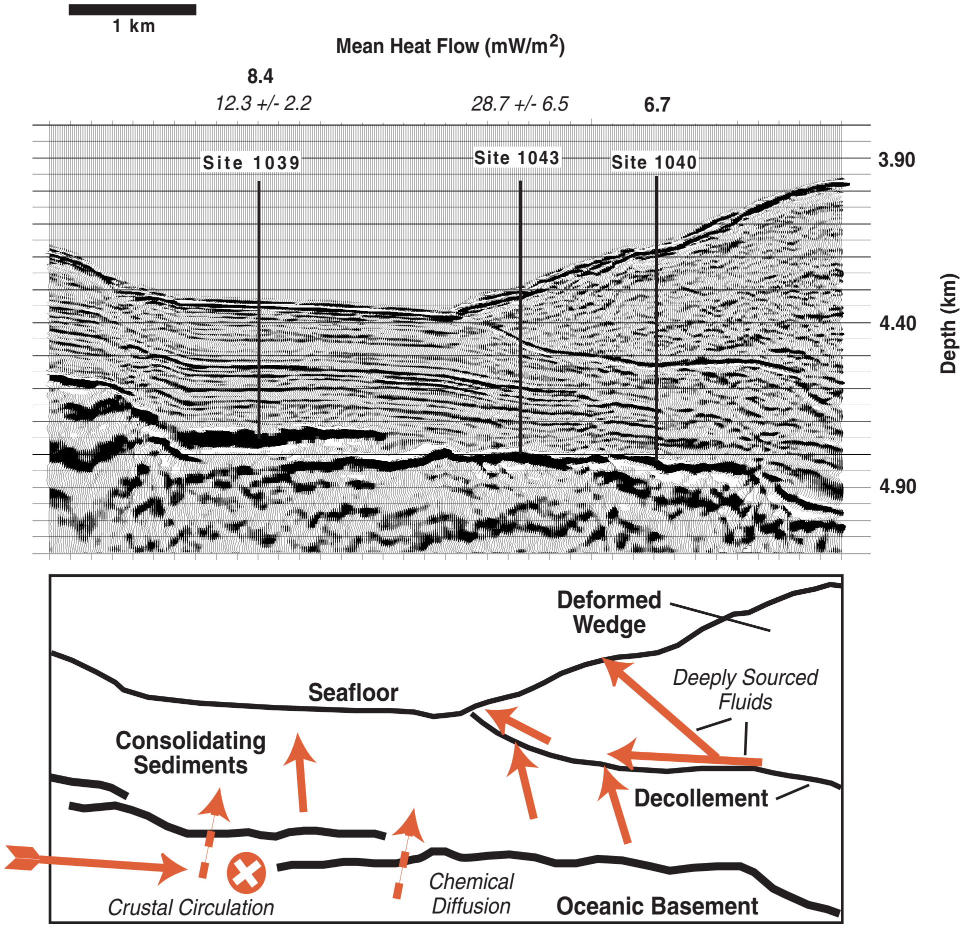

Figure 2. *Seismic profile offshore northern Costa Rica showing rapid decrease in thickness of underthrust sediment with depth. Numbers at the top of the ODP sites are mean values of borehole (bold) and surface (italics) heat flow. Lower schematic diagram shows expected fluid advection (solid arrows) and chemical diffusion (dashed arrows) gradients. Circle with x indicates out of plane flow. Note that drilling at Site 1039 may have actually bottomed in a sill close to basement, not the actual oceanic basement.*

ence of the overlying plate often is used as evidence of removal of underlying material by subduction erosion.

Evidence for Non-Accretion

Leg 170 operations offshore Costa Rica documented complete bypassing of the incoming sediment section beneath the forearc, and an absence of frontal accretion. Cores and logging results document that essentially all the incoming strata slide beneath the overlying plate with no loss to accretion. The completeness of the sediment subduction was surprising because seismic data image a deformed sedimentary wedge at the toe of the slope, and that wedge had been assumed by all observers to be accreted from the incoming section. However, the drilling results showed that the wedge consists of the same material as that of the sedimentary apron blanketing the slope above and not of the underthrust lower plate material. Although the wedge is sedimentary and highly deformed, it is not accreted from the lower plate. If the incoming section is not being offscraped at the front of the convergent margin it may be accreted to the base of the forearc at depth (underplated) or carried to greater depths to participate in the magmatism. In the case of Costa Rica, seismic images suggest underplating beneath the accretionary prism (Leg 170); the geochemistry of the arc volcanoes indicates young sediment is not involved in magmatism (Morris et al., 1990).

Evidence for Subduction Erosion

Offshore Peru, Leg 112 drilling demonstrated that continental sediments associated with Andean basement rocks underlie the middle to lower slope region, implying a small or no accretionary prism. Seismic reflection data suggest a small accretionary wedge at the base of the slope. Studies of benthic foraminifera from Leg 112 cores show a deepening from shallow water Eocene sediments to the present bathyal depths, and that much of the subsidence occurred in late Oligocene to early Miocene time. Significant vertical motions after the early Miocene appear to have been associated with subduction of the Nazca Ridge (von Huene and Lallemand, 1990). Erosion of the forearc is supported by eastward migration of the volcanic axis through time.

Off Costa Rica an ODP site (Leg 170) penetrated the lower slope apron into the highly reflective and higher velocity material forming the forearc prism. This site recovered thrust slices of Miocene breccias, with sandstone clasts cemented by carbonates. Vannucchi et al. (2000) interpret the cement as having formed in shallow water. If their interpretation is correct, it implies significant subsidence (nearly 4 km) since the middle Miocene. Such subsidence could reasonably be ascribed to subduction erosion.

What Controls Accretion Versus Non-Accretion and Subduction Erosion?

ODP drilling and seismic reflection data show that the incoming sedimentary sections (pelagic sediments, hemipelagic sediments and trench deposits) are generally thick where accretion occurs and thin were non-accretion and subduction erosion occur. In the Peruvian and Costa Rican (Legs 112 and 170) examples the thickness is less than 500 m. In contrast, Southwest Japan (Leg 131) and Cascadia (Leg 146) subduction

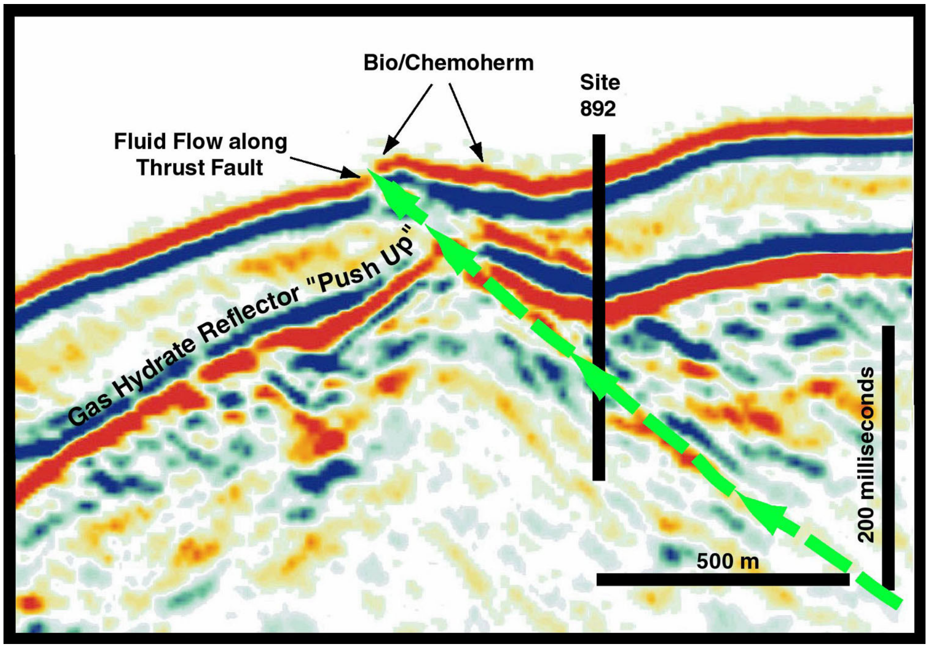

Figure 3. *Seismic line across Hydrate Ridge of Oregon continental margin showing fault with fluid flow documented both by drilling and submersible operations. Large bio/chemoherm or accumulation of carbonate and chemosynthetic organisms forms on upper plate of fault. Warm fluid flowing up fault raises thermal gradient and "pushes up" gas hydrate reflector. ODP site 892 hosts a long-term borehole monitoring system.*

zones, with one to several km of incoming section, form substantial accretionary prisms. Topographic irregularities such as seamounts (von Huene and Scholl, 1991) and emergent fault blocks may destabilize the inner trench slope allowing material to be shed into the trench for possible underthrusting. Thus, any small accretionary prism that may be formed, even by the accretion of thin incoming sediments (e.g., Vanuato, Leg 134), is subject to recycling along with older parts of the overthrusting plate of the subduction zone. The combination of thin incoming sediments and topographic irregularities on the lower plate prevent the systematic development of an accretionary prism and together destabilize and erode the inner trench slope. Conversely, the lower portion of thick incoming sediments masks the topographic irregularities on the subducting plate and the upper portion is available to build a classic accretionary prism.

SUMMARY

Ocean drilling at convergent margins has provided a broad understanding of the stratigraphic and tectonic architecture of the subduction processes. Investigations

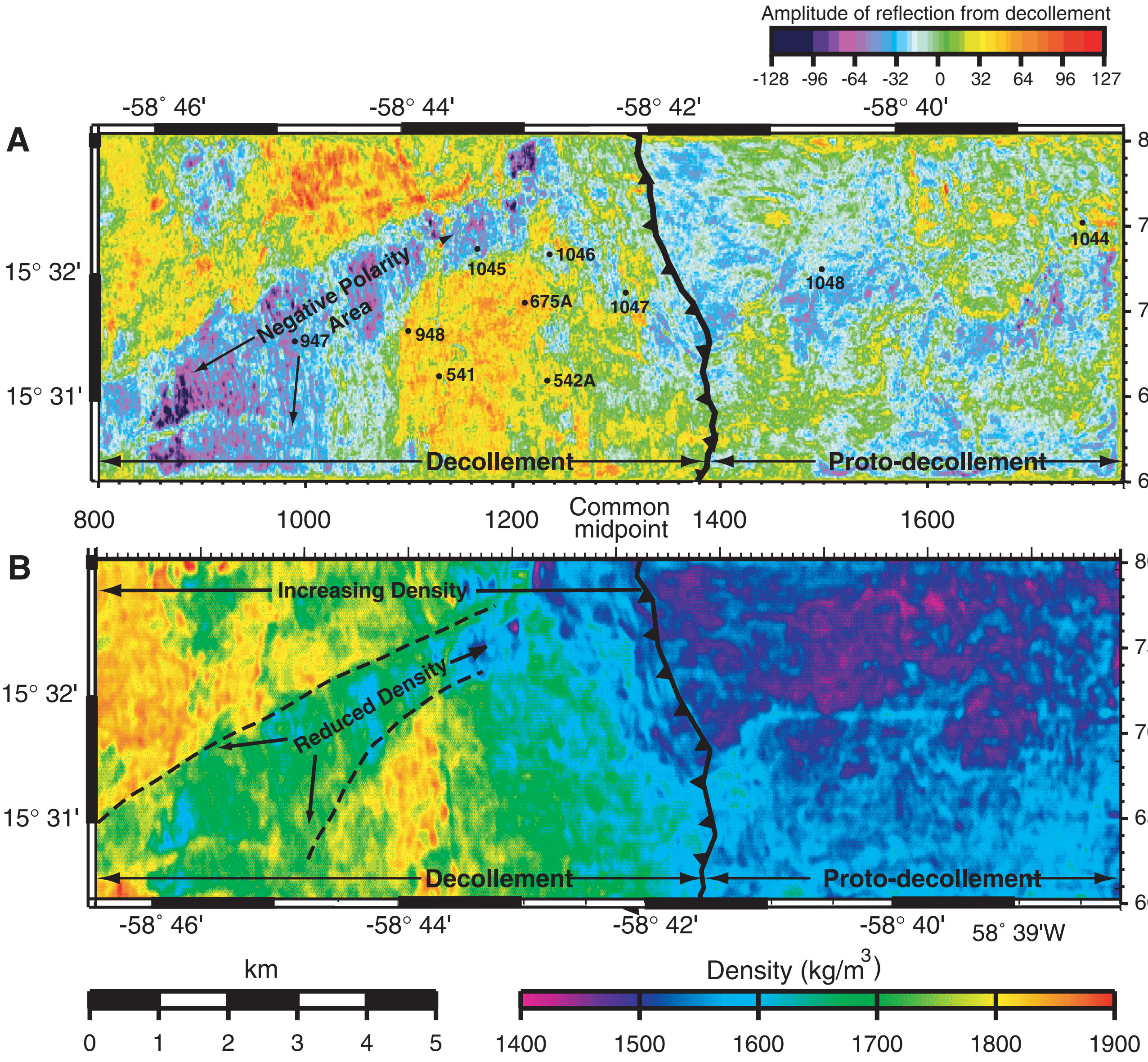

Figure 4. Maps of (A) peak seismic reflection amplitude from the decollement zone, and (B) density inferred from the inversion of the decollement zone reflection waveforms (for sources see Leg 171A Scientific Results frontispiece). Note the general increase in density from east to west starting at the deformation front. The area of negative seismic polarity is visible as the area of reduced density in the inversion. The patchy nature of the density decrease with underthrusting along the decollement thrust zone also is notable. Circles indicate the location of sites from DSDP and ODP Legs. These symbols are shown only on the reflection amplitude map for clarity.

of fluid migration and non-accretion/subduction erosion have shown that:

1) Ubiquitous localized fluid flow is indicated by anomalies in porewater composition and temperature along localized fluid conduits (commonly faults);
2) The geochemistry of the organically and inorganically-derived fluids in these conduits indicates fluid sources from several km to many km depth, suggesting long-distance lateral migration;
3) Fluid-rich zones presumed to be overpressured fluid flow conduits have been imaged on seismic data and their nature verified by drilling;
4) Km-wide to 10 km-wide zones of anomalously high and low temperature gradients, respectively, indicate regional upflow and downflow of fluids around convergent margins;
5) Virtually complete subduction of the incoming sedimentary section has been documented off Costa Rica;
6) At many convergent margins vertical subsidence in the km range and anomalously small accretionary prisms suggest subduction erosion; and
7) The transition from accretion to subduction erosion occurs with thinning sediment influx and increasing topographic irregularity of the lower plate.

RELEVANCE FOR IODP

A primary goal of IODP is to drill into the seismogenic zone of subduction zone thrusts, the location of the earth's largest earthquakes. Essential preparation for this activity involves sampling the composition and conditions (e.g., temperature and fluid pressure) of materials entering the subduction thrust in order to predict the nature of the seismogenic zone at depth. Current ODP drilling is directed towards measuring the state of this incoming material and provides a major context for IODP. The discovery of deeply sourced fluids at the front of convergent margins may provide a means of remotely sensing fault behavior at depth. ODP has initiated programs for monitoring fluids, seismicity and borehole conditions at the front of convergent margins that should provide the basis for evaluation of fault behavior at deep. Finally, ODP-sponsored seismic imaging of fault surfaces in subduction zones has developed expertise in the community, and some cases actual targets, that could be used in IODP investigation of the seismogenic zone.

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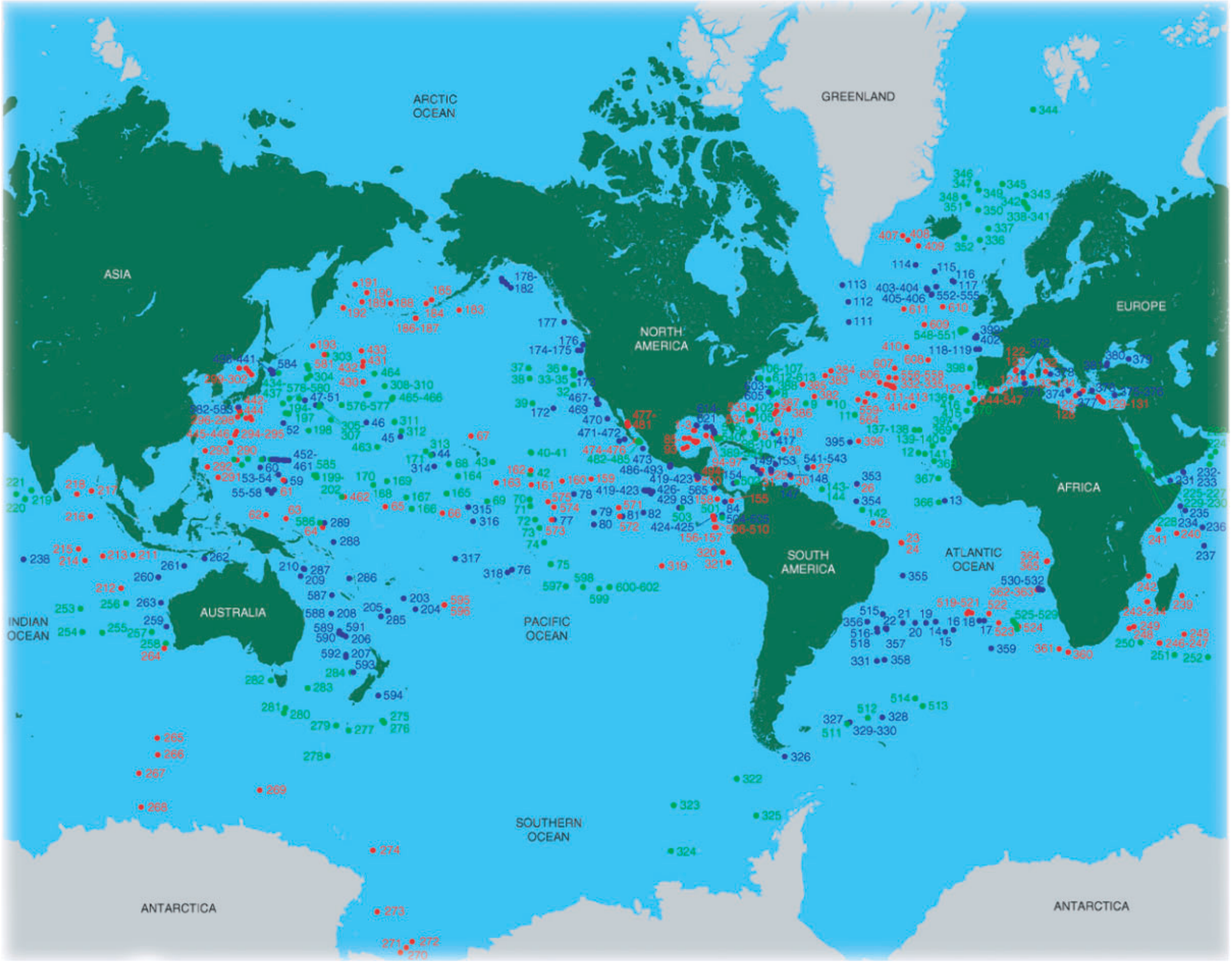

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