Opportunities In Geochemistry For Post-2003 Ocean Drilling

A JOI/USSSP Workshop

Convened by
Richard W. Murray,
Daniel P. Schrag, and
C. Geoff Wheat

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Front Cover:
Top. *Chikyu*, the new riser drillship being built by Japan for the Integrated Ocean Drilling Program, just before the hull was launched on January 18, 2002. Photo courtesy of Japan Marine Science and Technology Center (JAMSTEC).
Bottom. The Ocean Drilling Program's drillship, *JOIDES Resolution*. ODP drilling began in January 1985 with Leg 100, and will conclude with Leg 210 in September 2003. Photo courtesy of the Ocean Drilling Program.

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Held at the Boston University Corporate Education Center
in Tyngsboro, MA on October 12-13, 2000

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Executive Summary

Geochemistry figures prominently in the successes of almost three decades of scientific ocean drilling by the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). To continue to improve our understanding of the dynamic Earth we must expand upon this strong geochemical effort in the Integrated Ocean Drilling Program (IODP). In particular, we must observe and measure in increasing detail the interplay among physical, chemical, and biological processes. This need is growing as Earth's population demands increased access to natural resources, protection from changes in Earth's hydrosphere, and advance notice of major changes in Earth's surface resulting from either natural or anthropogenic forcings.

The international scientific community has initiated several parallel efforts to ensure the continuation of scientific ocean drilling after 2003. These efforts began with the development of the ODP Long Range Plan in 1996. More recently, administrative offices have opened to implement the new IODP and to further international collaborations. Along this journey from concept to implementation many researchers and educators contributed to efforts to ensure that the IODP maintains the collegiality and expertise developed during the previous programs while permitting adjustments in the program's scope and vision to account for changes in scientific paradigms.

As part of the overall planning effort for the IODP, members of the international marine and terrestrial geochemical communities met in Tyngsboro, Massachusetts in October 2000 to articulate a collective vision of geochemistry's role in the next decade of scientific ocean drilling and to identify geochemical problems needing further study. Discussions included shipboard and shorebased logistical requirements. The workshop was motivated by the need to identify common interests among diverse subsets of geochemists and to go beyond the scientific planning described in the IODP Initial Science Plan "Earth, Oceans, and Life."

The workshop participants collectively endorsed, with no priority implied, four large-scale geochemical themes:

- The Road to the Moho targets the recovery of a complete section, including solid and aqueous phases, through the oceanic crust and into the upper mantle. The journey of "The Road to…" is as important as the destination of "…the Moho," as a wealth of information will be gained by fully characterizing oceanic and transitional [continental] crust.

- Continental Margins as Biogeochemical Reactors targets the critical interface between land and sea, with all associated gradients in aqueous and solid phase chemistry, organic geochemical sources and sinks, microbiological communities, and the cycling among the four important carbon reservoirs (continents, seawater, marine sediments, and atmosphere). The highly variable nature of continental margins (e.g., passive vs. active, continental vs. oceanic island arcs, volcanic vs. non-volcanic provinces) leads to a variety of "reactor" operating conditions.

- Global Biogeochemistry Through Time targets the geochemical links among the hydrosphere, atmosphere, lithosphere, and biosphere, and addresses forcings and responses at all time scales. Specific research goals beyond the existing focus on paleo-temperature and paleo-CO_2 studies, such as the importance of biomarkers in reconstructing ocean history, need to be increasingly emphasized. The geochemical budgets and large-scale cycling of many elements are unconstrained.

- Linking Microbiology and Biogeochemistry targets the intimate relationship between microbial activity and geochemical properties, and considers that even basic questions, such as "What types of microorganisms inhabit the oceanic crust?" remain unanswered.

Figure 1. In the context of the opportunities presented by the multiplatform IODP, we recall a motto from the 1870s voyage of H.M.S. Challenger, *"What we get and how we got it," as written in the border of this figure. From:* Challenger Sketchbook: B. Shephard's sketchbook of the H.M.S. Challenger Expedition 1872-1874, *Edited by Harris B. Stewart Jr. and J. Welles Henderson, Philadelphia Maritime Museum, 1972.*

To best advance these scientific priorities, workshop participants identified several key, common approaches and recommendations that will facilitate progress in geochemical research during the IODP.

- **Increase Commitment to Thematic Consistency** by emphasizing the links among drilling expeditions with closely allied goals. The IODP should permit the grouping together of highly ranked drilling targets from several proposals using one or more drilling platforms to address scientific questions in an integrated and comprehensive manner.

- **Expand the Scope of Research Targets** to improve the IODP's ability to address integrative science questions and to better coordinate drilling activities with other large-scale geoscience initiatives. The current practice of parsing scientific proposals into small research questions that can be addressed within the time-span of a traditional two-month drilling leg has forced the community to "think small."

- **Increase the Use, Development, and Quality of *In Situ* and Other Instrumentation** by encouraging use of non-traditional sampling techniques and acquiring larger samples for analyses. Data acquisition from sources other than the mud and rock recovered by coring should also be emphasized (e.g., from seafloor and/or borehole observing systems and experiments). This will require significantly increased emphasis on shipboard and shorebased data acquisition, analysis, and management.

- **Expand the Capabilities of Shipboard Laboratories** to take advantage of, and develop, new technologies and high-quality instrumentation that are both robust and suitable for use in the shipboard operating environment. Geochemists must aggressively promote the use of such instrumentation, and recognize that new, high-quality data streams will benefit virtually all members of the scientific drilling community.

- **Improve Database Design and Increase the Scope of Data Capture** by integrating shipboard data (e.g., currently in JANUS) with the data generated during the post-cruise period, and link that database to the corresponding publications in the IODP and open literature.

- **Establish a Larger Source of Post-Cruise Funding** to meet the needs of shipboard participants as well as the broader scope priorities established for fundamental scientific objectives that emphasize post-cruise activities beyond the immediate core analyses. In addition to continuing a system of small "pilot project" grants that are cruise-specific, we recommend creating a new system of objective-based science support to provide opportunities for more detailed investigations, integrative studies, modeling, and *in situ* or long-term experiments and observations.

Introduction

Geochemistry has played an important role in the research advanced by scientific ocean drilling. Geochemical contributions to the understanding of physical, chemical, and biological processes have been widely disseminated to the scientific community and are now common in popular science journals and grade school texts. Geochemists have addressed a diverse suite of topics contributing to our understanding of chemical inventories, chemical sources and sinks, and chemical mass balances. This research will contribute to a complete Earth model and help predict the manifestations of anthropogenic and natural forcings on its hydrosphere, lithosphere, atmosphere, and biosphere.

Because geoscientists rely heavily on the geochemical analyses of materials recovered from scientific ocean drilling, geochemists felt it was necessary to target geochemical research questions to be addressed by the IODP. In October 2000, the Joint Oceanographic Institutions/United States Science Support Program (JOI/USSSP) thus sponsored a workshop entitled, "Opportunities in Geochemistry for Post-2003 Ocean Drilling." Fifty-two geochemists from the international community (Appendix 1), with a diverse set of interests, met to develop a blueprint for geochemical studies during the IODP. Representatives from the U.S. National Science Foundation (NSF), the JOI/U.S. Science Advisory Committee (JOI/USSAC), and the ODP/IODP scientific advisory structures also participated in these discussions. The two-day workshop was held at the Boston University Corporate Education Center in Tyngsboro, Massachusetts, which provided a retreat-like setting for the exchange of ideas.

Workshop results provide a framework for geochemists and other geoscientists to define new drilling proposals, measurement techniques, and other associated initiatives that will contribute to a successful future deep-drilling program. An explicit workshop goal was to strengthen ties to other members of the geochemical community by involving individuals who have had only limited interactions with DSDP/ODP. Thus, a wide range of scientific fields were represented by the workshop attendees. In addition, written comments were solicited from persons who were unable to attend, however, we recognize that not all of the goals, ideas, and needs of broad spectrum of geochemical research are incorporated into this workshop report. Nonetheless, the discussions, recommendations, and conclusions presented herein articulate a common vision for geochemical research in the next decade of scientific ocean drilling and provide this group's view of how to maintain the highest standards for chemical study in the IODP.

Each of the attendees, and other individuals that were unable to attend this workshop, were tasked to answer the following questions:

- What scientific problems should be of high priority to the geochemical community?
- What drilling objectives should be prioritized to address these scientific problems?
- What new technology is needed and/or what existing technology needs substantial improvement to address high-priority issues?
- What aspects of operational and funding issues need attention?

These questions formed the basis for discussions during the plenary sessions (Appendix 2) and helped identify common interests among the diverse fields of geochemistry represented at this workshop. This cross-fertilization carried over into the Focus Group breakout sessions, which addressed four broadly overlapping themes:

1 Formation and Alteration of Earth's Crust
2 Porewater and Sediment Chemistry
3 Chemical Paleoceanography
4 Microbiology and Biogeochemistry.

In each of these breakout sessions participants strove to arrive at a consensus on the IODP's scientific priorities related to geochemistry. This report summarizes the discussions held during the Focus Group sessions and distills them along common threads. We found that the geochemical interests were best organized into a set of targeted, large-scale objectives that are somewhat different from the organization of the Focus Group themselves.

Geochemical Objectives for Post-2003 Drilling

The Road to the Moho

Many fundamental questions regarding the formation, composition, and evolution of the oceanic lithosphere and the nature of its interactions with other major Earth reservoirs remain unanswered. These processes contribute to the chemical differentiation of our planet, therefore, an improved knowledge of such mechanisms will influence all branches of Earth science. It is important to establish the relative influence of magmatic processes responsible for the construction of oceanic crust versus secondary processes, such as fluid-rock interaction or tectonic forces that modify the lithosphere from the ridge crest until it is subducted.

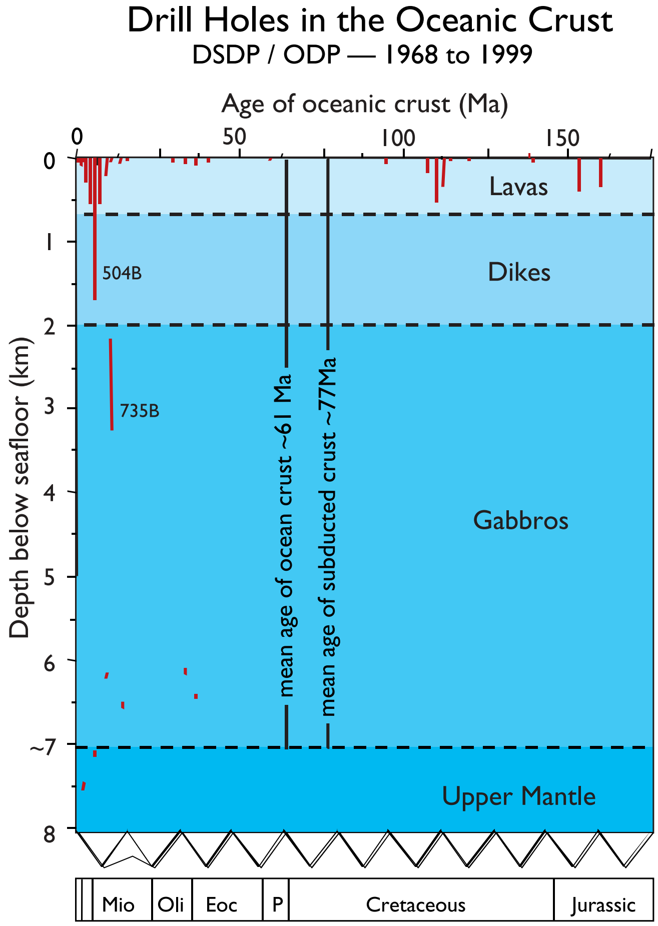


Figure 2. Drilling of the oceanic lithosphere, 1968-2000. Despite more than 30 years of ocean drilling, there are still relatively few drill holes in the oceanic crust and a very poor sampling distribution in terms of both depth and crustal age. Hole 504B remains the only penetration of the lava-dike boundary and there are currently no holes that cross the dike-gabbro boundary or the Moho. Figure compiled by J.C. Alt, D.A.H. Teagle, and modified by J. Natland.

Although remote-sensing techniques have produced important insights into the seismic properties of oceanic lithosphere, the physical and chemical nature of the seismic layers and of the transitions between these layers remain unknown. This uncertainty greatly impedes our understanding of the geologic processes responsible for the formation and evolution of oceanic crust. Although we have sampled altered and metamorphosed basalts, gabbros, and peridotites at many places in the ocean basins through dredging and the drilling of short holes, the composition of *in situ* oceanic crust, away from the influence of transform faults or other tectonic features, remains unknown (Figure 2).

Crustal Aging. We know relatively little about how the oceanic crust changes with age or how extensively fluids penetrate and react with it. In particular, does the Moho shift downward from an original position between gabbro and fresh peridotite as fluids partially transform the peridotite to serpentinite? Although a decade ago this question may have seemed far-fetched, most scientists would now admit that this question is valid, based on increased knowledge of the complexity of both oceanic crust and ophiolites, and can only be answered by drilling completely through the oceanic crust.

Seafloor Magnetization. The discovery of magnetic "stripes" on the ocean floor, which represent magnetic polarity reversals of Earth's magnetic field through time, was key to the development of plate tectonic theory, but our identification of the rocks responsible for the these magnetic anomalies is incomplete. The sources of marine magnetic anomalies have traditionally been considered to be tiny grains of quenched titanomagnetite within the erupted basaltic lavas, but studies of tectonically exposed lower oceanic crust and upper mantle indicate that secondary processes strongly influence rock magnetization. Gabbros and partially serpentinized peridotites commonly contain abundant secondary fine-grained magnetite and may therefore contribute to the source signature of these magnetic stripes. Whether these deeper assemblages can significantly influence the crustal magnetic field and whether such secondary mineralization is developed away from localized tectonic disturbances is untested. This test of the Vine-Matthews hypothesis has always been a major scientific ocean drilling objective, and could be achieved by characterizing gabbros and peridotites recovered by drilling in a normal, undisrupted setting between transform faults, and on a well-defined magnetic stripe somewhere in the ocean basins.

Hydrothermal Exchanges. The seismic structure of oceanic crust and the origin of marine magnetic anomalies are both strongly influenced by the penetration of fluids into the oceanic crust, and the extent of geochemical reactions that transform wall rocks along fluid pathways. The products of high-temperature hydrothermal reactions are well known and manifest themselves as spectacular black smoker vents along the spreading axes, however, the geochemical consequences of these processes, and the fluid, thermal, and chemical fluxes involved, remain poorly known. These processes have profound influences on the thermal structure of oceanic crust, the crystallization of magma chambers, and seawater chemistry.

Although seawater exchange at ridge crests has dramatic effects, fully two-thirds of the hydrothermal heat loss that results from the cooling and subsidence of the oceanic lithosphere occurs off axis in crust older than 1 million years (Myr). A discernible conductive heat flow anomaly is present on average out to crust of 65 Myr in age. Low-temperature thermal and chemical exchange between seawater and rocks probably occurs in oceanic crust of all ages. Long-term changes in porosity, tectonic stress, and burial by sediments, or lack thereof, will affect the pattern and flow of fluids in the crust, and the character, extent, and depth of hydrothermal alteration. The fluid, chemical, and thermal fluxes and the competing influences of these processes in oceanic crust remain poorly known despite their profound influence on ocean chemistry and mantle heterogeneity that results from crustal recycling during subduction. Detailed knowledge of the depth of hydration and carbonation of the oceanic crust, and the extent of compositional and mineralogical recrystallization of the down-going plate, is necessary to understand the devolatilization of the altered oceanic crust and the physical and chemical processes that occur during subduction at convergent margins.

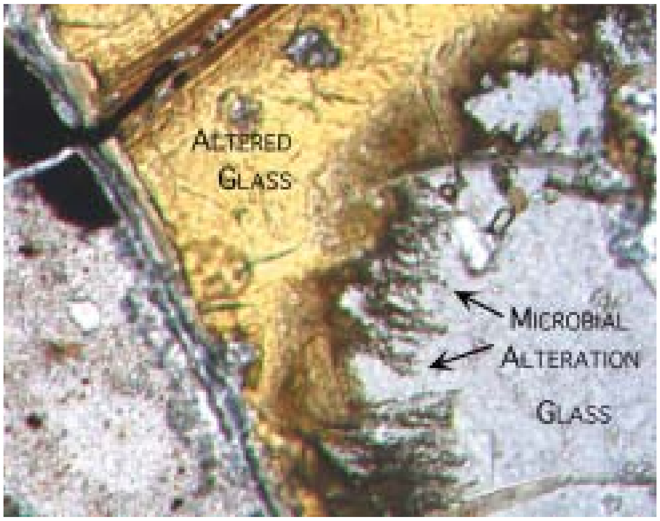


Figure 3. Microbially mediated alteration of volcanic glass from an ODP drill hole on the Southeast Indian Ridge. Microbial tubules can be seen along the boundary between clear volcanic glass and brown alteration products. Image courtesy of ODP Leg 187 Science Party.

Deep Biosphere. Recently, a deep microbial biosphere was discovered in fractured basalts, but the nature and abundance of these communities and their thermal and physiochemical boundaries are very poorly known (Figure 3). What happens to these communities off axis as porosity and thermal structure changes, and as sources of energy diminish? Do they follow isotherms downward as cooling micro-fractures penetrate ever-deeper crustal rocks? If fracturing and fluids penetrate to the deepest levels of the crust, could biogenic carbon reach the Moho?

Moho. Even the precise nature of a seismic boundary as fundamental as the Mohorovicic discontinuity continues to be intensely debated. For example, although the Moho is defined in terms of changes in seismic velocity, the mechanical and petrologic changes associated with this boundary are unknown. Is the boundary defined by this transition located between gabbros and peridotites, or alternatively is it defined by a serpentinization front within the upper mantle?

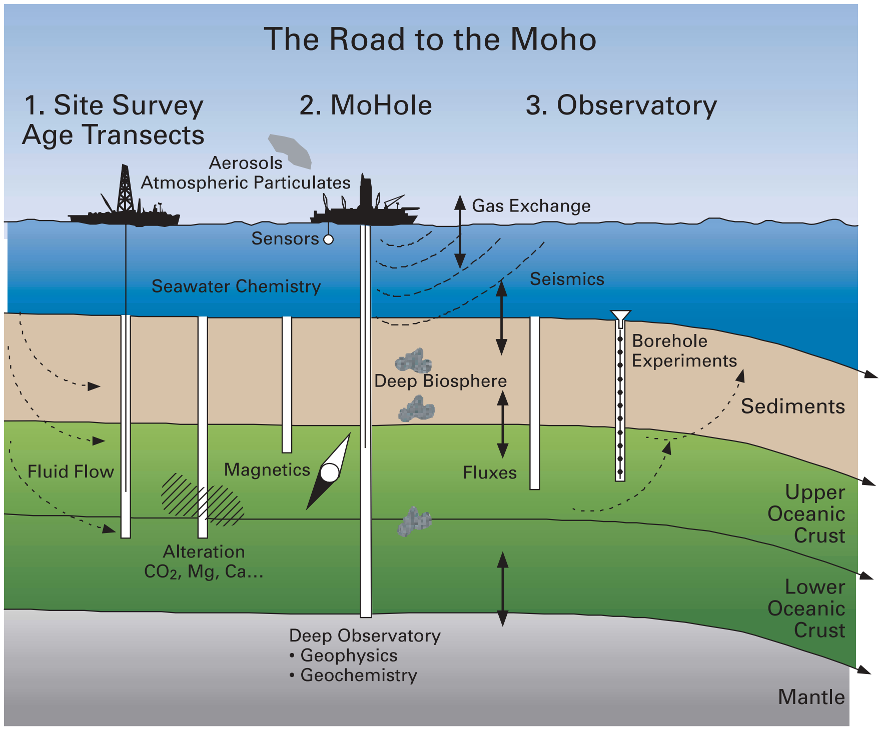


Figure 4. Cartoon describing the exploration strategy required to characterize the oceanic lithosphere to best site a deep drill hole that penetrates the entire oceanic crust and into the upper mantle. This deep hole will provide a wealth of currently inaccessible information relating to the construction and maturation of oceanic crust and its interactions with other constituents of the deep sea. Figure courtesy of Bernhard Peucker-Ehrenbrink, Woods Hole Oceanographic Institution.

Drilling Strategy. The goal of drilling a complete section through the oceanic crust and into the upper mantle has been reiterated throughout the history of ocean drilling. This objective is embedded in the ODP's Long-Range Plan, and it is articulated as the "21st Century Mohole" initiative in the IODP's Initial Science Plan. With the construction of a riser ship for scientific drilling, which provides well control, we now have the technological capability to drill to the Moho at one or more selected locations.

To accomplish this goal within the next two decades we will need to thoroughly characterize the oceanic crust at a range of ages and spreading rates so as to define the best site(s) for deep drilling (Figure 4). This characterization will provide, for example, fundamental constraints on the hydrogeology of fluid flow in oceanic crust, the thermal and chemical effects of such exchanges, the possible existence of a deep igneous biosphere; insights into the mechanical behavior of the Moho, lower crust, and upper mantle; the magmatic construction and magnetization of oceanic lithosphere; the nature of magma chambers; and the composition and degree of hydration of the oceanic plate delivered to subduction zones. The complete characterization of the process of formation and alteration of oceanic crust (summarized as "The Road to the Moho") can thus be achieved by adopting a systematic approach to planning for deep drilling and coring that goes beyond anything thus far attempted by the DSDP and ODP.

The "Road to the Moho" is thus an exploration strategy for the oceanic lithosphere with the eventual goal of drilling a complete section of *in situ* oceanic crust, reaching into the upper mantle, that will address the primary scientific objectives outlined above. This strategy requires resolute long-term vision, a sea change in the mode of scientific drilling operations, and a different approach to project management. We emphasize that such a program will also significantly contribute to a number of geochemical (and other) objectives not usually considered in the context of the recovery of deep igneous basement; an essential component of "The Road…" will be to recover appropriate overlying sediments, fluids in all crustal layers, microbiological materials, and other essential integrative information. This collective endeavor cannot be realized by a planning structure that defines scientific objectives in the two-month context of a leg-by-leg, year-by-year, globally roaming schedule.

The Road to the Moho requires resolute long-term vision, a sea change in the mode of scientific drilling operations, and project management that emphasizes large-scale scientific goals.

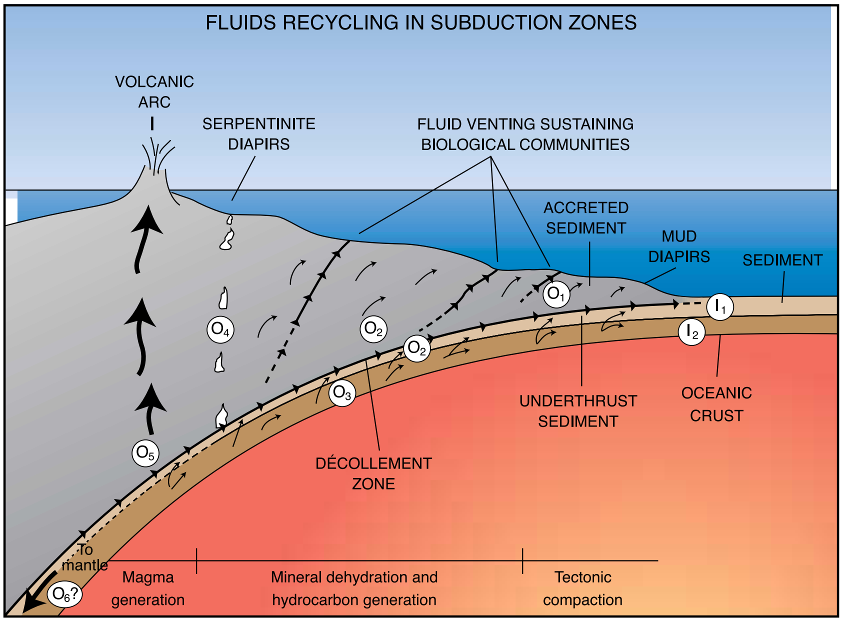
Continental Margins as Biogeochemical Reactors

The transition between land and ocean at the continental margin is one of the most profoundly important boundaries on Earth. At this boundary, waters carrying sediment and other materials transported by rivers are deposited in coastal and oceanic basins. Unknown quantities of groundwater carry unknown concentrations of particles and solutes beneath the coastal zone and enter the oceans along the continental shelves and slopes. At present, the fluxes of fluid, sediment, and ions between the continental source regions and sinks along the ocean margins and deeper basins are poorly known. Are these fluxes a significant fraction of global geochemical budgets? Do these fluxes affect biogeochemical cycling of the elements, and if so, on what scale? What are the implications for biological productivity and global climate?

Collisional Processes. Transport processes that affect mass fluxes are located in margin settings associated with subduction zones. The collisional process generates large earthquakes, causes active volcanism, and produces new continental lithosphere. During this process, (1) an unknown amount of oceanic sediment and seawater is subducted into the mantle, (2) a fraction of this subducted material is recycled through active volcanoes, and (3) a part of this material is returned to the overlying ocean (Figure 5). While great progress has been made, the system remains too poorly constrained to assess fluid and volatile fluxes among mantle, oceanic crust (overlying sediment and pore water), water column, and atmospheric reservoirs. What is the impact of these fluxes on the generation of volcanism and the origin of earthquakes in the seismogenic zone?

> The continental margin reactor incorporates an energy-rich mixture of chemical, biological, and physical processes, which can only be accessed through a long-term commitment of drilling resources.

Climatic Boundary. The continental margin also represents a fundamental climatic boundary separating sites of net evaporation (the oceans) from sites of net precipitation (land surface). Differential warming of the continents causes large-scale monsoonal-type circulation in tropical latitudes, which is part of the global-scale Walker circulation of the atmosphere. Likewise, shore-parallel winds created largely by differential warming of the continents relative to the ocean in many coastal zones bring about coastal upwelling and greatly enhance marine biological productivity. How do these fluxes control global climate, and do they support deep crustal microbial communities?



I = Input O = Output

↗ = Diffuse fluid flow

↗ = Focussed fluid flow along the décollement and other high permeability faults

FLUID MASS BALANCE

$I_1 + I_2 = O_1 + O_2 + O_3 + O_4 + O_5 + O_6 + R$

I_1 = Sediment with pore fluid
I_2 = Hydrated oceanic crust
O_1 = Tectonic compaction
O_2 = Dehydration of hydrous minerals and hydrocarbon generation
O_3 = Dehydration of oceanic crust
O_4 = Serpentinization and diapirism
O_5 = Magma generation
O_6 = To mantle (?)
R = Residual fluid

Figure 5: Fluids play a central role in the mechanical, thermal, and geochemical evolution of subduction zones. Future deep drilling targets in these tectonically dynamic regions will provide new insights into chemical and isotopic global budgets and the potential relationship between earthquake cycles and the generation and flow of liquids. Figure from M. Kastner, 1997, Recycling processes and fluid fluxes in subduction zones, ODP's Greatest Hits, Joint Oceanographic Institutions, Inc. p. 16.

Hydrocarbons. Rivers and groundwaters, sediment accretion and subduction, coastal upwelling and biological productivity all combine, to varying degrees in various locations, to make the sediments of the deltas, shelves, and slopes of continental margins an energy-rich mixture, a so-called "biogeochemical reactor." What is the nature and timing of petroleum and natural gas (hydrocarbon) formation and accumulation in basins of the deep continental margins? What are the maturation histories of the sediments in these basins and the nature of their source materials? What are the pathways of hydrocarbon and other fluid migration? How important are microbes to the processes of hydrocarbon formation and breakdown? Under what conditions does abundant organic matter avoid microbial degradation?

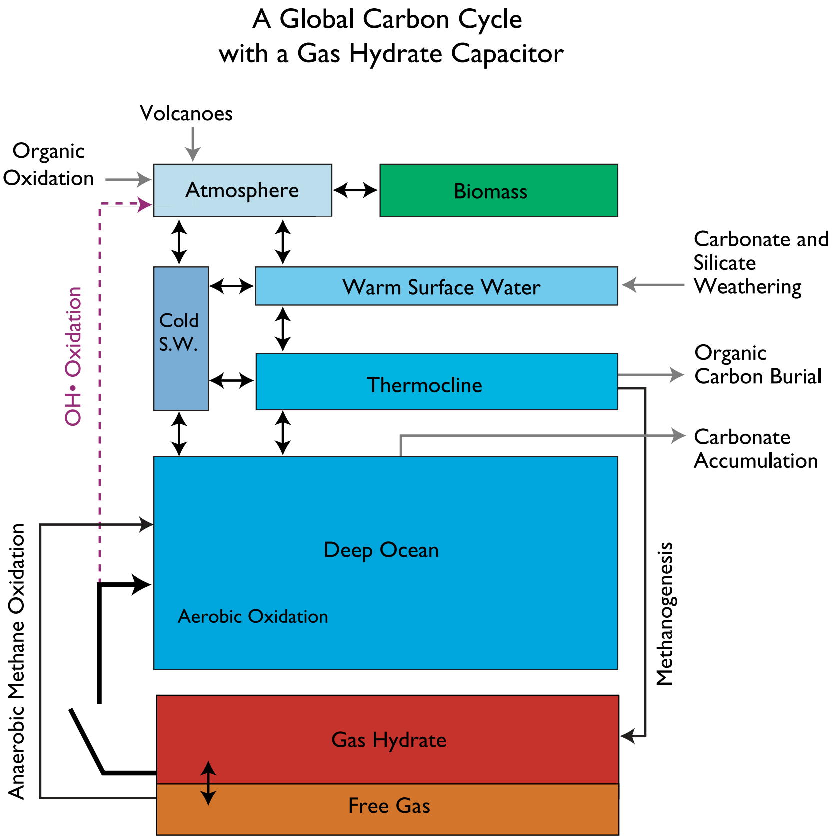


Figure 6: The global exogenic carbon cycle with a bacterially mediated gas hydrate capacitor. Carbon enters the capacitor as a fraction of sedimentary organic matter is converted to CH_4 through bacterial methanogenesis. This CH_4 saturates pore waters to form CH_4 hydrates, which are buried past gas hydrate stability conditions to form free CH_4 gas. Although much of the free gas is returned to gas hydrates, some CH_4 leaves the system through anaerobic CH_4 oxidation by bacteria in shallow sediment. The capacitor concept arises when a significant fraction of gas hydrates are converted to free CH_4 gas during an increase in temperature. This CH_4 is added directly into deep water where it is oxidized by aerobic methanotrophs. From Dickens, G., 2001, On the fate of past gas: What happens to methane released from a bacterially mediated gas hydrate capacitor?, Geochem., Geophys., Geosyst., *2, paper no. 2000GC000131, http://g-cubed.org/gc2001/2000GC000131.*

Microbial Biogeochemistry. Chemical potential energy from the process of photosynthesis is used by marine microbes to maintain a large subsurface community. Microbial activity is responsible for the subsequent remineralization of organic compounds that returns nutrients to the water column for reuse. At the same time, microbial activity results in a wide variety of products having geological significance, for example, apatite in phosphorous ore deposits, dolomite, pyrite, and large deposits of biogenic methane that are preserved as methane gas hydrates under particular conditions. Organic matter that escapes microbial degradation in the shallower sediments of the continental margins, for as yet unknown reasons, can persist to burial depths and temperatures sufficient to form petroleum.

Shallow-water sediments also exert a major influence on atmospheric composition, both through the steady return to the ocean and atmosphere of CO_2 produced by microbial oxidation of organic carbon or precipitation of calcium carbonate by shallow-water benthic biota, and through the episodic (and occasionally catastrophic) release of large amounts of methane from gas hydrate or petroleum reservoirs (Figure 6). What limits microbial activity in marginal sediments (nutrient elements, organic carbon availability, electron acceptors, temperature)? Are there novel catalytic processes from which microbes can derive energy? How do the microbial communities evolve in space and time? To what extent do biogeochemical processes vary between active and passive margins? What are the sources and sinks for methane? These and other important questions speaking to the connections among chemical, biological, and physical processes acting in the continental margin reactor, remain unanswered.

Global Biogeochemistry Through Time

Earth's global biogeochemical cycles are dynamic and operate over a range of time scales, from seasonal to millions of years, with a large variety of potential forcing mechanisms and feedbacks. The sediment and pore fluid geochemical records are natural archives that provide insights into the processes that modulate Earth's environment and the spatial and temporal evolution of these processes through Earth history (Figures 7 and 8). Therefore, the solid and aqueous phases within a given sedimentary sequence are fundamental tools that can be used to investigate Earth's history and evolution. It is only by understanding the history of Earth's integrative systems that we can attempt to predict its future, a future that may involve far-reaching changes on human and societal time scales. Such changes are likely to reflect a combination of anthropogenic and natural causes. Scientific ocean drilling must address these issues beyond the shallow subsurface depth (time) range of other types of traditional coring methods.

Geochemical Paleoceanography. The multifaceted nature of the science of paleoceanography has been amply addressed in the IODP Initial Science Plan, and it is clear that this broad field is very active and well-recognized. This workshop did not reiterate the justifications for such studies. However, from the geochemical point of view, there is a tremendous opportunity for the study of ocean history to make contributions beyond the traditional paleoceanographic emphases on the reconstruction of oceanic paleo-temperatures and paleo-CO_2 concentrations. While these topics are undeniably central issues for understanding ocean history, unresolved topics in geochemical paleoceanography include quantifying the geochemical budgets of many significant elements and, most importantly, understanding the relationships among the physical, chemical, and biological systems controlling the distribution and speciation of these elements. For example, the relationships between the input of micronutrients, such as Fe, to the ocean and the associated biological response over decadal, centennial, and millennial time scales (orders of magnitude longer than the open ocean Fe enrichment experiments) remain unknown.

The links between water column and sediment redox state and the delivery of organic matter to the seafloor, which is in turn at least partly related to paleo-export production, is an important issue in local basins that preserve superb paleoceanographic records (e.g., Cariaco Basin), as well as regionally (e.g., the California Margin, the Benguela Current system). How changes in weathering rate affect sediment supply, and how both of these variables are perhaps driven by large-scale tectonic and/or climatic changes (e.g., such as in the fluvial systems of Papua New Guinea), is also of key interest to geochemists. Interactions between organic geochemists and climate scientists are also becoming increasingly productive, as evidenced by the development and application of biomarkers to the study of ocean history.

Tracing Biogeochemical Behavior. The biogeochemical links among the continental, oceanic, and atmospheric reservoirs are poorly understood. Many interpretations are based on

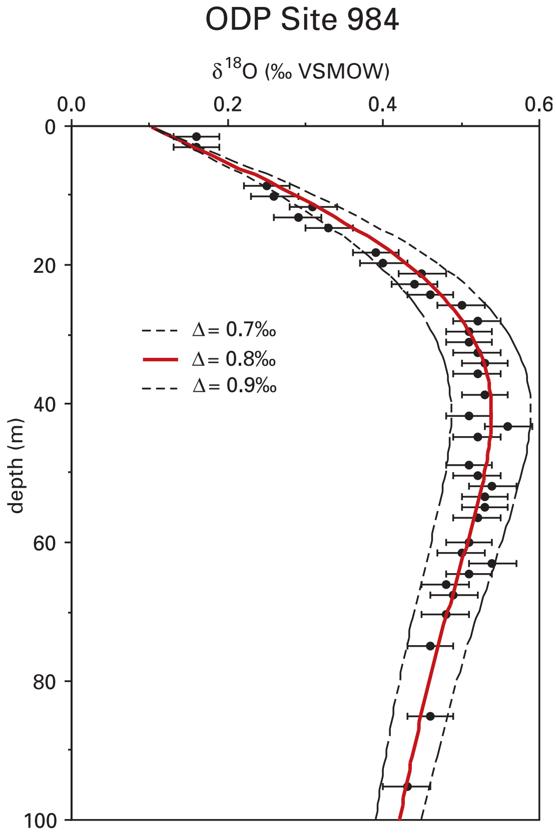


Figure 7. Oxygen isotope data from ODP Site 984 in the North Atlantic. These data constrain the local change in the $\delta^{18}O$ of seawater during the LGM to be 0.8 per mil higher than the Holocene value and the bottom water temperature to be -1.5° C. Schrag, D.P., J.F. Adkins, K. McIntyre, J.I. Alexander, D.A. Hodell, C.D. Charles, J.F. McManus, 2002, The oxygen isotopic composition of seawater during the Last Glacial Maximum, Quaternary Science Reviews, *21, 331-342.*

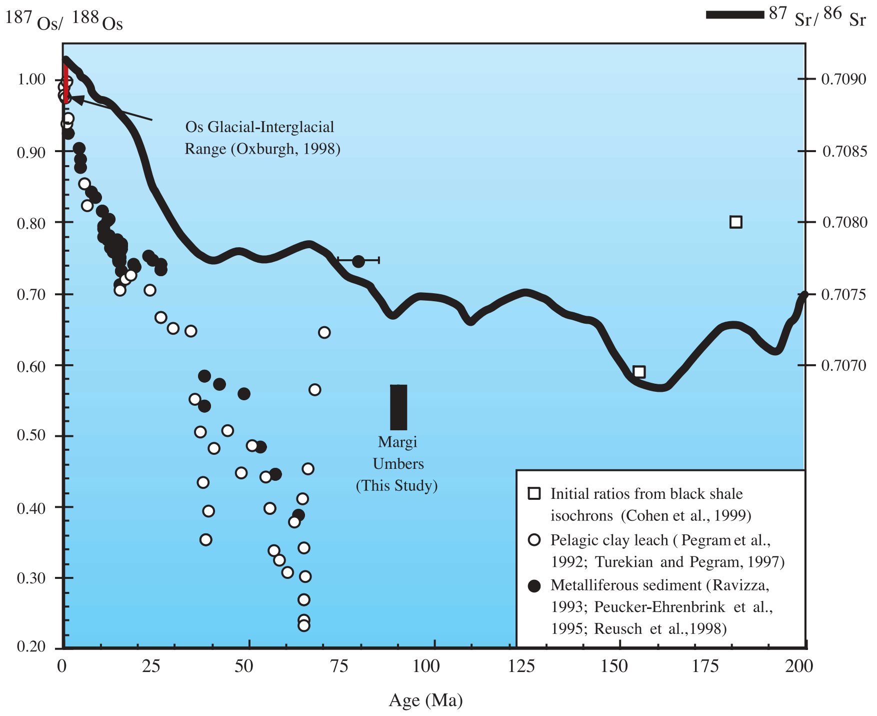


Figure 8. Plot comparing the marine Sr and Os isotope records over the last 200 million years. The size of the black rectangle corresponds to the range in ^{187}Os/^{188}Os and age uncertainty associated with the Margi samples. The representation of the marine Sr isotope record is based on the compilation of Howarth, R.J. and M.J. McArthur, Jour. Geology, 105, 441-456, 1997. Figure from: Ravizza, G., R.M. Sherrell, M.P. Field and E. A. Pickett, Geology, 1999, 27, 971-974.

the application of chemical proxies that trace various components of these complex systems. Because of the emphasis placed on individual proxies, one of the greatest concerns facing biogeochemical paleoceanographers is our current lack of understanding of the preservation and fidelity of such proxies. For example, how do fluid flow, pressure effects, and diagenesis affect the preservation of geochemical records? Because fluid flow through the oceanic crust has only been a focus of research during the past two decades, there is a need to develop and verify new and redundant proxies that are not affected by biogeochemical reactions during fluid flow. While it is clear that any single proxy will not provide a panacea, there is a need for continued development of new and more quantitative proxies that address issues to be targeted by future scientific ocean drilling.

The broad field of biogeochemical paleoceanography is closely allied to the initiatives discussed in the “Continental Margins as Biogeochemical Reactors” and “Linking Microbiology and Biogeochemistry” sections of this report. With the availability of both existing and new proxies, researchers will be prepared to address questions about the rates and extent of chemical transport and transformations across ocean margins, such as: What is the flux of carbon (as well as nutrients and other elements) through the land-sea interface and how does it vary through time? A variety of first-order geochemical tracers have been developed, but they need to be more quantitative in order to improve our ability to determine: (1) terrestrial versus marine sources of organic matter, (2) the rate of carbon sequestration and fluxes, (3) the extent of alteration of organic matter, (4) redox state and diagenetic processes, (5) the amount of nutrient regeneration, weathering fluxes, climate and environmental conditions, (6) microbial processes, and (7) major nutrient and productivity processes.

Similar questions pertaining to the global carbon budget and related diagenetic processes are important in the deep sea. For example, how long has the North Pacific Ocean been a silica-dominated zone and do the biogenic processes responsible for this situation cause a short circuit in the carbon cycle? How do the cycles of carbon and silica vary spatially and temporally? Are these processes associated with changes in climate and oceanic circulation? Reconstruction of the history of biogeochemical processes in the open ocean provides an avenue for examining these processes and changes.

Continental Margins Through Time. By virtue of their high sedimentation rates and rich variety of constituents from both oceanic and continental sources, the sediments of continental margins can provide detailed time series of continental orogeny and erosion, sea-surface temperature and salinity, marine biological productivity, and sea level change. By virtue of the antiquity of many oceanic margins, deep drilling into their sediments can provide an early history of continental breakup, including Mesozoic (or perhaps earlier) episodes of anoxia and salt deposition, and the generation of polymetallic sulfide ores and extreme biological environments during the initial stages of oceanic rifting.

> It is only by understanding the history of Earth's integrative systems that we can attempt to predict its future.

Linking Microbiology and Biogeochemistry

The key issues that were identified under this workshop theme can be stated as two complementary questions:

- What types of microorganisms inhabit the oceanic crust and its overlying sediments?
- What effect does microbial activity have on the geochemistry of this environment?

It has long been recognized that microbial activity plays a critical role in shaping the vertical distribution of various compounds routinely quantified in DSDP and ODP cores (e.g., sulfate and methane). Due to this intimate relationship between microbial activity and subsurface geochemical properties, knowledge of the types of organisms present permits the prediction of biologically mediated geochemical transformations based on the metabolic potentials of these organisms. Conversely, knowledge of the subsurface geochemical profiles permits the prediction of, and search for, metabolic activities, including previously unknown metabolic pathways. Mass balance estimates can be used to constrain the rates at which various metabolic processes are proceeding, and give some indication of the vigor of the buried microbial community.

The importance of obtaining spatially resolved mass balances of microbially driven processes is critical to addressing the link between microbiology and biogeochemistry.

The Distribution of Life. Because the oceanic crust and its overlying sediment are temporally and spatially restricted from ocean water, it is hypothesized that many unique organisms inhabit this subsurface environment (Figure 9). It is therefore of great interest to determine what types of organisms populate this vast habitat and what evolutionary pathway(s) they have followed to compete in this environment. Are the strategies employed to carry out basic functions fundamentally different from those used by surface-dwelling organisms, or are the differences minor?

One example of how the ODP and IODP can uniquely contribute to the exploration of this question is in the area of high-temperature biology. The current view of the phylogenetic organization of life on Earth places thermophilic prokaryotes at the base of evolutionary "tree of life." This presents extremely interesting opportunities when drilling into high-temperature sediments. The downhole temperatures measured in a few ODP sites (e.g., Site 1174) have exceeded the current known thermal limit to life (113°C). How does pressure modify biological tolerance to high temperature? There are some indications that high pressure may perhaps extend this thermal range (i.e., DNA is more thermostable at high pressure). Can we then expect to push the known temperature limits even further? The possibility of using organisms isolated from this environment for biotechnology-related applications is significant. Of particular interest are those enzymes that function in these extreme conditions (e.g., high temperature and/or pressure). Despite the selective nature of culturing microbes from these environments, the study of these organisms in pure culture allows for detailed analyses that are not possible otherwise. Therefore, efforts to obtain isolates from recovered cores should be emphasized in the remaining years of the ODP and in the IODP. It was also noted that much can be done with DNA extracted from the cores, even in the ab-

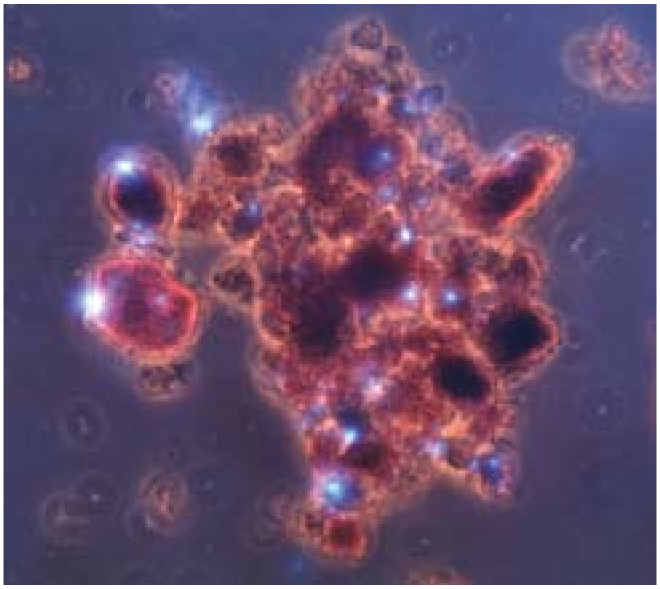


Figure 9. Combination phase contrast/fluorescence micrograph showing DAPI-stained cells of hyperthermophilic archaeon GR1 attached to iron oxide particles. The iron oxide aggregate is approximately 50 microns in diameter. GR1 was isolated from an event plume associated with the 1996 North Gorda eruption. Isolate GR1 was probably resident within the oceanic crust prior to the eruption, and is most similar to a new isolate from Hole 857D at Middle Valley. Photo courtesy of Melanie Summit, Washington University.

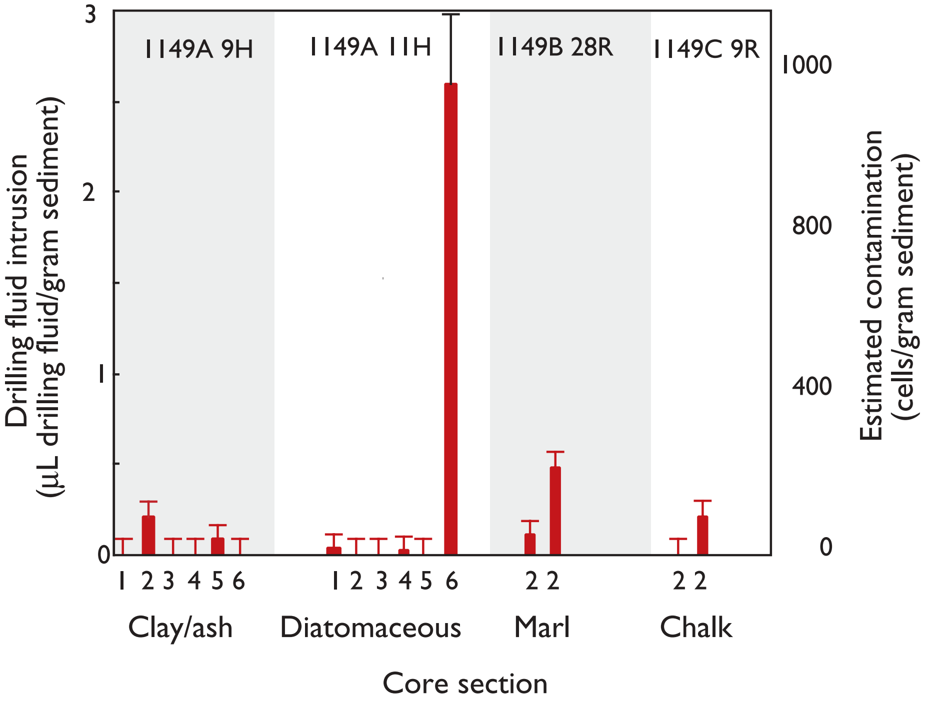


Figure 10. Volume of drilling fluid intrusion, as determined by perfluorocarbon tracer analysis, into the interior of sediment samples from four sedimentary cores exhibiting different lithologies. Estimates of introduced bacteria are based on a surface water (drilling fluid) concentration of 420 bacteria per L. The error bars represent the average deviation of duplicate samples. Figure courtesy of David Smith, University of Rhode Island.

sence of obtaining the organisms in culture. DNA sequences can be screened for a gene of interest and cloned into other microorganisms that can be routinely cultured.

Biomarkers. Several approaches are necessary for the advancement of these microbial studies in deeply buried marine sediments and oceanic crust. The expanded use of biomarkers for identifying the types of microbes that exist in the subsurface biosphere is a high priority. These methods are independent of culturing these organisms, and therefore are not subject to the inherent bias that culturing techniques impart. Distinctive lipids and nucleic acid sequences are the most obvious targets for the use of biomarkers and these have already been successfully employed. For example, profiles of domain-specific (i.e., Archaea and Bacteria) lipid biomarkers in ODP cores suggest that Archaea took advantage of an ocean anoxic event to greatly expand their occurrence in the ocean. This observation may be further expanded to ask how indicative are these biomarkers of oceanic oxygen levels (redox conditions) in general? Can they be further used to constrain paleo-circulation and paleo-climate interpretations? Can the presence of biomarkers specific to certain metabolic activities be correlated to porewater analyses, sedimentological observations, and geochemical models? What role did microbial activity have in shaping the geochemical history of the ocean?

Acquisition of Microbiological Samples. Although the role of microbial processes has been observed and studied from the earliest pore water investigations conducted during the DSDP, microbiologists have only begun to participate on ODP cruises during the past few years. Nevertheless, the importance of this field has captured the imagination of both the drilling and non-drilling oceanographic community, and microbiological investigations are now an integral part of the current ODP and the future IODP. An extensive database of direct observations of prokaryotic cells in sediments cored at ~20 sites has lead to generalizations regarding the distribution of these organisms in the marine subsurface environment. Recent results from ODP Legs 185 and 190 have demonstrated that drilling-induced contamination of the recovered cores with bacteria from the drilling fluid is minimum (Figure 10). These results justify the resources expended in collecting these samples and allows for more confidence in interpreting these results. With this confidence in hand, it is now time to develop standard protocols and analyses for drilling-related microbiological investigations in order to further the community's interest. Once standardized, the routine employment of such protocols on all future legs will allow researchers to analyze these data on spatial and temporal scales that are only possible with extensive datasets, as has been the case with pore water geochemistry. In addition, specific steps should be initiated by the ODP and IODP to archive samples as a resource for future for microbiological studies.

Radioisotope Facility. Efforts to develop or implement additional techniques need to be addressed. These efforts should include the use of compound-specific isotopic analysis (e.g., ^{13}C, ^{2}H) of biomarkers. In addition to these compound-specific analyses there is a need to include a radioisotope isolation facility onboard the ODP or IODP drillship(s) for tracer experiments to quantify rates of biologically mediated geochemical transformations (e.g., sulfate reduction and methanogenesis). Protocols for the coexistence of radiotracer techniques and radiocarbon-based geochronology efforts must be in place prior to their implementation. These potentially conflicting interests currently coexist on UNOLS vessels, which can serve as a useful model for future capabilities on board the IODP drilling vessels. While this is being addressed on a leg-by-leg basis in the final phase of the ODP (e.g., Leg 201, "Equatorial Pacific and Peru Biosphere"), these capabilities need to be routinely available in the IODP. Interest in the upper-most layers of the sedimentary column, which are currently not being adequately sampled, are also of interest to microbiologists, yet these interests may be better served using alternate drilling and sampling platforms.

Integration with Other Fields. The fact that microbes catalyze many of the reactions that are of interest to geochemists does not permit a distinct separation between the fields of microbiology and chemistry. Indeed, the characterization of microbiological activity through scientific ocean drilling will benefit from the continuing traditional geochemical studies. Fundamental advances in the study of life in the marine subsurface will come from the concerted efforts of microbiologists and geochemists jointly applying their specific skills. For example, chemical and isotopic measurements of interstitial waters and sediments, coupled with modeling of the diffusive transport through the sediment column, can be used to constrain rates of various microbial processes, including methanogenesis, methanotrophy, and sulfate reduction. Such studies may also help to define the limits of bacterial growth under various conditions. When combined with new techniques in microbiology and organic geochemistry through the collaborative opportunities provided by the ODP/IODP environment, such a broad, multidisciplinary research effort can provide a comprehensive description of the role of mirobiological communities in the oceanic crust.

> Interdisciplinary study has been the hallmark of ODP research in the past and serves as a model for maximizing the usefulness of IODP materials in future deep biosphere research.

Common Issues Uniting Uncommon Needs

Regardless of specialty, workshop participants identified several common approaches and recommendations that would facilitate progress in geochemical research during the IODP.

Increase Commitment to Thematic Consistency

Recognizing that the DSDP and ODP have been single platform community endeavors (with associated practical and logistical limitations), the participants strongly believe that increasing the links among individual legs with closely allied scientific goals would encourage and facilitate consistent community involvement, and would result in greater scientific integration. The scientific problems described in the previous sections cannot be solved with one, two, or three drilling legs. While it is unclear whether the ODP's relatively rigid two-month leg system will continue for the riserless ship in the IODP, we recommend that the IODP permit the grouping together of highly ranked drilling targets to significantly advance the scientific research in a particular direction. There must be a greater commitment on behalf of the IODP planning committees to respond favorably to highly regarded scientific proposals that may require four, six, or eight months of ship time to acquire the data sets required to answer questions of prime interest to the geochemical community.

Recommendation: The IODP should emphasize the links among drilling expeditions with closely allied goals by permitting the grouping together of highly ranked drilling targets from several proposals using one or more drilling platforms to address scientific questions in an integrated and comprehensive manner.

Expand the Scope of Research Targets

The DSDP and ODP have strong records of success in the Earth and ocean sciences. Geochemists and other discipline scientists have an opportunity in IODP to expand the scope of the targeted scientific problems and to "think outside the box" in terms of the global nature of scientific inquiry. The workshop participants agreed that increasing the coordination with, and the ties to, other national and international marine geoscience initiatives (e.g., MESH, MARGINS, RIDGE, GERM), as well as to terrestrial projects (e.g., continental drilling), would help expand the IODP's scope. An additional benefit would be the recruitment of new geochemists into the marine drilling community.

Our ability to expand the IODP's scope will naturally flow from an increased commitment to thematic consistency. Workshop participants discussed how the current practice of parsing scientific drilling proposals into small problems that can be addressed with only a two-month drilling program has, by necessity, forced us to "think small." This system does not challenge the community to develop ambitious plans to make large steps forward in their science. While the scale of the research infrastructure associated with scientific ocean drilling is large (one or more ships, hundreds of million of dollars expended collectively over the life of the program), the questions being addressed remain disproportionally small.

Recommendation: The IODP should expand the scope of targeted research problems to better coordinate activities with other large-scale geoscience initiatives and to improve its ability to address integrative science questions. The current parsing of scientific questions into two-month drilling legs has forced the community to "think small."

Increase the Use, Development, and Quality of *In Situ* and Other Instrumentation

To date, one of the fundamental objectives of scientific ocean drilling has been to recover solid and aqueous samples for shipboard and shorebased analysis. While the use of logging, downhole tools, and other avenues of data acquisition (e.g., long-term observatories) have been increasing in recent years, a concerted effort needs to be made to facilitate the acquisition and integration of these data and *in situ* experiments with the more traditional types of sample recovery. The ability to recover sediment, rock, and porewater samples at *in situ* temperatures and pressures should be highest priority. Greater flexibility is needed to improve sample archiving, to allow special sample handling for particular needs (shipboard and shorebased), and to allow larger sample sizes for the battery of geochemical techniques now available to the community.

Recommendation: Greater flexibility should be provided to permit non-traditional sampling techniques and larger sample sizes for analyses in support of shipboard and shorebased investigations, and to better integrate with *in situ* experiments and long-term observations.

Figure 11. Gerald R. Dickens (Rice University) examines the ICP-emission spectrometer in the JOIDES Resolution's *chemistry lab. Photo by Roy Davis, ODP/TAMU.*

Expand the Capabilities of Shipboard Laboratories

As chemical instrumentation becomes more robust and better able to tolerate the shipboard environment, there is an opportunity for the IODP to greatly expand its analytical capabilities. The recent additions of gas chromatography-mass spectrometry, ICP-emission spectrometry (Figure 11), and other instrumentation onboard the *JOIDES Resolution* are welcome additions. They should be considered as examples of the capabilities offered by the next generation of chemical instrumentation, which should be routinely available in the IODP. Instrument acquisitions need to be considered in the context of the increasing interdisciplinary nature of research and drilling targets. For example, increased organic chemical apparatus will be essential for Deep Biosphere research in both sedimentary and igneous environments.

The ability to use "objective-specific," non-standard instrumentation onboard the riserless drilling vessel needs to be addressed. While the fixed laboratories on the current vessel are impressive and are the result of many years of effort, there needs to be an increased opportunity for individual investigators to use non-standard techniques where appropriate.

Great progress can be made through the integration of an onboard radioisotope isolation facility, the operation of which is deemed essential for the success of the Deep Biosphere initiative. This capability will permit tracer experiments that will provide estimates of the rates of biologically mediated geochemical transformations. While protocols for the coexistence of radiotracer techniques and radiocarbon-based geochronology onboard the vessel need to be in place prior to installation of a radioisotope facility, these potentially conflicting interests currently coexist on UNOLS vessels, which can serve as useful models for future capabilities on board the drilling vessel.

Recommendation: The IODP should expand shipboard laboratory capabilities to take advantage of, or develop, new technologies and high-quality instrumentation that are both robust and suitable for use in the shipboard operating environment. In particular, a radioisotope facility is essential for the success of the Deep Biosphere initiative.

Improve Database Design and Increase the Scope of Data Capture

As the number of high-resolution analytical instruments deployed onboard the ODP and future IODP drillships increases, the amount of data generated rapidly becomes immense. While the ODP has performed admirably in retaining this first-generation of data capture (e.g., JANUS), within the IODP this need will become even more acute. The geochemists at the workshop highlighted the importance of real-time data acquisition and availability, with a particular emphasis on increasing the capability to link data from disparate sources (e.g., pre-cruise seismics and cruise-measured physical properties such as porosity and porewater chemistry).

An equally important issue that is becoming of increasing concern is the ability to add post-cruise results to this electronic database and to integrate these data with the corresponding publications. Post-cruise publications, which are often published years after the Initial Reports (IR) or Scientific Results (SR) volumes, should be linked to the primary databases that archive or store these data so as to increase the usefulness of both data types. Because post-cruise data are more varied than the measurements made during a cruise, the resulting post-cruise database will need to be highly flexible. This can be achieved, and should be a priority, as the ability to synthesize and bring together large data sets from multiple legs will become even more critical during the IODP.

Recommendation: The IODP should make a priority the integration of shipboard data (e.g., currently in JANUS) with the data generated during the post-cruise period, and link that database to the corresponding publications in the IODP and open literature.

Establish a Larger Source of Post-Cruise Funding

The availability of post-cruise funding is particularly important for geochemical studies that use materials obtained from scientific ocean drilling. Although much geochemical data are collected onboard the ship, most investigations require detailed laboratory analysis for many years following the cruise. In the current JOI/USSSP program, immediately after a drilling leg, U.S. scientists can apply for limited funds for pilot projects to meet primary cruise objectives; disbursement decisions are made by JOI Program Managers based on a peer-review process. Although these funds need not be distributed uniformly, awards are generally similar in size, on average approximately $20k to $30k per researcher over two years. Most shipboard scientists can expect to receive some support following the cruise.

The JOI/USSSP post-cruise funds often serve as seed money for the development and submission of larger proposals to national funding agencies, where these proposals are focused on scientific objectives that require more substantial resources, and which can support graduate student efforts. Additional post-cruise funds are also needed to meet the analytical requirements of peer-reviewed papers in the open literature, especially where there is considerable shore-based participation. In the current system, any substantial post-cruise research investigation must compete for funds in larger programs outside of the ODP, which are primarily programs administered from the NSF-Marine Geosciences Section (NSF-MGS). With the possibility of simultaneous riser, non-riser, and alternate platform drilling, the annual contingent of U.S. scientists will be significantly larger in the future, and will possibly be more varied than in the past, thereby placing greater demands on the limited funding available for post-cruise research.

For geochemists, the problem of such limited support is particularly acute. While the support provided by JOI/USSSP has increased since the earliest days of the ODP, it has not kept pace with analytical inflation. The cost of doing cutting-edge chemical research is increasing dramatically, and for a variety of reasons. While per-sample costs for general analyses (e.g., routine major and trace elements) has decreased, the number of samples needed to be analyzed to answer a given problem has increased. For example, in the field of geochemical paleoceanography, data sets of 100s or 1000s of samples are becoming routinely necessary. Additionally, the increasing complexity of measurements available—and needed—to the geochemist (e.g., isotopic analyses) adds an additional burden. These and other reasons contribute to a significant decline in buying power for post-cruise research over the past ten years.

The establishment of a larger source of post-cruise science support in the United States is critical to the success of any future scientific ocean drilling program. The limited support for immediate post-cruise work is important and should be maintained. Indeed, some critically important post-cruise data would not be gathered were it not for this financial support, and such studies in certain cases would not be appropriate for full NSF review. One potential mechanism for substantially augmenting post-cruise science would be to establish a new U.S. science support program, funded as part of the overall U.S. drilling effort. All proposals for this new program should be competitive and subject to full, NSF-style peer review. Rather than allocating a certain level of funding to each individual cruise, as with the more limited post-cruise funding provided by the existing JOI/USSSP program, proposals for such a new program should be objective-based, emphasizing potentially integrative contributions following the recovery of samples or expanding on the findings from previous drilling legs. Proposals would be evaluated for overall importance to the drilling program and also more generally as a contribution to the larger efforts of the scientific community.

Funding decisions for objective-based proposals would reflect the priorities for the science objectives of the successful drilling proposals, which should be considered as part of a program plan (similar to a RIDGE or MARGINS program plan). The national and international partners have made a substantial investment in obtaining these precious samples—and the scientific justification to acquire them in the first place has been thoroughly vetted through the leg-selection process. It thus is consistent to provide adequate support to work on the samples after they have been obtained. These objective-based proposals would seek funds to meet the scientific objectives of the drilling legs but would not be restricted to core samples, as they might involve substantial modeling studies, multi-leg components, syntheses, and so on. Funds could be administered through NSF-MGS, would be peer-reviewed in normal NSF fashion, and decisions for new awards could be made on an annual or semi-annual basis.

Recommendation: Establish a larger pool of post-cruise funding for cruise-related science to meet the needs of shipboard participants as well as the broader scope priorities established for fundamental scientific objectives that emphasize post-cruise activities beyond the immediate core analyses. In addition to continuing a system of small "pilot project" grants that are cruise-specific, we recommend creating a new system of objective-based science support to provide opportunities for more detailed investigations, integrative studies, modeling, and *in situ* or long-term experiments and observations.

Conclusion

The participants profited greatly from the collegiality at the workshop and the ability for open exchange and discussion of common interests uniting the broad subdisciplines of geochemistry. While it is clear that the IODP offers great opportunities for advanced geochemical study, it is equally clear that the geochemical community must continue to articulate its needs through the statement of a common vision, so as to capitalize upon the central role geochemistry plays in scientific ocean drilling. Regardless of subspecialty, the geochemists present at the workshop readily identified the unifying needs of the community, and were encouraged and optimistic about the potential for increased capabilities and scientific sophistication in the IODP. This report provides the basis for future geochemical successes by emphasizing the scientific objectives of prime interest to geochemists and providing specific recommendations for the future program.

Figure 12. Earl Davis, Keir Becker, Geoff Wheat, and Bill Rhinehart attaching OsmoSampler to bottom of cable during initial stages of deployment on ODP Leg 168 (Juan de Fuca Ridge). The OsmoSampler was deployed for three years. Upon recovery, the sampler yielded weekly fluid samples, thus providing a unique time-series of the chemical composition of formation fluids in an open borehole. These data are used to assess the rate of seawater flow within the upper permeable basaltic basement and to constrain the composition of formation fluids. Determining the composition of these fluids has been a long-term goal of DSDP and ODP and is critical to our understanding of crustal alteration and evolution. An amazing result from this work is that even after three years, the hydrologic system has not recovered from drilling operations. Photo courtesy of Keir Becker, University of Miami.

Appendix 1: Participants

Conveners

Richard W. Murray	Boston University
Daniel P. Schrag	Harvard University
C. Geoff Wheat	University of Alaska, Fairbanks

Focus Group Coordinators

Paul Baker	Duke University
Louis Derry	Cornell University
Gerald Dickens	Rice University
John Hayes	Woods Hole Oceanographic Institution
Julie Morris	Washington University
James Natland	RSMAS, University of Miami
Adina Paytan	Stanford University
David Smith	GSO, University of Rhode Island
Damon Teagle	Southampton, United Kingdom

Workshop Participants

Mark Altabet	University of Massachusetts, Dartmouth
Wolfgang Bach	Woods Hole Oceanographic Institution
David Burdige	Old Dominion University
Colleen Cavanaugh	Harvard University
George Claypool	Independent Consultant
Paul Dauphin	National Science Foundation
Eric De Carlo	University of Hawaii
Margaret Delaney	University of California, Santa Cruz
Steven D'Hondt	GSO, University of Rhode Island
Katrina Edwards	Woods Hole Oceanographic Institution
Gabriel Filippelli	Indiana U./Purdue U., Indianapolis
Frederick Frey	Massachusetts Institution of Technology
Lisa Gilbert	University of Washington
David Goldberg	Lamont Doherty Earth Observatory
Barry Hannan	San Diego State University
Stanley Hart	Woods Hole Oceanographic Institution
Sidney Hemming	Lamont Doherty Earth Observatory
Gideon Henderson	Oxford University, United Kingdom
Timothy Herbert	Brown University
Matthew Higginson	U. of Massachusetts, Dartmouth
Rachael James	Open University, United Kingdom
Miriam Kastner	Scripps Institution of Oceanography
Lee Kump	Pennsylvania State University
Susan Lang	University of Washington
Braddock Linsley	State University of New York, Albany
Mitchell Malone	ODP, Texas A&M University
Kevin Mandernack	Colorado School of Mines
Scott McLennan	State U. of New York, Stony Brook
Phillip Meyers	University of Michigan
Bernhard Peucker-Ehrenbrink	Woods Hole Ocean. Inst.
Terry Plank	Boston University
Vincent Salters	Florida State University
Frank Sansone	University of Hawaii
Kathleen Scott	Harvard University
Arthur Spivack	GSO, University of Rhode Island
Peter Swart	RSMAS, University of Miami
Marta Torres	Oregon State University
Karen Von Damm	University of New Hampshire
Kuo-Yen Wei	National Taiwan University
David Wray	Greenwich, United Kingdom

Appendix 2: Agenda

Boston University Corporate Education Center
Tyngsboro, MA; October 12-13, 2000

Thursday, October 12

Introduction

9:00.......Welcoming Remarks: Rick Murray
Goals and Orientation of Workshop: Rick Murray, Dan Schrag
New Program Overviews: Rick Murray
Comments from NSF: Paul Dauphin
Instrumentation & Technology: Geoff Wheat

Sequential Plenary Sessions: The State of the Art

10:00 ......Formation/Alteration of Ocean Crust: Julie Morris, Jim Natland, Damon Teagle
10:30 ......Sediments, Porewaters, and Chemical Paleoceanography: Paul Baker, Lou Derry, Adina Paytan
11:00 ......Biogeochemistry and Microbiology: John Hayes and David Smith
11:30 ......Borehole Instrumentation: David Goldberg
12:00 ......Lunch
1:00.......Breakout Focus Groups
5:00.......Refreshments and dinner

Friday, October 13

8:30.......Breakout Groups
12:00 ......Lunch
1:00.......Plenary Session: Reporting of Breakout Sessions
3:00.......Funding, Logistics, Planning
5:00.......End of Workshop

Back cover:
Top. The Deep Sea Drilling Project's drillship, *Glomar Challenger*. From 1968 until 1983, during 96 drilling legs, the ship traveled over 600,000 km and collected more than 97 kilometers of core. Photo from the Deep Sea Drilling Project archive.
Bottom. H.M.S. *Challenger* sailed from Portsmouth, England on December 21, 1872. During the four-year round the world expedition, physicists, chemists, and biologists collaborated with expert navigators to map the sea. Figure from: "*The Voyage of the H.M.S. Challenger, A Summary,*" Second Part, Library Call Number Q115.C4, 1880 Summary, pt. 2.

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