HYDROGEOLOGY OF THE OCEANIC LITHOSPHERE

Report of a Workshop Co-Sponsored by:

Joint Oceanographic Institutions/U.S. Science Support Program

and the International Lithosphere Program

(JOI/USSSP and ILP)

The University of California, Santa Cruz, USA
December 11 and 12, 1998

HYDROGEOLOGY OF THE OCEANIC LITHOSPHERE

A Workshop Convened by

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Hosted by Andrew T. Fisher at
University of California, Santa Cruz, USA
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WORKSHOP CONCLUSIONS AND SUMMARY RECOMMENDATIONS

- Significant advances have been made recently in approaching the overall goal of understanding the history of mass and heat transport through the oceanic crust.

- The most useful work has involved truly inter-disciplinary studies including geochemistry, geophysics, numerical modeling, and long-term observatories.

- Recent advances underscore both the pivotal role played by scientific ocean drilling in providing in-situ samples and experimental capabilities as well as the emerging importance of including microbiology in crustal hydrogeological studies.

- Future work must be truly inter-disciplinary (i.e., spanning fields from microbiology to geophysics), and should generally focus on two approaches: (1) detailed studies at a few select sites to understand ocean crustal hydrogeological processes well, and (2) efficient reconnaissance surveys in "representative" but poorly understood settings, particularly in older ocean basin environments, to assess the levels of hydrologic activity and hence to improve quantitative estimates of global fluxes.

- The sampling and long-term subseafloor observatory capabilities represented in scientific ocean drilling are crucial to these future objectives. It is our hope that this report will be useful in planning hydrogeological drilling objectives in the ridge flank and ocean basin environments.

1. INTRODUCTION

We convened an international workshop on the hydrogeology of the oceanic lithosphere on December 11 and 12, 1998, at the University of California, Santa Cruz, with co-sponsorship from JOI/USSSP (Joint Oceanographic Institutions/U.S. Science Support Program) and the ILP (International Lithosphere Program). The objectives of the workshop were to review present knowledge and articulate plans for future work on the hydrogeology of the ridge flanks and ocean basins that represent the majority of the Earth's surface. Spreading center and subduction zone hydrogeology are also very important, but were not included in the scope of this workshop, as they are well-developed foci of the RIDGE and MARGINS programs and their international counterparts. We concentrated on the ridge flanks, which are generally accepted to host by far the greatest proportion of total fluid fluxes through the seafloor yet remain relatively under-studied (Figure 1). Given present technology, ridge flanks also represent the best opportunities to utilize ocean drilling for hydrogeological experiments in the oceanic crust.

The workshop was attended by a diverse group of 45 international geoscientists representing disciplines such as geophysics, geochemistry, petrology, alteration, continental and submarine hydrogeology, and microbiology. The first day of the workshop began with invited presentations summarizing the state of our understanding in these fields, and then moved on to open, panel-led discussions of unresolved and new problems in ocean crustal hydrogeology. The second day began with presentations of the contributions from modeling studies and long-term borehole and seafloor observatories, then moved to discussions of poorly explored environments, new tools and techniques, and new possibilities for multi-disciplinary experiments in the future.

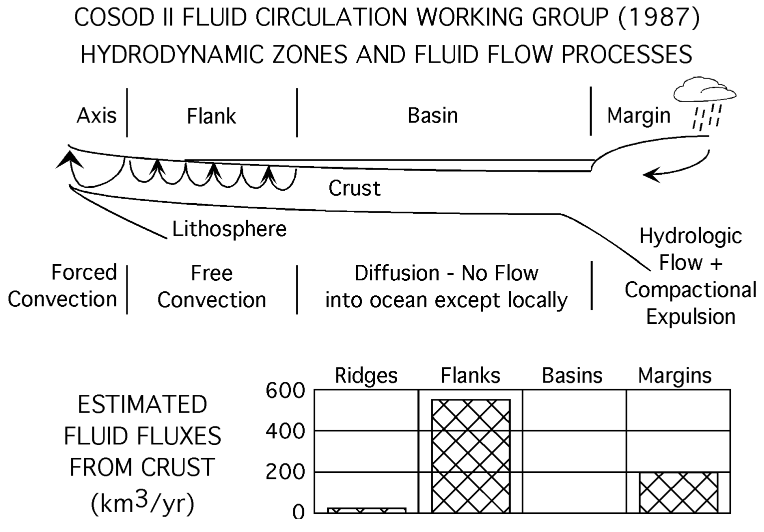

Figure 1. Cartoon of fluid flow regimes in oceanic lithosphere and estimated crustal fluid fluxes. Modified from COSOD II Report (1987).

The agenda for the workshop is reproduced in section 8. Workshop attendees (listed in section 9) participated freely and actively in all the discussions, which were illuminating and fruitful. This report is not meant as a complete record of all presentations and discussions, but instead represents the co-convenors' best summary of the discussions and conclusions of the workshop. Similarly, while we have drawn on a few representative, classical references and figures in this report, we have not attempted to assemble either a complete bibliography or a thorough review of the many recent developments. Those are included among the objectives of an AGU Monograph currently being planned as a result of the workshop.

2. HISTORICAL PERSPECTIVE

While the significance of the hydrogeology of the oceanic crust was first made evident from reconnaissance geological and geophysical surveys through much of the ocean basins, the greatest advances in our understanding have undoubtedly arisen from detailed studies at selected "type examples". Most of these well-studied examples share one important characteristic - relatively thick sediment cover at a relatively young crustal age. This readily allows both detailed spatial mapping of the surface expressions of sub seafloor hydrogeology via standard techniques such as heat flow and coring, as well as access to the sub-seafloor via scientific boreholes for sediment and basement cores, logging and downhole measurements, and most recently, long-term in-situ experiments. The most important type-examples include the following, arranged somewhat in historical order:

2.1. The Juan de Fuca Ridge

The northernmost segment and eastern flank of the Juan de Fuca Ridge (JFR) are covered by thick turbidites shed from the nearby North American continental margin. Here, detailed heat flow surveys dating back to around 1970 (Lister, 1972; Davis and Lister, 1977) revealed the strong influence of fluid circulation and inspired some of the seminal concepts of hydrothermal circulation in oceanic crust (Figure 2). The importance of co-located seismic surveying was firmly established here in understanding the influence of basement and basement structure on hydrothermal processes (e.g., Davis et al., 1989, 1992; Section 4 below). Reconnaissance and detailed surveying has been carried out nearly continuously in the past two decades, focusing more and more on two key type-examples: a) the sedimented spreading segment at Middle Valley, now the best-surveyed example of a sedimented spreading center; and b) the well-sedimented eastern flank of the Endeavour segment, where several classical type-settings in terms of sediment-covered basement topography have been exceptionally well documented (Davis et al., 1989, 1996). Investigations at both sites have also included ODP drilling, logging, and long-term hydrological observatories (Legs 139, 168, and 169). Recent results from both detailed surveys and borehole studies at these locations figure prominently in the summary of topics and issues below.

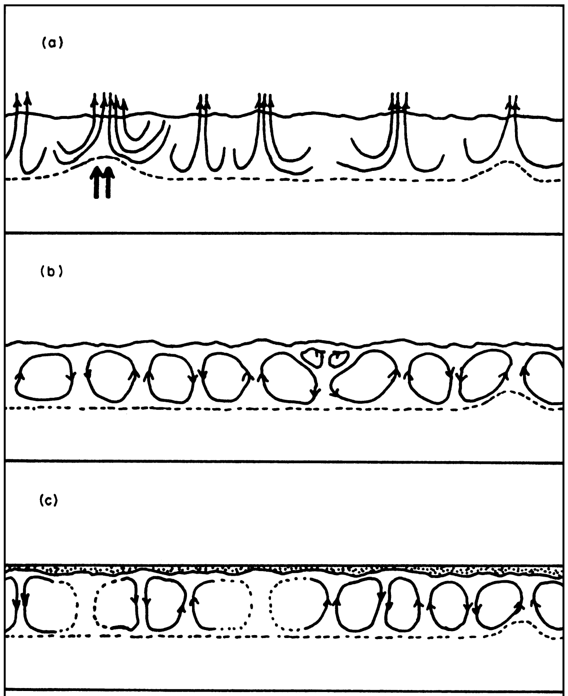

Figure 2. Lister (1972) conceptual cartoon for patterns of convection for three type settings in oceanic crust: (a) bare-rock ridge crest and nearby flank, (b) thin, impermeable sediments (not shown) overlying basement topography, (c) thick, impermeable, flat-lying sediments overlying basement topgraphy.

2.2. The southern flank of the Galapagos Spreading Center

On the southern flank of the Galapagos Spreading Center (GSC) at 86°W, pelagic sedimentation rates are very high, and detailed heat flow transects on young crust in the 1970's (e.g., Williams et al., 1974; Green et al., 1981) revealed that average seafloor heat flow reached values predicted for conductive cooling of the lithosphere at a very young age, ca. 1 Ma. These surveys also revealed a regular, sinusoidal variation with a similar wavelength to that of the underlying basement topography (Figure 3). These observations inspired an influential set of numerical simulations of the cellular hydrothermal circulation system in young ridge flanks (Fehn et al., 1983), with depths of circulation approaching the heat flow wavelength. This segment was also the site of the first discoveries of axial venting, albeit low-temperature, as well as the best example of off-axis hydrothermal precipitate mounds. These were investigated with deep-tow surveys, submersible surveys, piston-coring, and the Deep Sea Drilling Project (Legs 54 and 70). Profiles of pore water chemistries and in-situ temperatures determined on both piston cores and DSDP cores from the mound field show curvatures characteristic of both recharge and discharge through the sediments (Maris and Bender, 1982; Becker and Von Herzen, 1983). Since Leg 70 in 1979, there has been surprisingly little additional work done in this classic example of an off-axis hydrothermal system.

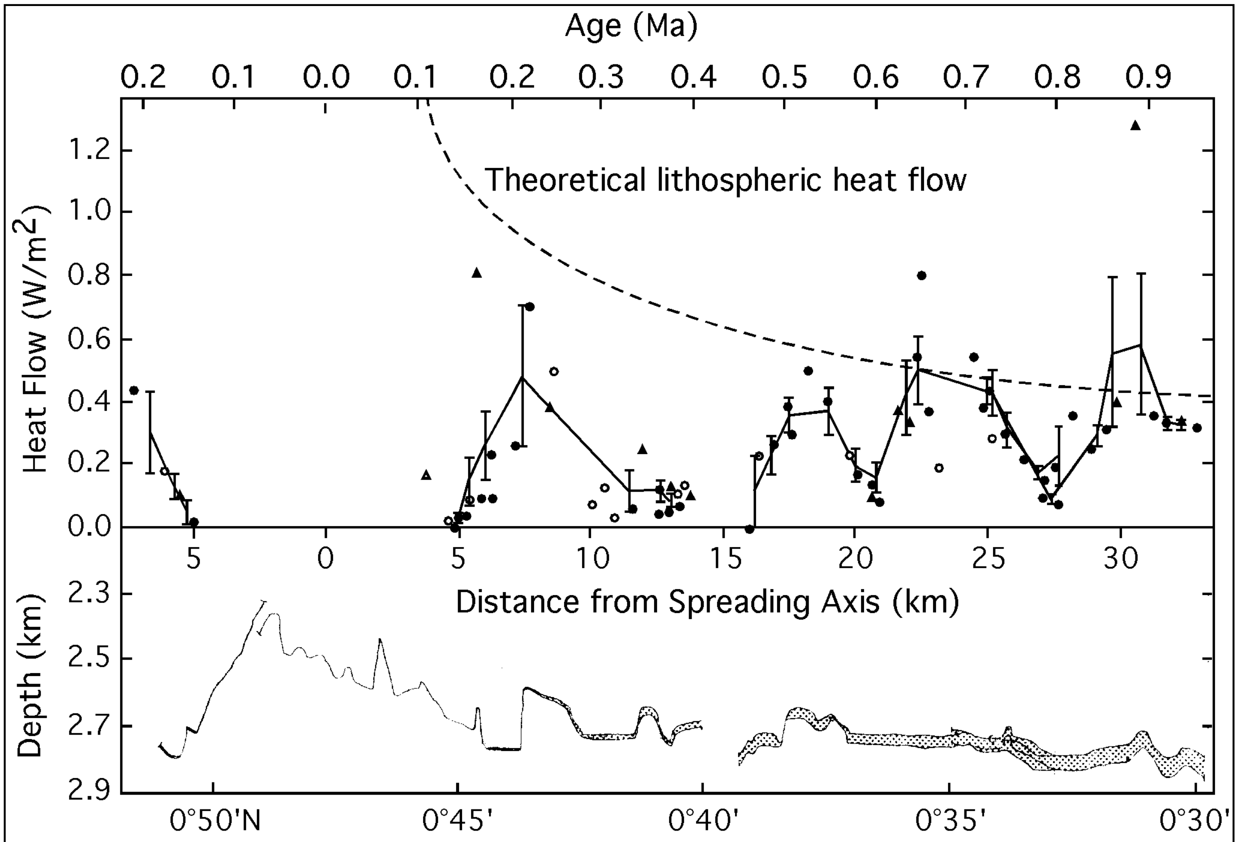

Figure 3. N-S profile of heat flow, topography, and sediment thickness on the southern flank of the GSC at 86°W, modified from Williams et al. (1974). On the heat flow profile, closed symbols are located within 2 km of profile; open symbols are farther away. The solid line connects 2-km running averages of heat flow plotted every km along the profile.

2.3. The southern flank of the Costa Rica Rift

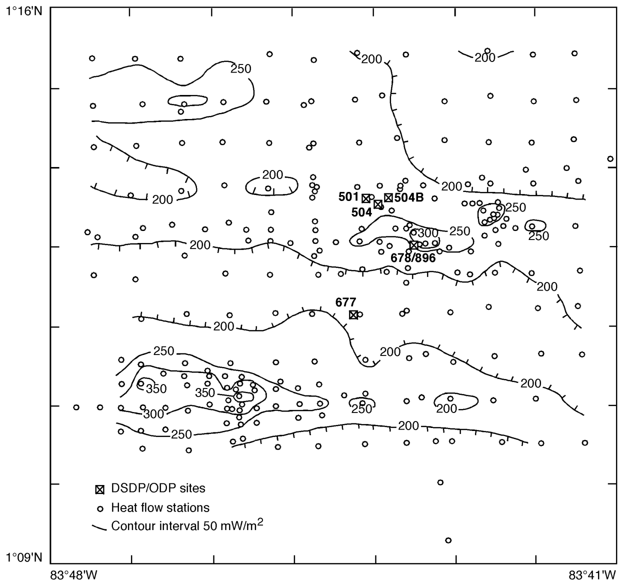

Figure 4. Detailed heat flow survey (Langseth et al., 1988) and locations of DSDP/ODP sites on the southern flank of the Costa Rica Rift.

On the southern flank of the Costa Rica Rift (CRR), pelagic sedimentation rates are nearly as high as at GSC and a detailed heat flow transect in the 1970's revealed that the measured heat flow also reaches the predicted value at a young crustal age, ca. 6 Ma (Langseth et al., 1983). Based on these hydrogeological survey results, it was surmised that the upper crust would be altered enough to be cored more easily than young crust elsewhere, and a DSDP site was spudded in 1979 for upper crustal hydrogeological studies - a hole that fortuitously became the deepest DSDP/ODP penetration into oceanic crust by far, Hole 504B. The multiple drilling revisits (Legs 69, 70, 83, 92, 111, 137, 140, and 148) have produced a wealth of reference information on the chemical and physical state of the upper crust, and have also inspired several return heat flow, coring, and seismic surveys, as well as complementary drill sites nearby (Figure 4). Profiles of sediment pore fluid chemistries indicate upwelling through 170 m of sediment above the basement high at Site 678 and downwelling through 310 m of sediment above the basement low at Site 677 (Mottl, 1989). Downhole experiments in Hole 504B still provide the most influential reference for the variation of porosity and permeability with depth in the oceanic crust (Figure 5), and their relationship to seismic properties. For example, the results suggest a correspondence between seismic layer 2A and the most permeable section of upper basement (e.g., Becker et al., 1989), a relationship that is now applied in other settings to infer subsurface hydrologic structure from seismic surveys. Another important example is the correlation of the seismic layer 2/3 boundary not with a lithologic boundary, but instead with porosity and alteration (Detrick et al., 1994). The strong decrease in permeability and porosity with depth in 504B is considerably different than the permeability structure used in early GSC-inspired numerical simulations, and has figured prominently in a revival of numerical models of off-axis circulations also inspired by JFR results (e.g., Fisher et al., 1990, 1994).

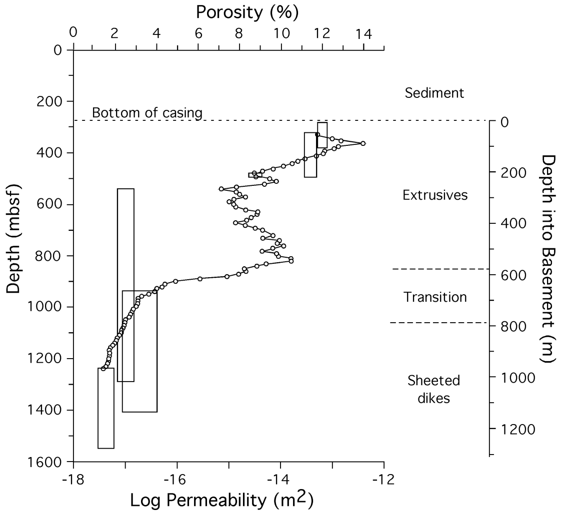

Figure 5. Depth profiles of bulk permeability and apparent porosity from resistivity in Hole 504B (Becker et al., 1989).

2.4. Young crust formed at slow spreading rates

In crust formed at slow spreading rates, basement topography is generally very pronounced, and the typical off-axis hydrogeological setting comprises isolated sediment ponds surrounded by extensive basement exposures. The best surveyed example is North Pond, in 7 Ma crust on the west flank of the mid-Atlantic Ridge. This is the setting of Hole 395A, another key reference hole in upper oceanic crust, which has been revisited by DSDP and ODP several times (Legs 78B, 109, 174B) for a suite of logging and downhole measurements almost as complete as in Hole 504B, as well as a long-term hydrological observatory currently in operation. Long after the hole was drilled, a detailed heat flow survey (Langseth et al., 1992) was conducted over the full expanse of the sediment pond (approx 6 x 15 km). The results, in combination with borehole measurements, suggest vigorous single-pass flow of ocean bottom water through the permeable upper basement that underlies the less permeable sediments (Figure 6; Langseth et al., 1984).

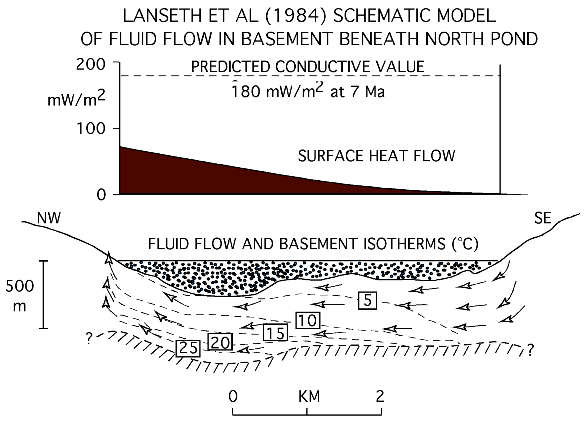

Figure 6. Conceptual model of fluid flow in basement beneath North Pond and resultant surface heat flow (Langseth et al., 1984).

2.5. The eastern equatorial Pacific

The regional heat flow low beneath the thick carbonate sediments in the eastern equatorial Pacific was one of the most striking and laterally extensive anomalies mapped in early reconnaissance heat flow surveys (Sclater et al., 1976). Explaining such an anomaly seemed to require fluid flow in crust older than the examples above, but follow-up heat flow surveys and coring did not show coherent variations on the spatial scales suggested by the examples above. Geochemistry of pore waters from cores collected from the region showed basement pore fluid compositions similar to bottom water (Figure 7) and finally suggested the explanation -- lateral flow in basement at regional scales comparable to the size of the anomaly (Baker et al., 1991). This example is discussed in more in the geochemistry section below. As detailed evidence for laterally extensive basement fluid flow in the younger type-examples has accumulated, this explanation has become more accepted despite the great scales of circulation required.

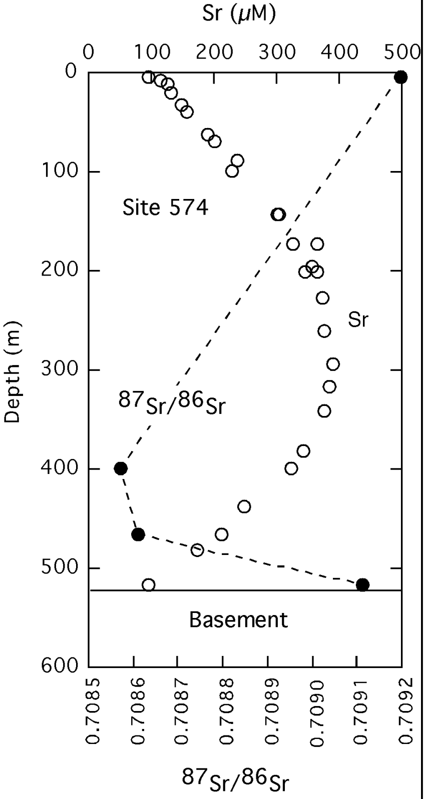

Figure 7 (right). Strontium concentrations and isotope ratios in pore fluids from DSDP Site 574 (after Baker et al., 1991).

2.6. Middle-aged and old crust

In contrast to young seafloor environments, few detailed studies have been carried out in crust older than 10 Ma. Most inferences concerning the magnitude of hydrothermal heat and chemical fluxes in such settings have been made on the basis of relatively widely spaced heat-flow observations and core samples, and with modest to poor control from seismic reflection data. Most studies in old areas have been carried out to determine regional average lithospheric heat flow, not to study crustal fluid flow. In fact, effects of fluid flow were to be avoided at all costs in many of these cases. However, instances of locally anomalous values of heat flow (i.e., values that cannot be accounted for by bottom water temperature transients, sedimentation effects, or conductive focusing of heat through heterogeneous structure) occur with surprising frequency. Some important examples include 18-55 Ma Indian Ocean crust (Anderson et al., 1977, 1979), 20 Ma Brazil Basin crust (Langseth and Herman, 1981), and 80 Ma northwest Atlantic crust (Embley et al., 1983; Figure 8). While these anomalies are often subtle, their presence, even in seafloor of Cretaceous or Jurassic age, warrants further investigation. Just as in younger settings, the anomalies are often associated with seamounts or other crustal structures that are thinly buried by sediment or exposed in outcrop. The possibility of significant fluid flow in old ocean basins is also supported by high measured permeability in a borehole drilled into the upper crust of the oldest ocean basin in the Pacific (Larson et al., 1993).

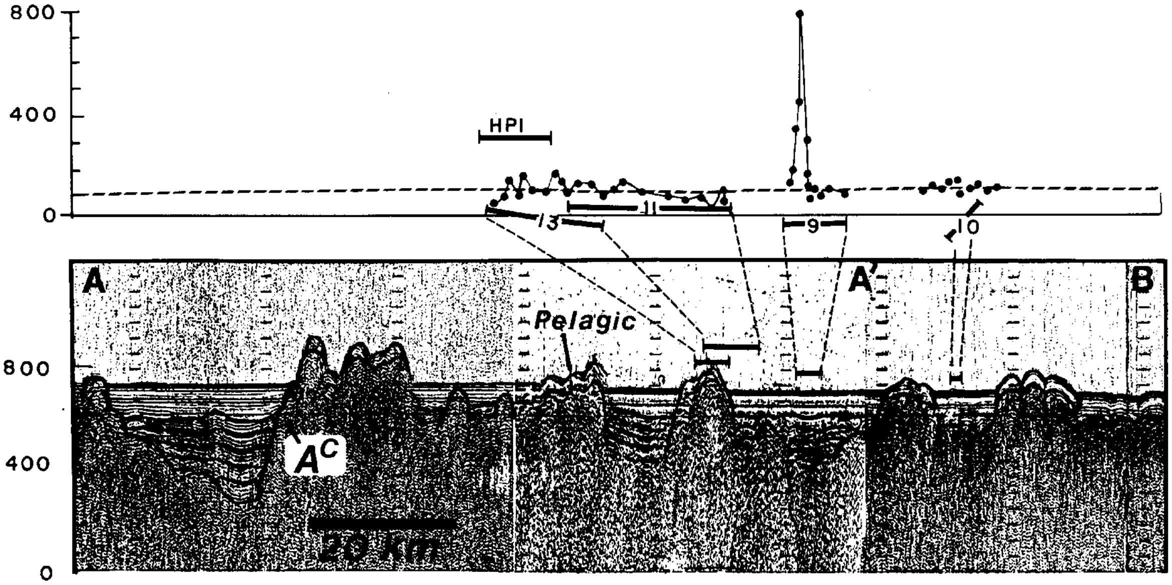

Figure 8. West-to-east heat flow and airgun seismic profiles across the eastern Nares abyssal plain , from Embley et al (1983). The sharp heat flow high of profile 9 occurs at a domed feature interpreted as a volcanic structure that focuses fluid flow from basement.

3. GEOCHEMISTRY

About the time that geophysicists noted the important contribution from the ridge flanks to the global heat loss inventory, geochemists surmised that reactions between seawater and the oceanic crust were required to balance global geochemical budgets (Garrels and Mackenzie, 1971). These reactions include early diagenetic reactions that occur in the upper few meters of the sediment column (e.g., Sayles, 1979) as well as chemical exchange in basaltic basement (e.g., McDuff, 1981). In each case the geologic setting supported only diffusion as the mode of chemical transport between the crust and the oceans. The potential effects of advective transport on global geochemical budgets were not quantified until Edmond et al. (1979) published their calculations for hydrothermally advected chemical fluxes from mid-ocean ridge axes. These calculations spawned the idea that chemical fluxes from advective hydrothermal transport on ridge flanks may be important to global cycles, because much of the global advective heat loss occurs on the flanks at a much lower temperature than on the axis. Thus the mass flux of seawater through the flanks is much greater than that through the ridges so that even a small chemical anomaly in hydrothermal fluids from the flanks could result in a significant global geochemical flux. At present the magnitude of these chemical fluxes is unknown, but geochemists are approaching the problem by either examining products of crustal alteration (e.g., Thompson, 1983) or systematic changes in the composition of crustal fluids (e.g., Mottl and Wheat, 1994, Elderfield et al., 1999; Figure 9 after Davis, Fisher, et al., 1997).

Geochemistry can be used to study hydrogeologic processes using two approaches. One is through observations of altered solid phases (the aquifer) as a way to understand flow paths, hydrologic variables, and mass fluxes between the crust and seawater. The second approach is through observations of the fluid phases (liquids and gases) as a way to map flow paths and estimate rates of flow. Chemical alteration of the fluids is often a more sensitive indicator of the extent of fluid-solid reactions than alteration of the solid because the concentrations of most elements are lower in the fluid than in the solid phases, but mass balance calculations require information on both fluid and solid compositions. Chemical and mineralogical alteration of solid phases directly influences hydrogeology, however, through its control of fundamental hydrological variables such as porosity and permeability.

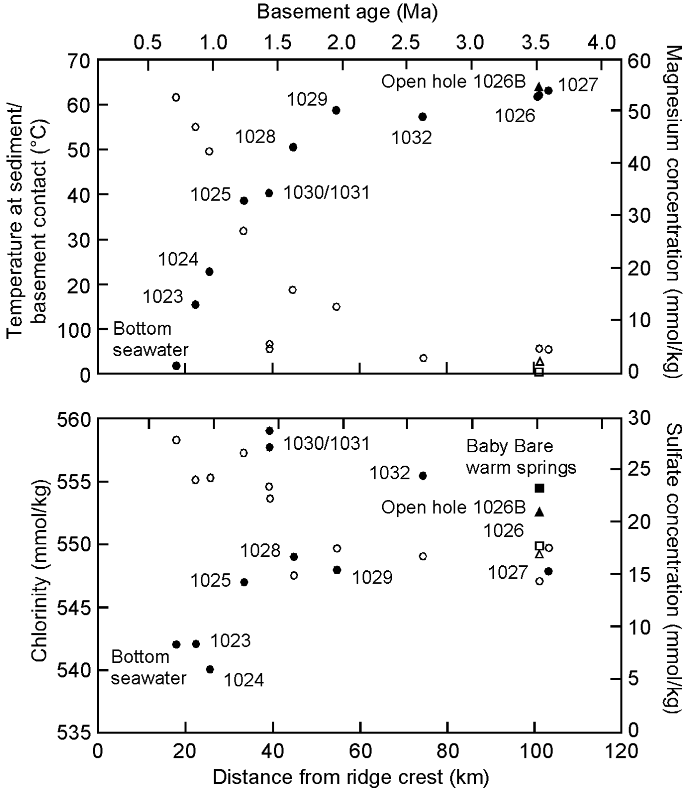

Figure 9. Variations of basement temperatures and pore-water compositions at Leg 168 sites on the east flank of the Endeavour segment, Juan de Fuca Ridge. Solid symbols are temperatures in upper plot, chlorinity values in lower plot.

Geochemistry provides a powerful tool to study the ties between microbiology, hydrogeology, and geology. These sub-disciplines are linked by inorganic and microbially-mediated reactions that can alter chemical compositions of fluids and the chemical and mineralogical compositions of solids. Ocean drilling has shown that microbes can live in a wide range of environments in the ocean crust and to depths of hundreds of meters within ocean bottom sediments. Both microbial and non-microbial reactions change the chemical composition of fluids and alter rock and sediment compositions and mineralogies. Such reactions have been observed as variations in sedimentary pore water compositions for decades (Claypool and Kaplan, 1974), and recent evidence has also been found for extensive microbial alteration of volcanic rocks (e.g., Fisk et al., 1998). Conversely, fluid, rock and sediment compositions may control the distributions of microbial species and their ecology. Deviations from seawater values of the chemical compositions of fluids can provide valuable information on the types of reactions including microbially mediated and non-microbial reactions that might have occurred. By understanding the thermodynamic conditions (temperature, pressure, and compositions) required for these reactions, it is possible to identify the origins of the fluids. Variations in fluid compositions thus can provide natural chemical tracers for fluid pathways.

3.1. Fluid Chemistry

Chemical and isotopic tracers of fluid flow can be divided into several broad categories depending on the chemistry of the fluid-solid reactions, the solutes involved, and the extent of changes of the solute concentrations. During the workshop, the geochemistry of many of these tracers were discussed in terms of their early contributions to understanding hydrogeology of the oceanic lithosphere and how they may be useful for future studies. Certain elements, such as Mg, Ca, and Sr are sensitive to basalt-seawater interaction, and the combination of changes in Sr concentrations and isotope ratios can be used to quantify the extent of alteration of basaltic crust and resulting mass fluxes between crust and seawater. Other elements (e.g. Cl, Br) are commonly assumed to behave conservatively in reactions between basalt and seawater. If these elements are conservative, changes in their concentrations can be used to determine mixing proportions between various water sources. Recent measurements of Br/Cl ratios in pore water trapped in volcaniclastic sediments and deviations from seawater values of Cl isotope ratios indicate that these elements may take part in reactions involving volcanic material (Magenheim et al., 1995; Ransom et al., 1995; Martin, 1999). These reactions can provide new tools to look at the reactions and new tracers for flow.

Some dissolved components (SO_4, NO_3, H_2S) are sensitive to reactions involving organic matter and are important tracers of fluid-solid reactions and/or flow paths within the sedimentary section of the ocean crust. These components are largely controlled by microbial reactions and thus changes in their concentrations can be used to identify regions and extent of microbial activity. The alteration of organic matter within sedimentary sections, whether caused by thermal degradation or by microbially-mediated reactions can generate overpressured zones because of the volume expansion associated with the conversion from solid to liquid or gaseous hydrocarbons (Bredehoeft et al., 1994; Martin et al., 1997). Overpressure has important implications for hydrogeology including providing a driving force for fluid flow, changing the rheology of sediments, varying the porosity structure, and increasing permeability through hydrofracturing.

Reactive solutes have also been used to document large-scale convection within the well-sedimented basaltic crust of the eastern equatorial Pacific (Baker et al., 1991). Although diagenetic alteration changes the Ca, Mg, Sr, and SO_4 concentrations and $^{87}Sr/^{86}Sr$ ratio in pore water of the sedimentary section from seawater values, the composition of pore water at the sediment-basalt interface returns to modern seawater values (Figure 7). The observed compositional profiles indicate that flow velocities are on the order of 1 to 10 m/yr through the basement rocks, although the calculations require numerous assumptions including the locations of discharge and recharge.

Distribution of some radioactive elements provides chronometers as well as tracers for fluid origins. Concentrations of noble gases may be used to trace flow paths. Radiocarbon dating may be used to define fluid ages. Uranium series isotopes and tritium are also used for these purposes. For example, ^{226}Ra activities have been used to estimate groundwater fluxes to the South Atlantic Bight (Moore, 1996) and radium could be useful in other sedimented marine settings. The radium isotope quartet (^{223}Ra, ^{224}Ra, ^{226}Ra, and ^{228}Ra) provides four isotopes with half lives ranging from 3 days to 1600 years. Ratios of these isotopes could provide constraints on the length of time and extent of fluid vented from sedimentary sections.

Another class of fluid-solid reactions that is linked to flow involves gas hydrates, an ephemeral solid phase formed of gas molecules surrounded by a solid cage of water molecules. Dissociation of gas hydrate releases large volumes of gas, thereby generating excess pressures, similar to the microbial and thermal degradation of solid organic matter. Gas hydrates are largely confined to thick sedimentary sections which are rich in organic matter, and are thus unlikely to be common on ridge flanks. Other regions with thick sedimentary sections, particularly along continental margins could be important locations of gas hydrates.

3.2. Crustal Alteration

The fluid chemical composition of hydrothermal vent fluids provides some information about mass fluxes from the crust to the oceans but they may not provide information about the flux of mass from seawater to the crust. Diffuse low temperature flow could also contribute significantly to crustal alteration, but the extent and distribution of this flow mechanism is poorly constrained. Recent evidence also suggests that much of the alteration in the shallow portions of the crust depends on microbial activities. Crustal alteration is heterogeneously distributed and difficult to observe, however, because current drilling techniques recover only a small fraction of the drilled material. Volcanic glass tends to make up the most altered material but commonly is poorly recovered in drill cores. Compositions of both altered and unaltered glass are required to calculate the extent of alteration during seawater-basalt reactions. The depth of this alteration and the extent of the alteration at great depths requires better recoveries of material.

The type of crustal alteration provides information about the distribution and timing of flow. The distribution of alteration products (e.g. celadonite and other clay minerals, micas, oxyhydroxides, pyrite, carbonate vein minerals) reflect the distribution of oxidation/reduction reactions in the crust (Figure 10). The intensity of the alteration indicates at an order of magnitude scale the volume of water required to generate the alteration of the crust. These solid interactions provide an integrated picture of flow that when coupled with the instantaneous picture from fluid compositions can perhaps constrain the evolution of the entire hydrogeologic systems.

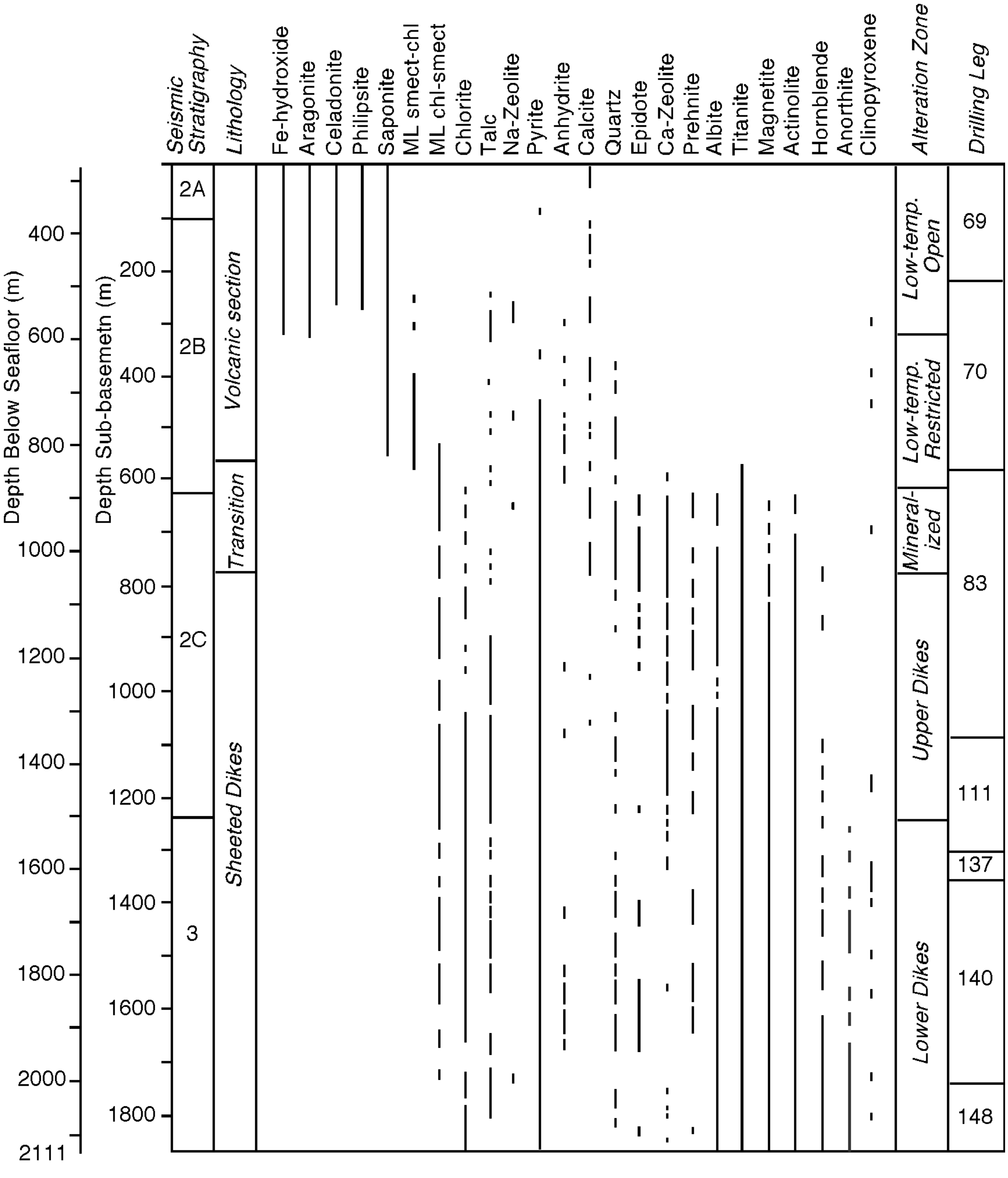

Figure 10. Lithostratigraphy and distribution of alteration mineralogy in Hole 504B, after Alt et al. (1996).

4. ISSUES, THEMES, AND PROBLEMS

A working model of crustal hydrothermal circulation emerged 30 years ago to explain the large scatter in marine heat flow observations, and the discrepancy between average seafloor heat flow at a given age and that expected from the cooling of oceanic lithosphere. The model involves flow hosted by the permeable part of the igneous oceanic crust (Lister, 1972). In young areas, water is exchanged freely between the crust and the oceans. This exchange is progressively inhibited with the accumulation of low permeability sediments, and the circulation internal to the crust is retarded by mineralization that accumulates in fractures and voids as a result of the fluid circulation. (The word "sealing" has been used in the literature in reference to both of these independent processes). This model is consistent with a wide variety of observations, although much work is required to improve the quantification of a number of its primary aspects.

4.1. Distribution and nature of crustal flow

Marine hydrogeological studies in the last two decades, and particularly in the last 10 years, indicate that fluid flow in basement over distances of kilometers to tens of kilometers is common. That the pattern of measured (conductive) heat flow on ridge flanks is often well below expected values until the crust reaches an age of about 65 Ma (Figure 11; Anderson et al., 1977; Stein and Stein, 1984) is robust evidence that large amounts of fluid must move through basement at velocities on the order of meters per year or more within much of the seafloor. As noted above, in some old crustal settings, heat flow surveys have revealed variations, often correlated with basement relief, that seem to require significant fluid flow in oceanic basement continuing out to great ages. Borehole packer measurements in Jurassic basement, some of the oldest remaining in-situ oceanic crust, indicate permeabilities similar to those measured in 3.5 to 7 Ma crust in other areas.

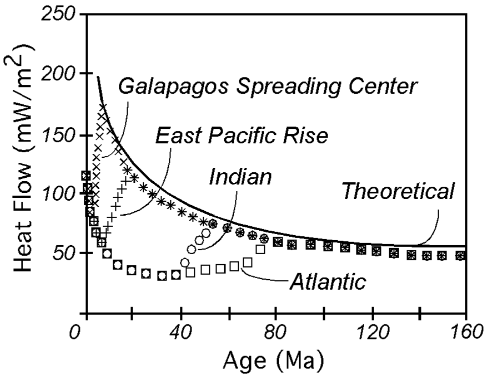

Figure 11. Composite of average heat flow versus age for mid-ocean ridges, after Anderson et al. (1977).

Ubiquitous, high-velocity fluid flow within oceanic basement that is buried beneath a nearly continuous blanket of low-permeability sediments requires that the lateral scales of flow in basement extend to tens of kilometers or more in many cases. The driving forces available to move fluids laterally within oceanic basement on ridge flanks appear to be limited to pressure differences between warm and cool columns of hydrothermal fluid, and this also requires that effective basement permeabilities be relatively high. Resolving the depth-scales of flow within basement of ridge flanks is difficult; deeper flows could be more efficient at "mining" heat from the crust, provided there are high-permeability pathways that allow discharge and recharge, but the small number of vertical boreholes that have penetrated into crust below the upper extrusive layers suggest that bulk permeabilities are relatively low. New technologies and experiments will be required to resolve the depth distribution of permeability in oceanic basement and its variation with scale.

4.2. Roles of sediment cover and basement topography

Numerous studies of oceanic sediment permeability have demonstrated that, although this property is highly variable, sediments tend to have permeabilities that are one to several orders of magnitude less than that of upper oceanic basement. Sediments tend to lose permeability with increasing depth of burial, although thin layers of sediments may retain near-seafloor permeabilities until several tens of meters have accumulated. Because the available driving forces are modest, even a few tens of meters of sediments are sufficient to reduce fluid discharge to levels that are below the thermal detection limit (millimeters per year or less). Seepage fluxes of mm/yr are sufficient to influence the chemistry of the fluid and surrounding sediment, but certainly comprise a tiny fraction of the total fluid flow that is required to pass through the crust to result in the observed suppression of heat flow.

Basement relief commonly correlates with observed parameters (e.g., Figure 12) and may play a critical role in ridge-flank hydrogeology in several ways. First, basement highs tend to accumulate sediments at a lower rate than do basement lows, particularly near continental margins where turbidites are common. Thus basement highs may remain "open" to fluid exchange for a much longer time than the surrounding seafloor. Second, basement relief is often associated with faulting at the edges of abyssal hills, and these faults are commonly associated with depressed or elevated heat flow, interpreted to indicate fluid recharge or discharge, respectively. Why some faults tend to focus recharge and others focus discharge is not well understood, but is the focus of ongoing field and numerical research. Finally, basement relief results in the formation of tilted boundaries at the top and within the basement "aquifer," inducing instability (essentially reducing the critical Rayleigh number required to initiate hydrothermal circulation to zero). Localized convection influenced by topography can homogenize basement temperatures and fluid chemistry, and may play a role in compartmentalizing hydrothermal flows in ridge flanks.

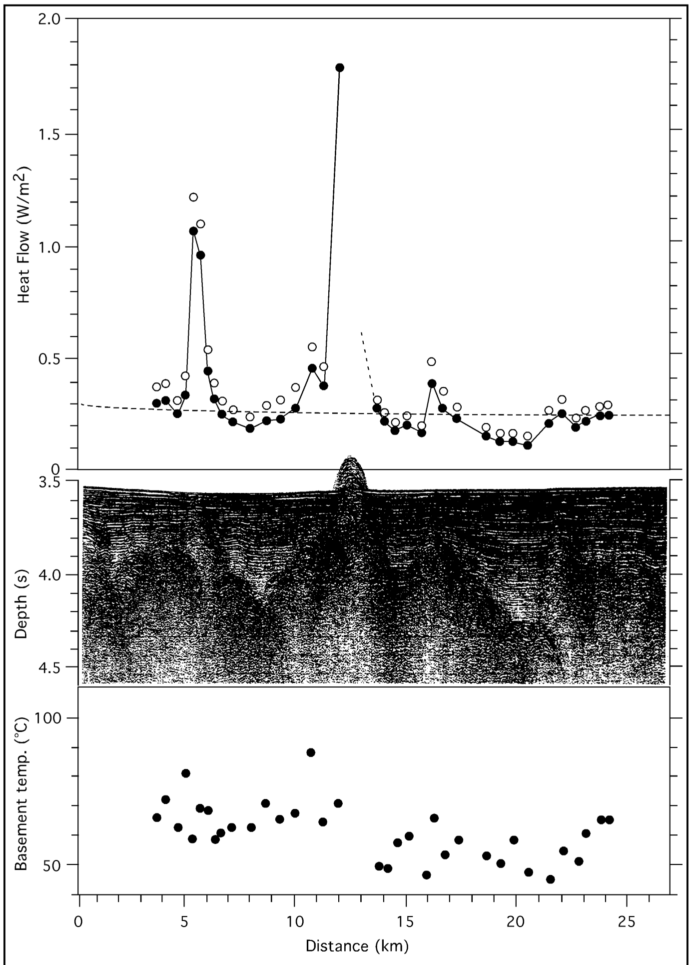

Figure 12. Heat flow and single-channel seismic profiles and estimated basement temperatures on a transect over a basement “permeable penetrator” on the sedimented flank of the Juan de Fuca Ridge. In the heat flow plot, solid circles are raw values, open circles are corrected for sedimentation, and the dashed line represents the theoretical lithospheric heat flow. After Davis et al. (1989).

4.3. Role of stratified basement permeability

High permeabilities (on the order of 10^{-13} m^2, or 0.1 Darcies or more) have been measured within upper oceanic crust in several settings, and the highest permeabilities have been measured where the youngest holes (close to 1.0 Ma) have been tested. But most of these measurements have been made in the upper 100-200 m of basement, and the tests have not allowed delineation of the vertical distribution of permeability with confidence, other than on a relatively gross scale through the sheeted dikes in Hole 504B. However, other indicators of crustal layering and heterogeneity (lithologic and alteration variations, cycles in resistivity logs, differences in the density of fractures) suggest that there may be distinct permeability compartments within oceanic crust. The vertical scales of compartmentalization have not been determined, but could be as small as several tens of meters.

4.4. Evolution of crust and hydrogeological systems

Recent compilations and surveys of seismic velocities in uppermost oceanic crust (Carlson, 1998; Grevemeyer et al., 1999) show a clear trend: velocity increases rapidly during the first few million years, then more slowly in older crust. Density calculations from near-bottom gravity measurements also show a rapid increase in the first 1 Ma (Holmes and Johnson, 1993), although wireline logs in older boreholes suggest only small additional increases with age. Until recently, borehole packer measurements were restricted to crustal ages <7 Ma and did not indicate any permeability evolution trend; instead, these data suggested a narrow range for uppermost oceanic basement, 10^{-13} to 10^{-14} m^2. Recent borehole measurements are now beginning to reveal a trend in permeability evolution within uppermost basaltic basement (Figure 13). Measured bulk permeability decreases rapidly as young crust ages, from about 10^{-10} to 10^{-13} m^2 (100 to 0.1 Darcies) over the first 3 to 4 Ma of evolution (Becker and Fisher, 2000; Fisher and Becker, 2000). Thus physical properties measurements are consistent with initially-rapid pore infilling by mechanical and magmatic processes during the earliest stages of crustal evolution, and by slower diagenetic processes as aging continues (e.g., Wilkens et al., 1991; Jacobson, 1992).

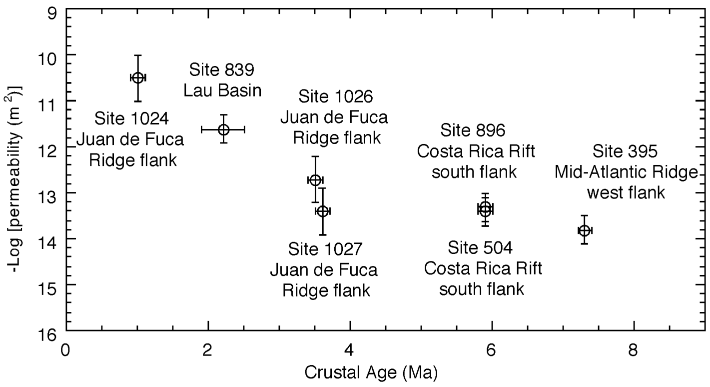

Figure 13. Permeabilities measured in uppermost oceanic basement versus crustal age (Becker and Fisher, 2000).

As described earlier, global heat flow compilations appear to conflict with this rapid aging model because they suggest that advective heat loss continues on average out to 65 Ma despite the early permeability reduction. One possible explanation for this discrepancy is that thermally significant fluid flow in ridge flanks older than a few Ma is largely restricted to widely-spaced channels and layers. Additional specific studies are needed, however, to resolve how permeability and flow are channelized and compartmentalized, how long flow persists in oceanic crust, and ultimately just how isolated certain sections become.

4.5. Global fluxes

Interaction of seawater with oceanic crust is a major mechanism for the transport of heat from the earth's interior to the ocean. It also plays an important but poorly quantified role in geochemical budgets. High temperature hydrothermal circulation at the axes of mid-ocean ridges is the most spectacular manifestation of this processes and is thought to play a significant role in defining ocean chemistry. But the advective heat loss through the ridge axis is less than one third of that at ridge flanks, and because this heat is lost at lower temperatures, the associated total water flux must be much greater than at axis. For thorough exposition of the state of current knowledge, see recent reviews by Elderfield and Schultz (1996) and Schultz and Elderfield (1997).

Extensive lateral fluid flow through oceanic crust off-axis on ridge flanks has been identified from heat flow and geochemical anomalies, yet there is still a very poor appreciation of the lateral scales and rates at which fluids and heat can be transported within oceanic crust and the integrated geochemical significance of these processes. Similarly, there is poor understanding of integrated fluxes in other characteristic hydrologic regimes (Figure 1), with the net result that a great deal still needs to be done to quantify global fluid, heat, and chemical fluxes through ocean crust and sediments. Determining these integrated fluxes is one of the most important and exciting challenges in the hydrogeology of the oceanic lithosphere; but it is one of the most difficult to approach, largely because of the range of time-space scales of the processes that contribute to the integrated fluxes coupled with limitations in the time-space resolution of the techniques available (Figure 14). Limitations like those represented in Figure 14 apply to all the problems in this section, but they are especially significant for determining global budgets.

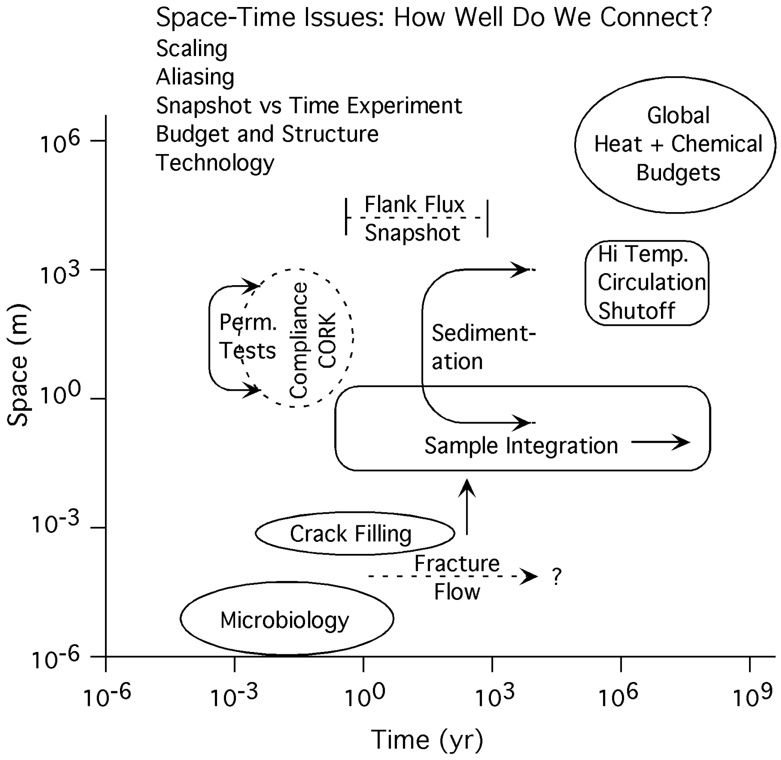

Figure 14. Cartoon illustrating space-time scales for just some of the processes in the hydrogeology of the oceanic lithosphere and space-time issues for available techniques of investigation. Modified from sketch presented by D. Chapman at workshop.

5. OBSERVATIONAL STRATEGIES AND TECHNIQUES

Understanding hydrologic processes, in which fluids move through or are confined within, and react with a host rock formation, requires determination of formation parameters, such as porosity, permeability, and constituent compressibilities, and the state of the formation, including pressure, head, temperature, stress, and composition. This must be done via a combination of techniques including remote imaging, in-situ measurements, rock and fluid sampling, and monitoring.

<u>Site selection</u>: The most efficient approach to studying processes must begin with choosing sites with care, with emphasis being placed on simplicity. The greatest understanding of a particular process comes from the study of simple, and not necessarily typical sites. Study sites should host representative processes so that results can be generalized, but excess complexity must be avoided as this can easily lead to ambiguous results.

<u>Imaging methods</u>: Basic hydrologic structure can be mapped in 3 dimensions using an appropriate combination of seismic reflection profiling and swath acoustic imagery (bathymetry and backscatter). This task is made easy in ocean crustal environments because the first-order structure is established by the upper igneous rocks and the sediments that cover them. These units differ greatly in both acoustic and hydrologic properties. Faults are also well imaged by seismic and acoustic techniques in instances where there is a history of syn-sedimentary motion. Constraints on porosity, and to a limited degree permeability, can be had from seismic velocity and gravity data. Defining deep lithologic and tectonic structure may require multi- channel reflection profiling and refraction. Greater resolution and/or complementary information about hydrologic structure and parameters can be provided by near-bottom or seafloor seismic surveying, seafloor compliance, and electromagnetic profiling.

<u>Rates of fluid flow</u>: Constraints on thermal structure, fluid composition, and, by inference, rates of fluid flow can be gained efficiently through heat-flow measurements and core samples (squeezed for their pore fluids) collected at a density appropriate for the expected scale of spatial variations. Where flow through the seafloor is suspected or identified through these or other methods (e.g., chemical and/or thermal water-column profiling), direct measurements of rates of flow and samples of fluids can be had using "benthic-barrel" devices that employ samplers driven by osmotic pumps, and flow meters that utilize mechanical, thermal, or chemical-tracer sensors.

<u>Borehole studies</u>: While much can learned about marine hydrogeologic systems remotely (much more efficiently than in studies of onshore systems), at some point further progress requires borehole observations. With this step, many of the basic techniques used on land become available for subseafloor studies, although a somewhat different approach must be taken since there is a strong limit on the number of holes that can be drilled in pursuit of any specific goal. Although improvements to a number of tools are needed, there is a broad range of tools available. Formation testing is most commonly done with a drillstring packer that isolates the interval from the packer to the bottom of the hole. While efficient and flexible, wireline packers and straddle packers have been used with only limited success. In cases where permeability is high, a combination of pumping while logging with a flow meter has been used

to constrain the distribution of permeability. Time constraints usually preclude testing for more than a few hours, and with only minor exceptions, pumping and monitoring have been done in the same hole. In the future, cross-hole experiments will allow permeabilities to be determined for a much larger volume of rock, and storage properties to be inferred, not assumed.

Just as in the case of seafloor and remote observations, it is important to integrate as much information as possible to characterize a hydrologic system that has been penetrated by drilling. Towards this end, downhole logs are critical. Resistivity, porosity, seismic velocity, self potential, electrical resistivity imagery (formation micro-scanner) and acoustic imagery (televiewer) logs all provide valuable constraints on the nature and heterogeneity of formation parameters.

Ground truthing: Core samples also provide information about formation parameters, although core recovery is usually far from complete in fractured rock, and the heterogeneity of many parameters create a scale dependence that makes data collected from cores difficult to interpret. Samples provide excellent information about current and past fluid flow and fluid-rock interaction, however. Information is provided by the composition of alteration minerals, vein-filling minerals, fluid inclusions, and interstitial pore-fluids.

Long-term monitoring: While formation parameters can be measured or inferred from observations made at the time of drilling, accurate observations of the state of the formation are nearly impossible then because of the large perturbations generated by drilling. Temperatures can be measured in low-permeability sediments with probes that extend below the bit, but measurements are not possible in permeable units. Open holes create hydrologic shunts between the formation and the water column, natural and thermally induced pressure differentials cause flow, and as a result, natural pressures, temperatures, and fluid compositions are usually impossible to determine once permeable horizons are intersected. To overcome this problem, holes must be sealed and left to re-equilibrate with long-term monitoring instrumentation left in place to observe the equilibrium state. Observations made in a number of sealed and instrumented holes demonstrate that even when holes are sealed very soon (a few days) after drilling, thermal, pressure, and compositional perturbations can last for years.

In addition to providing a means of observing the equilibrium state of a formation, long-term monitoring in sealed holes allow natural variations to be documented. A variety of natural variations have been observed that are associated with atmospheric, oceanographic (e.g. tides), and tectonic (earthquake stress change) loading. These signals allow large-scale hydrologic and elastic properties of formations to be determined, and the variations in stress related to seismic and aseismic slip to be witnessed. In the near-future, advances in monitoring capabilities will allow multiple levels to be isolated for pressure monitoring and fluid sampling.

One of the lessons learned thus far through drilling and post- drilling observations in oceanic crust is that buried or partially buried basement edifices serve as thermal "chimneys" and as such are "over-pressured" relative to local hydrostatic conditions. Holes drilled into these edifices provide a means by which crustal fluids can be naturally produced at the seafloor for biological and chemical monitoring and sampling.

While many of these various tools and techniques exist, there is a need to improve or expand the capabilities on a number of fronts in order to make hydrogeologic investigations more fruitful and efficient. A few examples include: (a) expanded borehole packer technology, (b) refined pumping hardware, (c) use of tracer testing, (d) execution of cross-hole hydrologic and geophysical experiments, (e) development of in-situ biological and chemical analyzers, (f) development of autonomous vehicles for water column profiling and seafloor heat flow measurement, and (g) deep drilling.

6. DIRECTIONS FOR FUTURE RESEARCH

The type-examples described above share one distinguishing characteristic that is not representative of most of the oceanic lithosphere: unusually thick sediment accumulations in relatively young settings. In addition, the first three examples cited in Section 2, which arguably include the two best-studied cases (JFR and CRR), are all in crust formed at medium spreading rate (3 cm/yr half-rate) and thus are unrepresentative of the large majority of ocean crust formed by slow and fast ridges. Therefore, while these examples are very important as process-oriented studies, they are not necessarily representative of global fluxes.

Hence, the workshop participants strongly endorsed a dual strategy for future studies: continuing detailed, process-oriented studies at a very few select sites, and at the same time conducting reconnaissance studies at other “representative” sites to quantify global fluxes. This is not a new strategy, but builds on recommendations made in the past in both COSOD I and COSOD II Reports and in several workshop reports (e.g., Purdy and Fryer, 1990).

Examples of “representative sites” for global fluxes would include the slow and fast-spread, thinly sedimented crust at a range of ages that is typical of much of the ocean floor, as well as examples of important unusual settings such as large igneous provinces, carbonate platforms, old-ocean basins, and regions of lithospheric flexure. Minimum requirements for reconnaissance surveys would include single-channel seismics coordinated with multi-penetration heat flow and coring (both conventional coring and exploratory ocean drilling) for multi-disciplinary analyses (e.g., fluid and solid geochemistry, microbiology).

As reconnaissance sites become better studied, some might provide justification for further intensive study as type-examples. Particular need exists for understanding processes at intensive-study sites in normally sedimented slow and fast spread crust and in old crust. These are critical in order to improve our currently poor understanding of the importance of low-temperature (ca. 10^{o}C) circulation in crustal alteration and ocean-crust biogeochemical exchange, and to explore just how isolated are some parts of the subseafloor.

Finally, there is a particular need for scientific ocean drilling in both reconnaissance and intensive studies of the hydrogeology of the oceanic lithosphere. To achieve the objectives set out in this report, future drilling will require development of improved core and formation-fluid recovery, expanded microbiological capabilities, refined shipboard hydrologic measurements, and sophisticated long-term in-situ experiments.

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8. AGENDA OF THE WORKSHOP

Friday, December 11

0800: Introductory comments
0830: Andy Fisher - Hydrologic architecture of oceanic crust
0900: Dick Von Herzen - Evidence (pro and con) from selected detailed geothermal investigations for hydrothermal circulation in older (>60 Ma) ocean crust
0930: John Baross - Potential environments for microbes

1000: Coffee

1030: Harry Elderfield - Chemical proxies for flow
1100: Hubert Staudigel - Estimating time-integrated chemical fluxes between seawater and the oceanic crust
1130: Jeff Alt - Alteration effects in the uppermost crust and relationships to fluid compositions and fluid flow
1200: Jon Martin - Water-rock interactions in non-igneous sections

1230: Lunch

1330: Mike Mottl / Jim McClain / Jeff Alt - Discussion: Unresolved problems in marine hydrogeology
1530: Adam Schultz / Greg Ravizza / Rachel Mills - Discussion: Unexplored problems

Saturday, December 12

0830: Dave Chapman - Scales and modes of flow - a view from the continents
0900: Earl Davis - Estimating formation-scale hydrologic properties
0930: Keir Becker - Advanced CORK capabilities
1000: William Wilcock - NEPTUNE / DEOS opportunities

1030: Coffee

1100: Miriam Kastner / Dave Vanco / Les Smith - Discussion:Poorly explored environments

1230: Lunch

1330: Martin Sinha / Paul Johnson / Roger Morin / Hajimu Kinoshita - Discussion: Ideas for new tools and techniques
1530: Dave Chapman /John Baross / Ralph Stephen / Geoff Wheat - Discussion: Ideas for new multi-disciplinary experiments
1700: Conveners - Wrap-up

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