

*Draft*

# Hydrogeology Program Planning Group Final Report

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## Executive Summary

The hydrosphere, along with the atmosphere, lithosphere, and biosphere is an integral part of the complex earth system. Fluids play a vital role in linking various physical and chemical processes by transporting energy and solutes in the earth at a wide range of spatial and temporal scales. Over the last decade, the Ocean Drilling Program (ODP) has made significant technological advances in measuring and monitoring hydrological parameters. However, many important questions remain concerning the role of fluids and associated hydrogeologic processes in sub-seafloor environments. Fluid flow is a critically important factor in seismogenic zone dynamics, global chemical cycles, gas hydrate formation, mid-oceanic hydrothermal systems, sub-seafloor biological community development, and diagenetic processes in carbonate platforms (Figure 1).

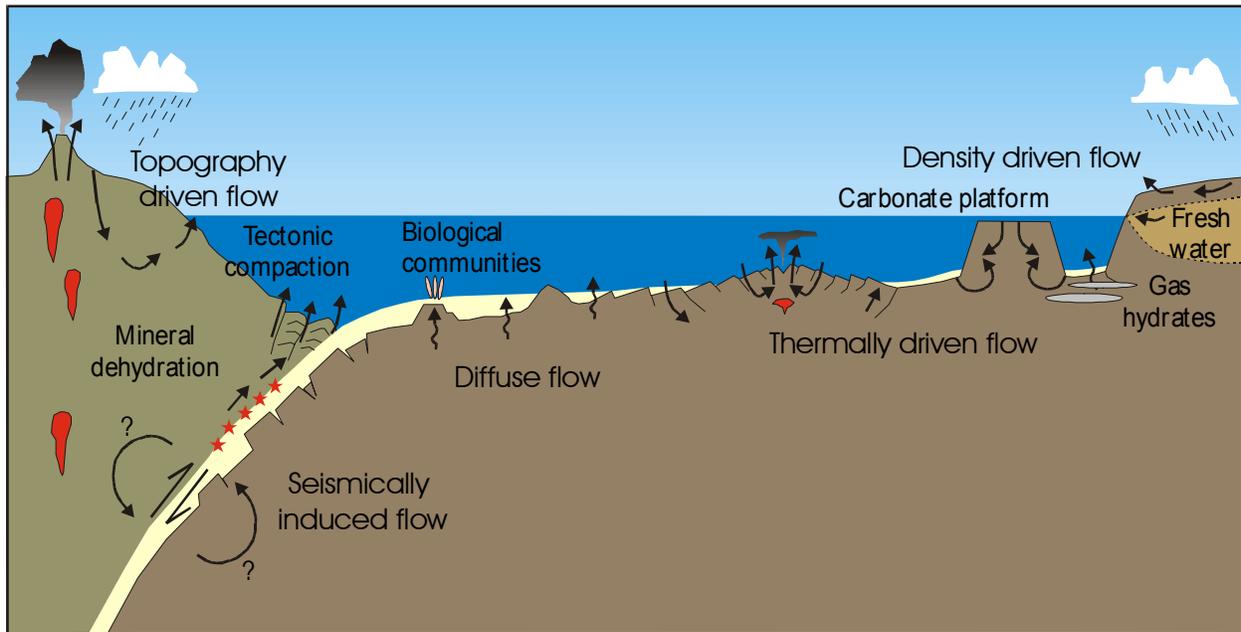


Figure 1. Schematics showing the involvement of sub-seafloor fluid flow systems in a variety of geologic processes [modified from a figure courtesy of Earl Davis].

The need for long-term monitoring of in-situ pore pressure and fluid flow is well articulated in Integrated Ocean Drilling Program's (IODP) Initial Science Plan, ODP's Long-Range Plan and the Complex Report. The transition from ODP to IODP presents our scientific community with an unprecedented opportunity to develop new tools and to integrate hydrologic studies into future scientific ocean drilling endeavors. These studies will provide important new insights into the poorly understood realm of sub-seafloor hydrogeology, and broaden the perspective and deepen the understanding of numerous scientific issues that have long been central to ocean drilling research.

JOIDES established the Hydrogeology Program Planning Group (PPG) at the end of 1999. The overall goal of this PPG was to define and prioritize the main problems in submarine hydrogeology. The group met three times during 2000 and 2001, leading to the production of this report. In the main body of the report, we first outline the important hydrogeologic questions. We

then provide an overview of the fundamental principles of fluid flow in coupled geologic processes. Next we review the methodologies in hydrogeologic studies focusing on modeling and hydrogeologic testing. Finally, we make six recommendations for addressing the scientific issues and suggest strategies for implementing the recommendations.

### **Key Scientific Questions**

It is our strong consensus that one can comprehend the dynamics of geologic processes within the earth only if one can understand how fluids move and how they transport mass and energy. Once rocks are formed in the earth's crust, the moving fluids become the principal transport mechanism by which mass and energy are redistributed. It is, therefore, vital for geoscience researchers to understand the following fluid-related questions:

- What is the current state of the fluids in terms of pressure, temperature, and composition?
- What are the sources of fluid and driving forces for fluid flow?
- What is the direction and rate of flow?
- How are the moving fluids transporting mass and heat?
- What was the past state of fluid systems (paleohydrogeology)?
- How did the paleohydrogeologic system transport mass and heat?
- What are the magnitude and distribution of porosity and permeability?

### **Research Methodologies in Hydrogeologic Studies**

Studying hydrogeologic systems begins with establishing conceptual models. A conceptual model is a description of the postulated flow system and includes the expected direction and rate of flow, the driving forces and boundary conditions, whether flow is steady or transient, the postulated sources and sinks of fluid and solutes, and the spatial variation in flow due to varying permeabilities or changes in driving forces. An important part of a conceptual model is the development of a water budget. This requires specification of water sinks, sources, and flow directions. Water inputs may involve thermally driven seawater, topographically induced flow of meteoric water, and compaction and diagenetic source of pore waters. Some fluid outputs may be readily identified based on direct observation of seafloor vents. Diffuse discharge may be more difficult to identify. Compared to focused flow, manifestations of diffuse flow in processes such as gas hydrate accumulations, perturbations to geothermal or geochemical profiles, seafloor mineralization, and seafloor biological communities are more subtle. By implementing the important features of the conceptual model in computer simulations, the scientific hypotheses related to fluid flow can be tested. Feasibility can be explored, which is an essential step in formulating a sample plan.

Hydrogeologic mathematical models, derived from the governing principles of hydrogeology, quantify conceptual models of sub-seafloor hydrogeologic flow systems. The mathematical models frequently turn into numerical or computer models in practice. Conceptual models of fluid flow are usually based on scanty observations and the intuition of hydrogeologists. Formalization of the conceptual model with a computer model is an essential part of any comprehensive hydrogeologic study. Computer models of flow systems are developed from formation geometry, boundary and initial conditions, and formation properties. Such models are

useful and cost effective tools for testing hypotheses and assessing conceptual model feasibilities. The complexity of hydrogeologic modeling endeavor varies. When limited data is available, it is often best to start with one- or two-dimensional analytical solutions derived from well-defined boundary value problems. Such solutions provide insights for the systems of interest. In sub-seafloor settings, numerical models are often necessary in order to account for complex formation geometry, rock-property heterogeneity, variable-density fluids, simultaneous heat and solute transport, chemical reactions, and rock deformation. To incorporate as many relevant geologic features as possible, new computer models may need to be developed and tested. The broader the capability of the computer model, the greater is the range of conceptual models that can be quantified.

Hydrogeologic tests in sub-seafloor environments are carried out to estimate the hydraulic parameters that control the transmissive and fluid storage capacity of a formation, e.g., geometry, permeability, porosity, and compressibility. Knowledge of these characteristics is essential for successful modeling of hydrogeologic flow systems. In the past three or four decades, there have been many attempts to constrain hydrogeologic parameters through indirect means, e.g., the analysis of borehole temperature logs, seismic profiles, and fluid chemistry. Efforts to determine hydraulic parameters through direct methods by borehole hydraulic tests and naturally occurring seafloor loading processes have been quite limited. Existing methods include shipboard experiments using drill-string packers for pressurized slug and constant-rate injection or withdrawal tests, experiments using submersibles to conduct constant-drawdown and constant-discharge tests at CORKed boreholes, and interpretation of pressure fluctuations in multiple sealed boreholes due to natural variations in seafloor loading. Slug or drill-stem tests are convenient to run because they are short-lived, but they yield only the permeability of the material immediately adjacent to the borehole. If aquifer parameters are to be obtained with reliable accuracy it is essential to run multi-well hydrologic tests. Long-term constant discharge or constant pressure tests should be run in sealed wells with observations made in nearby sealed boreholes.

## **Recommendations**

To understand the vital role fluids play in many sub-seafloor processes, sufficient hydrogeologic data and ability to model complex hydrogeologic systems are the key. We recommend establishment of a global suite of ocean hydrogeologic observatories for systematic long-term measurement of the nature and extent of regional groundwater circulation beneath the ocean. This should include a number of instrumented study sites in locations representative of a range of geologic settings, seven of which we explore in more detail in this report. In addition to dedicated hydrogeology legs to study these settings, a basic suite of hydrological measurements should be made on all research legs, irrespective of primary leg objectives. Six specific recommendations are described below.

### ***1. Establishing Global Ocean Hydrogeologic Observation Stations***

We recommend the establishment of a suite of ocean hydrogeologic observation stations as a long-term goal of IODP. Currently, little is known from the limited existing observations about the nature and extent of regional fluid circulation beneath the ocean, largely because limited

basic hydrogeologic data exists. Shallow-depth observations of the physical and chemical state of fluid can provide insight into deep geologic anomalies, global advective heat flux, evolution of ocean chemistry, areas of potential magmatism, zones of intense deep fracturing, regions of potential petroleum accumulation, and unknown areas of enhanced sub-seafloor biotic activity. Collection of basic physical and chemical measurements will enable fundamental issues to be addressed, such as discovery of large-scale sub-seafloor fluid flow systems, detection of regional thermal and chemical convection systems, establishing a baseline of chemical and thermal signatures of fluid through the sub-seafloor systems, locating regions of anomalous fluid pressures in the oceanic crust, and deducing the three-dimensional hydrogeologic architecture and the global pattern of vertical flow through the ocean floor.

Cost-effective strategies can be utilized to implement this task. They include better utilizing existing hydrogeologic observatories already in place, compiling hydrogeological data from the existing ODP database, adding a hydrogeologic component to non-hydrogeology focused legs whenever appropriate, and installing hydrogeologic observatories at strategic locations where data gaps are identified. Once a framework is established, additional data may require dedicated hydrogeology legs. This ambitious but important task may require an effort spanning several decades. But the investment will lead to a comprehensive coverage of the oceans and significantly enhance our ability to address the important sub-seafloor hydrogeological issues at a variety of temporal and spatial scales.

## ***2. Dedicated Hydrogeology Legs in Selected Settings***

We recommend IODP dedicate hydrogeology legs in selected type settings where fluid flow clearly plays an important role in sub-seafloor processes. We identify seven settings: 1) mid-ocean ridges and flanks, 2) subduction zones, 3) seismogenic zones, 4) coastal zones, 5) carbonate platforms and passive margins, 6) the deep biosphere, and 7) gas hydrates. Locations chosen for investigating these settings should have a limited set of identifiable driving forces that control fluid flow and transport dynamics. Furthermore, it would be advantageous if there has been preliminary work carried out during previous drilling legs at the sites of interest, so that existing site survey data can be utilized.

Mid-ocean Ridges and Flanks Sub-ocean hydrology at mid-oceanic ridges is characterized by buoyancy-dominated flow. Water is driven through and reacts with highly permeable rocks at temperatures of 300 – 400 °C and higher. A better understanding of the fluid flow systems can shed light on a variety of processes occurring in this setting, such as cooling of lithosphere, deposition of large mineral deposits at the seafloor, and nourishment of unique vent communities and sub-seafloor microbial populations. All these processes are possibly a consequence of rapid exchange of water, heat, and elements between the crust and oceans. While substantial understanding of the hydrogeology in this environment has been accomplished by ODP, future drilling into the ridges and igneous crust still presents a challenge due to the highly incompetent nature of fractured young extrusive rocks. Information gained from drilling into the igneous environment is important to characterizing hydrologic circulation structure of spreading centers, investigating phase separation in high temperature and highly reactive zones, providing opportunities to observe rare events associated with extensional faulting, and determining the extent of biological activity at depth.

Subduction Zones The fate of sediments, crust, and mantle entering a subduction zone and the impact of their transformation in the subduction process are of great interest to the broad earth science community. Water enters the system not only as interstitial fluid but also as constitutive water bound in minerals. Water is released at different stages with increasing temperature and pressure, which plays a major role in decollement formation, sediment accretion, faulting, mineral transformation, mantle alteration, intraslab seismic rupture, and magmatism. Driving forces for fluid flow in subduction zones are complex. Compaction near the trench, mineral dehydration, diagenetic reactions, and metamorphic transformation at high temperature locations can all contribute to fluid flow by generating fluid sources or changing permeability. Furthermore, these processes often operate in concert and are linked by upward fluid flow along the plane between the subducting and overriding plates. Also important for understanding subduction zones is the permeability of fault zones and the decollement. Multi-well tests using CORKs need to be conducted to obtain permeability information at formation scales.

Seismogenic Zones One of the main goals for studying seismogenic zone processes is to understand the temporal relationships among stress, strain, pore pressure, and water chemistry throughout the earthquake cycle. Fully coupled models of mechanics, fluid flow, heat transfer, and chemical transport are essential to achieve this goal. However, models studying the behavior of the seismogenic zone mechanics are insufficient partially due to a lack of reliable material parameters and inadequate constraints on the transient nature of pore pressure, temperature, and water chemistry at seismogenic zone depths. The enhanced capability of the new riser ship will provide opportunities to drill deeper. Sampling water chemistry and long-term monitoring of pore pressure or fluid flux in decollement or faults will provide valuable information for quantifying fluid migration in seismogenic zones. A dedicated hydrogeology leg could utilize one of the two sites selected by Seismogenic Zone Experiments in Japan and Central America.

Coastal Zones Building a comprehensive understanding of the origin and dynamics of submarine pore water requires a detailed examination of the processes that operate at ocean/continent boundaries. There are several unsolved scientific questions related to a basic understanding of these areas. For example, how far offshore do continental flow systems extend and how do such systems influence water chemistry in marine sediments? How does the distribution of fresh and brackish water offshore relate to past sea level changes? What is the relative importance of compaction driven flow? To answer these questions, it is essential to invest a major effort in obtaining data from coast to shelf at depths less than one kilometer, which will require shallow water drilling capabilities. The types of data needed are pore pressures, fluid density profiles, fluxes at the sea floor, temperature profiles, permeability measurements from core to formation scales, and geomorphology and biota distributions. These data will provide necessary constraints for integrated process modeling that will shed light on the transient nature of the coastal zones.

Carbonate Platforms The relatively large volumes of fluids known to circulate through many carbonate platforms drive significant water-rock interaction due to the permeable and reactive nature of carbonate sediments. These processes also have an important influence on the chemistry of the atmosphere and the oceans, regulating climate, and controlling the fate of atmospheric carbon dioxide. Previous ODP investigations have provided useful sedimentological and paleoenvironmental results, and offered tantalizing insights into processes controlling fluid

flow, which include density contrasts due to temperature and salinity. However, a comprehensive understanding of the nature, rates, and controls on fluid flow remains elusive. We need to develop an understanding of the nature of permeability in carbonate platforms, which is characteristically variable due to depositional and subsequent diagenetic processes. Feedback between large-scale fluid flow, porosity/permeability, and diagenesis is still poorly understood. Finally we need determine the effect of changing climate and sea-level on fluid flow in carbonate platforms. A dedicated leg can focus on a carbonate platform where previous drillings or other studies have indicated that significant fluid flow.

Flow Systems Supporting the Deep Biosphere Studies over the last 15 years have definitively established that large and diverse microbial populations are active below the seafloor. Although fundamental questions such as the maximum depth and temperature for viable organisms remain open, the most compelling question for hydrogeologists is the mechanism of supplying nutrients to the subsurface population. Because numbers of microorganisms vary in the subsurface, it is clear that a better understanding of the role of subsurface flow in supplying nutrients is needed to predict the abundance of the sub-seafloor biosphere. Eventually it should be possible to predict the expected microbial activities in sub-seafloor environments on the basis of broad hydrologic and geologic categories. Any drilling plan, designed to investigate nutrient supply for sub-seafloor microbial communities, must include a conceptual model of the flow system and describe the necessary measurements to test it. A minimum plan would include pore pressure measurements sufficient to establish the regional pore pressure gradient and superimposed local variations. Long-term monitoring may be required to determine the temporal variability in pressure, temperature, or chemistry. For identifying zones of active flow supporting microbial activities flow, characterizing the relative permeabilities is more important than determining absolute values. This may initially be accomplished through physical property and logging observations.

Gas Hydrates Gas hydrates are an ice-like form of water and low-molecular weight gas (e.g., methane) stable at the pressure-temperature conditions common in continental margin marine sediments and permafrost regions. One of the fundamental objectives of gas hydrate research is to delineate the dynamics of gas hydrate deposits. Gas hydrate formation and stability are often viewed as a function of only pressure and temperature, although the amount, composition, and solubility of hydrate-forming gases also play a critical role in determining the thickness of free gas, gas hydrate, and dissolved gas zones in hydrate reservoirs. Field observations, laboratory and seafloor experiments, and modeling studies underscore the fundamental link between rapid fluid advection and the formation and concentration of gas hydrate. Taken together, these studies imply that an understanding of the hydrologic processes responsible for supplying and concentrating gas will be required to unravel hydrate system dynamics. More effort is necessary to acquire the data needed to constrain fluid flow in these settings at multiple spatial and temporal scales and from a process-oriented approach. Analysis of gas hydrate provinces as hydrologic systems also requires constraints on the driving forces for flow, pore pressure gradients, and hydraulic parameters (e.g., permeability). There is emerging evidence that free gas as well as dissolved gas migrates through these environments, sometimes within the gas hydrate stability zone. Predicting the dynamics of free gas migration will therefore require application of the techniques developed for studying multiphase flow systems.

### ***3. Collecting Routine Hydrogeologic Data on All Legs***

In order to better understand the role of fluid in heat and mass transport processes in the sub-seafloor, and effectively implement the recommendation of establishing the global ocean hydrogeologic observation stations, we recommend that IODP make collecting hydrogeologic data a baseline task for future legs. Despite the acknowledged importance of fluid flow in controlling sub-seafloor processes, a significant number of legs exclude hydrogeology from their primary objectives. Nevertheless, these legs offer potential for collection of data on some hydrogeologic parameters, enabling us over the long-term to build up a broad-based hydrogeologic database. In particular this effort will allow assessment of the degree to which observation sites are representative of their type settings.

We identify a set of state parameters necessary for hydrogeologic studies: pore pressure, fluid temperature, fluid chemistry, and stress. Other hydrogeologic properties include permeability, storativity, thermal conductivity, and porosity. Permeabilities in different directions, and different scales are needed in order to characterize flow systems. Fluid flux can be derived from pore pressure gradient and permeability, or inferred from observations of thermal or chemical variations. Pragmatic considerations require that acquisition of hydrogeologic data must not require significant additional ship time, although some beneficial investment in equipment and manpower is justifiable. Relatively simple hydrogeologic measurements, including in-situ temperature and permeability, should become routine on most legs, and a case must then be made on a leg-by-leg basis for their exclusion rather than for their inclusion. Acquisition of additional measurements should become recommended practice.

### ***4. Developing, Improving, and Maintaining Tools***

Technologies and tools are a crucial component of any successful hydrogeologic study. Areas we strongly recommend IODP to invest future efforts in are as follows.

Developing expanded packer capabilities, such as a multi-set bottom-hole-assembly packer. Improved capabilities are needed to allow estimation of natural formation pressure, permeability, and stress. These are all important parameters that are difficult to obtain in other ways. It is critical that IODP be equipped with reliable packer capability.

Improving shipboard low-flow pumps and real-time downhole pressure monitoring tools. To carry out experiments with packers of any type, improvements are needed to better control and monitor pressures and flow delivered to packers and to the formation, particularly in weak, low-permeability material such as accretionary prism sediments, where determinations of pressure, permeability, and stress are badly needed.

Improving the capability and strategy for downhole water sampling. The simpler task of fluid sampling in producing holes will most certainly continue to be desired, so maintaining downhole fluid sampling capabilities is important.

Enhancing the ability to recover fluid samples from the pressured core sampler. Recovering fluid samples without depressurising a sample remains a challenge. Improvements could be made to

the manifold subassembly of the pressure core sampler by using a different closure design if a larger diameter drill pipe were adopted by IODP.

Developing and improving temperature measurement tools. The next generation temperature tools for piston coring need to allow more rapid determinations of temperature through faster time response and greater thermal isolation from the massive part of the core cutter and easier servicing through greater battery lifetime and simplified data retrieval.

Establishing new apparatus for measuring electrical conductivity on the ship. Diffusivity of sediments is a critical parameter for estimating chemical fluxes by diffusion through a porous medium. Formation diffusivity can be estimated from electrical conductivity measurements on the working half of sediment cores. A calibrated device with a digital read-out should be built and maintained for use in the shipboard corelab.

Improving tool maintenance and management Annual calibration of temperature and pressure tools should be established. A full set of spare parts including a spare data logger should be carried on the ship. Written guidelines on deployment of the downhole tools are necessary for paving the way to better quality observations.

### ***5. Pre- and Post-Cruise Modeling Studies***

Pre-cruise hydrogeologic modeling should be carried out because the modeling can give scientists a conceptual understanding of a hydrogeologic system. This can help in formulating hypotheses and defining investigative strategies when only limited data are available. Models provide predictions of flow rates that can be tested during the drilling leg from measurements of pore pressure gradients and permeabilities. At the pre-cruise stage, it is likely that most of the modeling effort will be in developing the conceptual model, rather than on complex numerical solutions. Modeling studies can often be accomplished by means of analytical solutions to relatively simple boundary-value problems. However, if more complex hydrogeologic features are needed one may have to develop numerical models.

Post-cruise modeling is done to synthesize and demonstrate the state of knowledge following a drilling leg. This can be accomplished by revising a pre-cruise model or by developing a completely new model. Such modeling endeavors can become an integral part of reporting the results in the open literature. Post-cruise modeling can also be used to demonstrate where understanding of processes occurring in a given setting is lacking and point the way for future investigations. Post-drilling modeling should be identified as a major outcome of legs with hydrogeological objectives, and the necessary post-cruise funding should be provided. Moreover, the designing of drilling and testing programs should include consideration of the data requirements of such modeling efforts.

### ***6. Encourage Larger Hydrogeological Community Involvements***

We recommend holding future hydrogeology-focused workshops as a way of informing and encouraging participation of the interested hydrogeology community.

We recommend staffing hydrogeologists on all relevant IODP cruises and making a good-faith effort to nurture hydrogeologists who were not previously involved in ODP/IODP experiences. In addition, we suggest fostering and scheduling more research legs devoted to fluid flow studies, and supporting one or more fluid flow analyst or modeler for each of the type settings described in this report.

We also encourage bringing scientists with hydrogeology expertise into as many scientific advisory panels and committees as appropriate. Evaluation of proposals should be conducted by a multi-disciplinary panel that includes land-based hydrogeologists and marine geologists.

To implement the recommendations outlined in this report, it would be prudent to provide necessary funding for hydrogeologic studies. We recommend that IODP pay special attention to the needs of developing new tools for hydrogeologic measurements, and of pre- and post-cruise modeling studies in order to achieve specific hydrogeologic objectives.

## **1. Introduction**

Fluids play a vital role in virtually all subsurface processes. The transport of chemical constituents and heat by circulation of fluids is the principal control on a range of diagenetic processes. The mechanisms by which crustal rocks and sediments deform are strongly influenced by the presence of fluids. It has been widely recognized that pore-fluid pressures play a significant role in earthquakes. On a broader scale, pore-fluid pressures influence the mechanical processes that control rock deformation at plate margins. The volume of fluid carried to deeper levels in subduction zone complexes appears to influence the rate and depth of melting, which determines the locales of volcanism in the overriding plate. Development of rigorous models of crustal processes requires a substantial body of well-constrained data as well as an in-depth understanding of fluids in the crust.

Exploring the dynamics of the sub-seafloor hydrogeologic system has been identified repeatedly in scientific themes and initiatives described in benchmark documents including the Long-Range Plan [1996], CONCORD [1998], COMPLEX [1999], and the Initial Science Plan [2001]. Sub-seafloor fluid flow and associated transport processes alter the mineral makeup of the oceanic crust. Fluid exchange across the seafloor influences the chemical composition of the ocean. With inquiries into the environment of deep microbial communities, heat and solute transport by fluid circulation becomes increasingly important. In gas hydrate settings, heat and fluid may circulate through the hydrate stability zone and cause a redistribution of methane. These studies have called for a quantitative understanding of fluxes and pathways of fluid, organic matter, and heat transport. Studies of continental margins, large igneous provinces, and carbonate platforms return frequently to the role of fluids in driving and mediating critical processes. In addition to fluid dynamics, fluid composition often provides key information on past geologic processes and global conditions, which can be used as a valuable archive in earth science investigations, notably in climate change studies. With a multi-platform program and new technologies, the scientific dream of exploring the dynamics of sub-seafloor fluids can be turned into a reality of systematic characterization.

In this report, we present an overview of the role of fluids in geologic processes and key scientific questions in Section 2. In Sections 3 and 4, we provide the background on sub-seafloor hydrogeologic processes, research methodologies, and achievements to date. Section 5 presents six specific recommendations for addressing the major scientific issues and strategies for implementing the recommendations.

## **2. Key Scientific Questions**

Present day exposures of geologic materials indicate that fluids have been present at all crustal levels. Field measurements, isotopic, fluid inclusion, and phase equilibrium studies, mineral-filled fractures from shallow crustal depths, vein and pegmatite masses from intermediate crustal depths, and gneissic rocks from deeper crustal depths all indicate that fluids were present in significant quantities. Consistent with fluids at all levels of the crust is the repeated observation that fluids have played a dominant role in the transport and concentration of metals in most ore deposits. Geophysical studies of the crust have also shed light on the nature of deep fluids in the crust. Electromagnetic and conductivity soundings reveal layers of low electrical resistivity in

the deep crust that indicate the presence of a broadly interconnected aqueous fluid phase. Seismic studies also indicate low velocity zones in the deep crust that have been interpreted as regions of high fluid pressure. The data suggest fluids and fluid circulation occur at depths of at least 10 to 15 kilometers.

For the past century, geology has been largely a "dry" science. Geoscientists have traditionally focused on the solids, minerals, and lithologic units in their studies of earth processes. The importance of the fluid phase in the rocks has often been overlooked. This is in part due to the difficulty of obtaining samples of the fluid. Investigations that have not taken into account the presence of water in the earth may inadequately or incorrectly describe the operative geophysical mechanisms. As we come to appreciate the role of fluids in earth processes, the science of geology is changed. If one can understand how fluids move and how they transport mass and energy, then one can better understand the dynamics of geologic processes within the earth. After rocks have formed in the earth's crust, moving fluids are the principal transport mechanism by which mass and energy is redistributed. The following fundamental questions provide a key to a better understanding of the role of fluids in different sub-seafloor settings.

- What is the current state of the fluids in terms of pressure, temperature, and composition?
- What are the sources of fluid and driving forces for fluid flow?
- What is the direction and rate of flow?
- How are the moving fluids transporting mass and heat?
- What was the past state of the fluid system (paleohydrology)?
- How did the paleohydrogeologic system transport mass and heat?
- What are the magnitude and distribution of porosity and permeability?

### **3. Governing Principles of Sub-Ocean Fluid Flow and Fluid-related Processes**

In the subsurface, the entire fluid-rock system is coupled chemically, thermally, and mechanically (Figure 2). With fluid-rock chemical interactions, dissolution, precipitation, ion exchange and sorption are possible. Many of these chemical reactions can change the properties of the rock matrix. Rates of reaction are affected by temperature and some reactions are endothermic while others are exothermic. Consequently heat transport is an important component of the system. Heat in turn affects the properties of the fluid, especially its viscosity. Heat, pressure, and chemical composition combine to affect the state of the fluid. For example, water may be liquid, gaseous, solid, or supercritical. The fluid pressure directly impacts the state of stress in the crust. Rocks deform as a consequence of changes in the effective stress. At high pore pressure, hydraulic fractures are created. Fractures in turn change the permeability of the rock mass. When the pore pressure is equal to the least principal stress, jointed rocks are frictionless. In this state, large deformations are mechanically feasible. It seems likely that all highly active tectonic regions have high pore pressures.

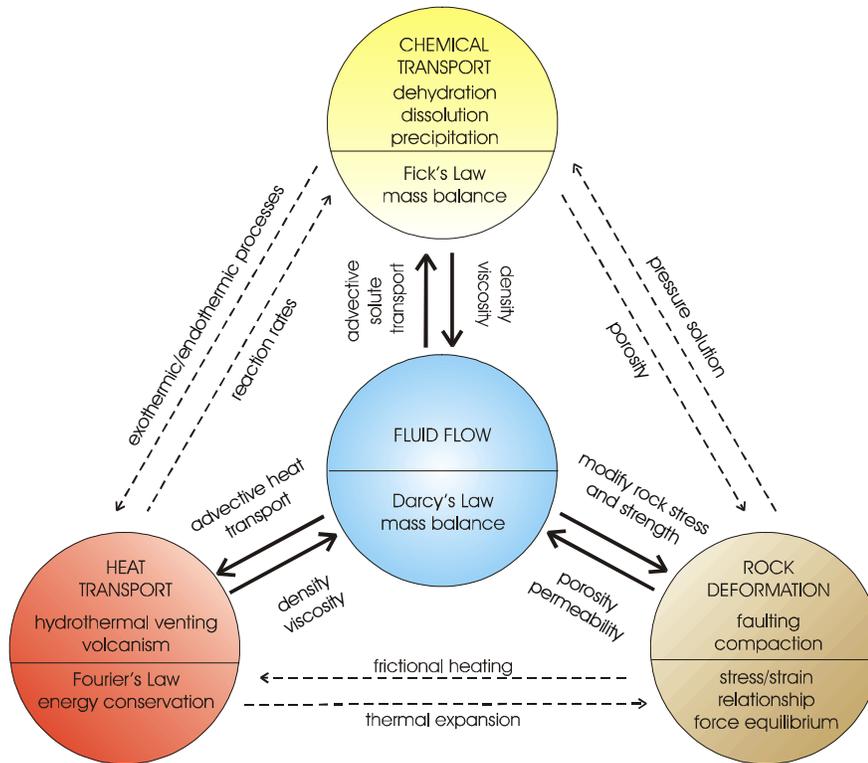


Figure 2. Relationships between fluid flow, chemical and heat transport, and mechanical deformation processes with the solid arrows elucidating the feedback mechanisms or coupling parameters. The dashed arrows may be considered as secondary coupling. In all the circles, the upper halves describe the generic and examples of common geologic processes. The lower halves enlighten the corresponding theoretical principles governing these processes [courtesy of Shemin Ge].

### 3.1. Governing Principles for Fluid Flow

The physics of subsurface fluid flow are described by a set of conservation statements for mass, energy, and momentum. Often in the subsurface the momentum can be neglected. The conservation statements lead to a coupled set of partial differential equations. The dependent variables of interest are the fluid pressure, the chemical composition of the fluid, and the temperature or enthalpy of the fluid. To describe the stress of the rock mass, force equilibrium equations are invoked along with rock rheology dependent constitutive relations. The stress-strain state of rocks is also coupled to the fluid pressure and fluid temperature. In general the coupled equations must be solved simultaneously. The equations are difficult to solve analytically; however, with today's digital computers, solutions to realistic problems of great scientific interest are now readily possible. While the dynamics of real systems may be complex, in principle the physics and chemistry are conceptually simple.

During the nineteenth century, experiments revealed a set of empirical laws describing the flux of mass and energy. The flux laws are comprised of Darcy's Law of fluid flow, Fourier's Law of heat conduction, and Fick's Law of chemical diffusion. Each of these laws has the general form that the flux is proportional to a gradient or a driving force. The constant of proportionality

incorporates properties of the medium through which the flux occurs. For example in Darcy's law, the fluid flux is proportional to hydraulic head gradient and hydraulic conductivity that is a function of rock permeability and fluid properties. Solutions of the governing equations give the distribution of hydraulic head, temperature, and solute concentration. Hydraulic head is defined as the sum of a pore pressure term and elevation. Consequently the gradients of these quantities are known. Using the flux laws, one can compute flux distributions for a given set of medium properties.

The general characteristics of flow fluid systems are controlled by rock permeability, the hydraulic head gradient, the fluid composition, the fluid temperature, and the amount of available fluids. At shallow depths of less than several kilometers these variables can be measured directly in boreholes. For rocks at greater depths the available information often is inferred from outcrops of rock that once resided at deep crustal depths. The outcrops provide a series of snapshots that, when integrated, allow interpretation of the nature of the fluid at different levels in the earth. These snapshots reflect the cumulative effects of fluid flow on physical and chemical processes that occurred in the outcrops. In such interpretations, rock permeability, fluid pressure, composition, and temperature can only be established within broad limits. Because the fluids in the exposed strata have long since escaped, the snapshots have the disadvantage of providing only a record of what the fluid effect was on the solid rock.

Permeability of natural earth materials can vary by as much as 15 orders of magnitude. Addressing the uncertainty surrounding the rock permeability remains a main task in charactering hydrogeologic systems. The permeability one chooses to represent the medium depends upon the problem one wants to solve. For example, in a fractured rock mass, the matrix of the rock between fractures has one permeability. Viewed from a larger scale the entire rock mass including the fractures has a generally higher permeability.

### **3.2. Driving Forces for Fluid Flow**

Fluid flows in response to a number of driving forces. Examining the driving forces provides considerable insight into the associated geologic phenomena. The potential driving forces are topographic relief, tectonic dilation and compression, diagenesis, fluid density gradient, and fluid sources. Other driving forces exist, such as chemical gradients across clay membranes (osmosis), and electrical potential, but they are generally small in relation to the forces listed above. One or more driving forces may operate a fluid system at a given time. The magnitude of the driving forces may vary with time as different geologic processes taking place. As a consequence, transient fluid flow is expected in response to changes in driving forces.

Pore pressure is the parameter that manifests the state of driving forces. High pore pressure is dissipated as fluid flows away from the source. The amount of pore pressure increase or decrease depends upon the rate at which fluid can flow away from the source, or into a sink. The rate of flow is controlled by the hydraulic diffusivity that is proportional to rock permeability. Since permeability can vary by 15 orders of magnitude, rates of flow can vary enormously. The maximum pore pressure increase is limited by the strength of the rock. At high pore pressure, rock failure can occur in either shear or tension. If the rock fails in tension the failure is a

hydraulic fracture. Tension fractures increase the permeability of the rock such that hydraulic fractures often allow the pore pressure to dissipate rapidly.

### ***3.2.1. Topographic Relief***

Topography is probably the dominant driving force for groundwater movement in stable continental settings. But, topographic relief is not a driving force for fluid flow beneath the ocean floor. However, near the coastline topographic relief onshore may move groundwater outward beneath the continental shelf. For example, off northern Florida and southern Georgia freshwater extends well into the offshore in the Floridan Aquifer.

### ***3.2.2. Tectonic Strain***

Tectonic strain has the potential to change the pore pressure as sediments and rocks are subjected to compression or extension. The degree to which pore pressure is increased or decreased depends upon whether groundwater flow can dissipate the change in pore pressure. There are two competing rates, the rate of tectonic strain and the rate of flow. The rate of flow is directly proportional to the permeability of the rock. It is easy to grasp intuitively the impact of these competing processes. For example, assume a region of the crust is undergoing tectonic compression, if the permeability is sufficient high pore fluids can flow away readily, and the increase in pore pressure caused by the tectonic strain will be negligible. On the other hand, as the permeability becomes lower the flow of the pore fluids is impeded and high pore pressures can result. It is the competition between the rate of tectonic compression and the rate of groundwater flow that determines the resulting pore pressure.

### ***3.2.3. Compaction and Diagenesis***

Due to the low compressibility of pore fluid, reduction of pore space associated with compaction tends to generate overpressures and, hence, induces pressure gradients that drive flow. This flow represents the expulsion of pore water due to compaction. Compaction caused porosity reduction is due to an increase in effective stress, the difference between total stress and pore fluid pressure. Both an increase in total stress, for instance due to sediment loading, and a decrease in fluid pressure due to fluid flow, enhance effective stress and, hence, compaction. A number of young geologic basins are actively receiving sediments where high pore pressures are observed such as in the Gulf Coast of the US and Caspian Basin. The simplest mechanism to generate the high pore pressures is one in which low permeability sediments are being deposited at a sufficient high rate that compaction cannot keep pace, this is so-called compaction disequilibrium. If the rate of sediment loading is sufficiently high that the fluids cannot escape rapidly enough pore pressure can reach lithostatic pressure. Under conditions of pore pressure approaching lithostatic pressure, there is little or no effective stress, and compaction does not take place.

Diagenesis can also lead to porosity reduction, which acts as another mechanism for driving fluid flow. In the compaction-disequilibrium model, porosity and permeability reduction only occur in response to an increase in effective stress. Under a constant effective stress, Walder and Nur [1984] proposed a time-dependent process in which porosity is lowered by diagenesis, e.g.,

pressure solution. This process could dry out the crust and under some circumstances where the permeability restricted the movement of fluid lead to high pore pressures within the crust. Diagenesis implies that fluid flow could occur in older basins where active or recent sedimentation is absent or negligible.

### ***3.2.4. Fluid Density Gradient***

The introduction of heat such as from an igneous intrusion or the cooling of oceanic crust and lithosphere creates a heat engine for groundwater flow driven by the heat-induced fluid density gradient. Often there is groundwater convection around intrusive bodies, which controls the rate of cooling of the intrusion. The convection can also distribute base and precious metals around the intrusive body and concentrate ore bodies. The change in pore pressure associated with heating can be large. Palciauskas and Domenico [1982] examined the problem taking into account the compressibility of the rock. They concluded that the change in pressure in low permeability rocks could be as large as 5 to 10 bars/ °C. In contrast, convection driven by background geothermal flux is far less rigorous, but in permeable formations such as the uppermost igneous oceanic crust, flow can be thermally and geochemically significant and persists for tens of million years.

Density contrasts can also result from differences in solute concentrations. This mechanism can be important for driving fluid circulation in coastal systems where fresh water mixes with seawater. Density contrasts from the combined effect of both heat and solute probably drive flow in shallow carbonate platforms. Dense brines found in connate waters or formed adjacent to salt formations may also migrate by density-driven flow.

### ***3.2.5. Sources of Fluid***

Close to the earth's surface on land, the usual source of groundwater is precipitation. Close to the ocean floor the obvious source of liquid is ocean water itself. High salinities may develop where surface seawater circulation is restricted, particularly within evaporite basins, leading to downward reflux of dense brines. Deeper in the earth there are other potential sources of fluid: 1) recrystallization of minerals in which dehydration occurs, 2) generation of oil or gas, 3) release of fluids from the mantle. Whether dehydration, hydration, or the generation of oil and gas changes the local pore pressure depends on whether there is a pore volume change associated with the reaction. Perhaps the most commonly discussed reaction is the montmorillonite-illite transformation that was first suggested as the cause of high pore pressure in the Gulf Coast [Burst, 1969].

## **4. Methodologies in Hydrogeologic Studies**

In this section, we highlight three components involved in hydrogeologic investigations: establishing a conceptual model for fluid flow, field testing of hydrogeologic parameters, and fluid flow system modeling. A conceptual model provides an initial understating of a fluid flow system in terms of overall fluid budget. Field testing is required to obtain the necessary hydrogeologic parameters to quantify the flow system. Modeling is an efficient means to synthesize all available data and to provide the details on how fluids interact with chemical,

thermal, and mechanical processes. The final section is a summary of the tools currently used in hydrogeologic testing.

#### **4.1. Establishing Conceptual Models**

Studying hydrogeologic systems begins with establishment of conceptual models. A conceptual model is a description of the postulated flow system and includes the expected direction and rate of flow, the driving forces and boundary conditions, whether flow is steady or transient, the postulated sources and sinks of fluid and solutes, and the spatial variation in flow due to varying permeabilities or changes in driving forces. The area considered in the conceptual model should be large enough to encompass the important mass sources and sinks and driving forces. An important part of a conceptual model is the development of a water budget. This requires specification of water sinks, sources, and flow directions. Water inputs may involve thermally driven seawater, topographically-driven meteoric water, and compaction and diagenetically produced pore waters. Some fluid outputs may be readily identified based on direct observation of seafloor vents. Diffuse discharge may be more difficult to identify than focused flow. This is because manifestations of diffuse flow in processes such as gas hydrate accumulations, perturbations to geothermal or geochemical profiles, seafloor mineralization, and seafloor biological communities can be subtle. By implementing the important features of the conceptual model in computer simulations, the scientific hypotheses related to fluid flow can be tested. Model results associated with contrasting hypotheses can be used to design a sample plan.

#### **4.2. Hydrogeologic Testing**

##### ***4.2.1. Background***

Hydrogeologic testing of sub-seafloor environments is carried out to obtain estimates of the hydraulic parameters that control the transmissive and fluid storage capabilities of a formation, e.g., geometry, permeability, porosity, and compressibility. Knowledge of these characteristics is essential for successful modeling of hydrogeologic flow systems and the quantification of a conceptual model. In the past three or four decades there have been many attempts by scientists to constrain hydrologic parameters through indirect means, e.g., the analysis of borehole temperature logs, drilling logs, seismic profiles, fluid chemistry, seafloor biota, and core. However, the number of attempts to determine hydraulic parameters through direct methods, e.g., borehole hydraulic tests and naturally occurring sea-floor loading processes has been quite limited. Likely reasons are difficulties encountered in operating from remote platforms in hostile environments, the time and expense involved, and limitations in technology.

In analyzing testing data, one sets up an appropriate local-scale model, hydrogeologic parameters are estimated by matching the measured hydraulic head variations and dimensionless theoretical responses called type curves. Unfortunately, head variations measured in the stressed well without corresponding measurements in a nearby observation well are not sensitive to the direction of fluid flow in the aquifer. Even under ideal circumstances with noise-free data, the best one can hope for is to obtain an estimate of the formation permeability-thickness product or transmissivity. Slug or drill-stem tests are convenient to run because they are usually short-lived, but they yield only the permeability of the material immediately adjacent to the borehole. This

material is often not representative of the aquifer in general. Additionally, it is usually difficult to determine the correct background initial conditions, which adds to the degree of uncertainty in the estimated parameters as a result.

If aquifer parameters are to be obtained with reliable accuracy, it is essential to run multi-well hydraulic tests. Ideally, long-term constant discharge or constant pressure tests should be run in sealed wells with observations made in nearby sealed boreholes. It is important to establish the initial condition of the formation pressure before starting the tests. Therefore, strategies such as pore pressure measurements ahead of drilling or measurements of shut-in pressure with packers need to be used.

#### ***4.2.2. Accomplishments in Hydrogeologic Testing***

In the 1990's, attempts to obtain the primary hydraulic parameters, formation permeability and compressibility, have involved shipboard experiments using drillstring packers, experiments using submersible vessels to conduct constant-rate tests in sealed (CORKed) boreholes, and interpretation of pressure fluctuations in multiple sealed boreholes from natural variations in seafloor loading.

##### Shipboard experiments, using drill-string packers for slug tests and constant-rate injection tests.

In various sub-seafloor settings, numerous shipboard experiments were made. Larson et al. [1993] determined permeability from packer experiments in Jurassic oceanic crust composed of hydrothermally altered basalt in the western Pacific Ocean. Sreaton et al. [1995] conducted packer experiments to estimate in-situ pore pressure and transmissivity in the sediments of the Oregon accretionary prism fault zone. Fisher and Zwart [1996] used shipboard packers to determine the permeability in the sediments of the décollement zone of the Barbados accretionary complex. Becker and Fisher [2000] conducted similar experiments in the basalt of the Juan de Fuca Ridge. Fisher [1998] provides a thorough review of the measurements of permeability in basaltic oceanic crust, where most in-situ measurements have been made.

While analysis of any hydrogeologic test requires simplifying assumptions, there are problems unique to sub-seafloor investigations. In previous shipboard experiments, difficulties included heave, poor control of pumping rates, and a lack of accurate real-time pressure data. While these difficulties can and should be addressed by improved shipboard facilities, greater problems are created by the remoteness of the sub-seafloor sites. Most significantly, this remoteness restricts the time duration of hydrogeologic tests and often precludes the installation of observation wells. Pressurized slug tests inject or withdraw only a small amount of fluid and therefore sample only a small region surrounding the borehole. Because of small-scale natural heterogeneity and disturbances due to drilling, this region will often have hydraulic properties significantly different than those of the targeted formation. Constant-rate injection or withdrawal tests may be preferable to slug tests as they sample a larger region around the borehole. However, constant-rate tests are often conducted in shortened durations for logistical reasons, which diminishes the advantage of using them and often violates assumptions in post-test modeling. Another important ingredient in applying analytical or numerical models to analyze test data is the knowledge of the background formation pressure. Determination of this quantity requires that the borehole be sealed and that the pressure be monitored for months or years. Because the permeability in the

zone of interest may be a function of the formation pressure, estimates of permeability will vary depending upon packer effectiveness and the time allowed for borehole pressure recovery after drilling and packer inflation. In spite of the difficulties encountered in shipboard operations, noise in the data, and apparent violations of model assumptions, some useful parameter estimates have been obtained from shipboard experiments and suggestions for improved methodology have resulted.

Experiments using submersibles Subsurface hydraulic tests using submersible vessels on CORKed boreholes have involved pressurized slug tests and constant-drawdown or constant-discharge tests. These were conducted in some of the same boreholes as were used for the shipboard experiments [Screaton et al., 1995]. The tests had obvious advantages over shipboard experiments. They were free of the difficulties that arise from using a remote and unstable platform thus have less noise and better flow controls. When the tests were conducted in CORKed wells where pressure transducers and thermistors had been left undisturbed for an extended period of time, the background pressure and temperature at least partially equilibrated with the environment. Therefore, the background or initial conditions are better constrained, which conformed favorably with the assumptions required by the models for post-test data interpretation. Long-term hydraulic tests from several hours to several days were conducted in a sealed borehole in the Oregon accretionary prism [Screaton et al., 1995] and similar short-tests were conducted in the décollement zone of the Barbados accretionary complex [Screaton et al., 1997]. Parameter estimates obtained from the tests conducted utilized similar analytical and numerical models as were used to estimate parameters from tests conducted aboard ship but with noticeably improved results.

Interpreting pressure fluctuations from natural variations in seafloor loading. Pressure transducers in sealed boreholes record natural pressure fluctuations induced by seafloor loading due to tides and other oceanographic phenomena [Wang and Davis, 1996]. These seafloor pressure variations are believed to propagate laterally through transmissive rock such as layered basalt from areas where the rock is exposed on the seafloor near a spreading ridge to regions where the transmissive rock is confined by low-permeability sediments on ridge flanks. The rate of lateral propagation of the pressure fluctuations and the change of phase of the tidal oscillations relate to the hydraulic properties of the rock. Davis and Becker [1999] suggested ways in which the natural tidal pumping might be used for estimating formation-scale hydraulic properties. Davis et al., [2000] analyzed pressure variations observed on the seafloor and in several sealed boreholes on the flanks of the Mid-Atlantic and Juan de Fuca Ridges. Their analysis yielded reasonable estimates of formation-scale hydraulic properties by using a one-dimensional analytical model [Wang and Davis, 1996]. It was possible to compare parameters estimated with different methodologies at different scales because the same boreholes had been used in shipboard experiments. The estimated formation-scale permeability is at the upper end of previous measurements reported by Becker and Fisher [2000] who used short-term packer and open-hole flow tests.

#### ***4.2.3. Future Hydrogeologic Testing - Multi-well Tests***

The shipboard and submersible hydraulic tests described above involve analyses of data obtained from the test-well itself. No observation wells are involved. Unfortunately this is a major

disadvantage because with a single-well test the best one can hope for is an estimate of the formation transmissivity. Wellbore storage, well skin effect, and unknown flow geometry in the aquifer adjacent to the borehole make identification of other hydraulic parameters, e.g., vertical permeability and formation compressibility next to impossible. To date, the only hydraulic test involving more than one borehole was in the Barbados accretionary complex wherein a pressure disturbance was recorded in a sealed borehole that was due to drilling-related activities in a nearby borehole [Screaton et al., 2000]. Although unplanned and uncontrolled the two-well test confirmed the existence of lateral fluid movement, demonstrated that multi-well tests were feasible, and made it possible to estimate permeability at a scale approximating the distance between the wells, which is estimated to be 45 m.

### **4.3. Hydrogeologic Modeling**

Mathematical models, derived from the governing principles of hydrogeology, help quantify conceptual models of sub-seafloor fluid flow systems. Conceptual models of fluid flow are usually based on scanty observations and the intuition of hydrogeologists. By mathematical specification of what is known of the formation geometry, boundary conditions, initial conditions, fluid driving forces, and background initial conditions in the case of dealing with a transient flow situation, formalized mathematical models of the flow system can be developed. A well-constructed model can be extremely useful and cost-effective tool for providing possible explanations for known or unknown conditions. They can be used to assess the feasibility of a conceptual model, test hypotheses, suggest drilling strategies, and otherwise guide the investigative process. The usefulness of models is limited, however, by the quantity and quality of available data. As additional data emerge, new features can be added to the model and/or adjustments can be made to the parameters that control rates of fluid flow and fluid accumulation. This process is iterative and should be continued until the understanding of the system under investigation, e.g., its geometry, driving mechanisms, permeability distribution, storage capacity, is satisfactorily consistent with observations.

Determining the type and complexity of a mathematical model to quantify fluid flow depends upon the type settings such as those described in Section 5.2 and the available data. With limited data, and as a starting point, it is often best to use one- or two-dimensional analytical solutions derived from simple well-defined boundary value problems. Such solutions often provide insightful explanations for field observations. In other sub-seafloor settings, numerical or computer models will be necessary in order to account for such factors as complex formation geometry, heterogeneous rock types, variable-density fluid flow with simultaneous heat and solute transport, different driving forces, chemical reactions, formation deformation, and temporally and spatially varying parameters. Complex multi-phase models may also be necessary to account for processes such as migration of methane gas and vapor-water conversion in the vicinity of magmatic heat sources. In studies involving active tectonics such as subduction, it is important that the model account for stress and strain of the formation as well as the fluid pressure and flow. Two- and three-dimensional numerical models are presently available for some of these conditions. To incorporate all relevant features new computer model codes may have to be developed and tested. The broader the capability of the code, the greater is the range of conceptual models that can be quantified. For a general reference that covers hydrogeologic modeling the reader is referred to Ingebritsen and Sanford [1998].

#### 4.4. Existing Tools and Technologies for Hydrogeologic Measurements

We summarized in the following table the existing tools, the parameters they measure, and their limitations and advantages. Compatibility of tools with ODP operations is discussed in Fisher and Becker [1993]. The parameter symbols are defined as follows:  $\phi$  is porosity,  $\rho_a$  is resistivity,  $\rho$  is density,  $\gamma$  is gamma-log,  $p$  is pressure,  $\bar{p}$  is average pressure,  $k$  is permeability,  $T$  is transmissivity, Temp is temperature,  $k_v$  and  $k_h$  are vertical and horizontal permeabilities, and  $\Delta p$  is pressure difference.

Combined Tool	Specific Tool	Parameter	Limitations Special conditions	Advantages
<b>Logging while drilling, (LWD)</b> Goldberg [1997], Moore et al. [1995]	Formation micro imager (FMI), Neutron, $\gamma$ - $\gamma$ , Natural $\gamma$ , $\rho_a$	$\phi$ , $\rho_a$ , $\rho$ , lithology	Limited set of tools available, resolution somewhat low	For horizontal and deteriorating boreholes, time efficient, drilling need not to be interrupted
<b>WSTP, Water-sampling temperature probe</b> Uyeda & Horai [1982]	Sampler	Water sample, temp	Degassing is to be expected (Sample pressure lower than formation pressure), interruption of drilling operations, unconsolidated formations	Established and well tested procedure
	Adara (APC) tool Von Herzen & Maxwell [1964]	Temp	Up to max. 100-150 m sediment cover, measurement during coring, unconsolidated formation	Undisturbed formation temperature
<b>Straddle Packers</b>	Packers Becker [1990]	$k$ , $p$	Hole has to be in gauge, Reentry holes, stable formations	Test in specific interval possible
<b>LTO Long-term observatories (CORK)</b> Davis et al. [1992]	Thermistor string	Temp	requires remotely operated vehicle (ROV) or ship for installation and retrieval	No disturbance from drilling operations, continuous monitoring
	Pressure sensor string	$p$		
	Sampler	Water sample		
<b>Flux meters (surface)</b>	Diffusion sampler	Water sample	requires ROV, potential contamination of sample by seawater	Independant of available borehole, continuous monitoring
	Fluid flow meter	Fluid flux	requires ROV, potential influence of seawater short circuiting	
	Temperature sensor	Temp	requires ROV, potential influence of seawater temperature	
<b>Pressure core sampler (PCS)</b> Pettigrew [1992]	Sampler	Water sample	Wireline technique, compatible with APC/XCB drilling hardware, unconsolidated formations	No degassing of water sample
<b>DVTP Davis-Villinger Temperature Tool,</b> Davis et al. [1997]	Temperature measurement	Temp	Unconsolidated formations, depths > 120m	Used at larger depths than APC-tool
<b>Squeeze test</b>	Double packer assembly	$k$ , $p$	Volume of influence relatively small, consolidated formations	Rapid test procedure for tight formations
<b>Fluid logging</b> Tsang & Hufschmied [1988]	Temperature log, el. Conductivity log	Position and T of active fractures	Requires constant head difference between borehole and formation over extended time period, consolidated formations	Location and relative production rate of open fractures
<b>Drill stem test</b> Karasaki [1990]	Drill string + packers	$k$ , $T$ , $p$	Sample contamination by drilling mud, Consolidated formations, casing required in unconsolidated formations	

<i>Flow meter</i>	Rotating Impeller	v, k	Mechanical, potential for breakdown	
<i>Point dilution</i> Novakowski & Lapcevic [1994]	Packer tool	v, flow direct.	Large time requirement in tight formations, consolidated formations	Only direct measuring technique for flow velocity
<i>Mud weight</i>		$\bar{p}$		
<i>Modular formation dynamics tester (MDT)</i>	Packer tool	$k_v, k_h, \Delta p$		Measures formation heterogeneity
	Sampler	Water sample	Large borehole diameter (min. 6 “), specialist personnel	least mud contamination, fluid $\rho_a$ monitored, multiple samples
<i>Combinable magnetic resonance (CMR)</i>	NMR type sensor	$\phi, k, \text{pore}$ sizes.	Large diameter borehole $\gg 6.5$ “	Contin. profile of k, lithology indep. $\phi$ , ident. of gas hydrates

## 5. Recommendations

It is critical that the scientific ocean drilling community recognizes the vital roles fluids play in many geological processes. Apart from its geologic relevance, sub-seafloor hydrogeology deserves to be studied in its own right as an important part of the Earth system. This section presents our recommendations to address the IODP relevant hydrogeologic issues. We recommend establishment of a suite of global ocean hydrogeologic observation stations for systematic long-term measurement of the nature and extent of regional groundwater circulation beneath the ocean. This should include a number of instrumented study sites in locations representative of a range of geological settings, seven of which are described in detail in 5.2. In addition to this focused and detailed hydrogeologic work, we recommend routine collection of a basic suite of hydrological measurements on all research legs, irrespective of primary leg objectives. We also make suggestions on future efforts for technology and tool development.

### 5.1. Global Sub-ocean Hydrogeologic Observation Stations

One long-term goal of the ocean drilling data collection effort should be the establishment of a suite of global ocean hydrogeologic observation stations. Currently, little is known about the nature and extent of regional groundwater circulation beneath the ocean. Basic hydrogeologic data do not exist for most regions of the oceans throughout the world. Observations of the physical and chemical state of groundwater at shallow depths can provide insights into deep geologic anomalies, global advective heat flux, the evolution of ocean chemistry, areas of potential magmatism, zones of intense deep fracturing, regions of potential petroleum accumulation, and unknown areas of enhanced sub-oceanic biotic activity. Collection of basic physical and chemical measurements would enable important fundamental issues regarding ocean physical and chemical hydrogeology to be addressed. These issues include

- discovery of large-scale sub-seafloor groundwater flow systems
- identification of regions of sub-oceanic groundwater recharge and discharge
- detection of regional convection systems
- relationship between terrestrial and oceanic groundwaters
- baseline chemical and thermal signatures of groundwater through the ocean
- determination of the geometry of suboceanic hydrothermal vent systems
- locating regions of anomalous fluid pressures in the oceanic crust
- deducing the 3D hydrogeologic architecture and the worldwide pattern of vertical flow

through the ocean floor

To address these issues and others, we recommend IODP begin by collecting data regarding the physical and chemical state of groundwater that lies beneath the oceans. A suite of monitoring wells should be established with the aim of determining the hydraulic head, chemical composition, and temperature of groundwater in sediments and the underlying basalts throughout the world's oceans. We further suggest that IODP make it a baseline task for future legs. That is, during each leg to a new area, piezometers would be installed, and physical and chemical data collected. Initially, the coverage of the stations would be dictated by other priorities within the IODP. Once a framework of stations was established, additional data could be collected in a dedicated effort that might span several decades. The ultimate goal would be the development of a comprehensive coverage of the oceans and the ability to address the hydrogeologic issues at a variety of spatial scales.

## **5.2. Dedicated Hydrogeology Legs**

We recommend IODP dedicate hydrogeology legs in selected type settings where fluid flow clearly plays an important role in sub-seafloor processes. We select seven settings composed of 1) mid-ocean ridges and flanks, 2) subduction zones, 3) seismogenic zones, 4) coastal zones, 5) carbonate platforms, 6) deep biosphere, and 7) gas hydrates. Locations chosen for investigating these settings should have a limited and identifiable number of driving forces controlling fluid flow and transport dynamics. There has been preliminary work carried out during previous ODP legs in some of these settings, so that existing site survey data can be utilized. In the following, we describe for each setting, the background, key issues, and recommendations.

### ***5.2.1. Mid-ocean Ridges and Flanks***

Nowhere is the presence of sub-seafloor hydrology more dramatically manifest than at mid-ocean ridges, where water is driven through and reacts with highly permeable rock at temperatures commonly reaching 300 to 400°C and higher. Fluid density contrasts that arise to generate buoyancy driven flow at ridges can be nearly 2:1. Consequences of circulation include rapid exchange of elements and heat between the crust and oceans, deposition of large mineral deposits at the seafloor, and nourishment of unique animal communities at seafloor vents and possibly large microbial populations in the sub-seafloor. The same physics of buoyancy-driven flow operates at points of discharge on ridge flanks. Discharge is focused through permeable pathways such as igneous outcrops, faults, or fractures, with the thermal plumes within the host rock inducing chimney like updrafts. The stability of the thermal structure resulting from the thermal capacity of the rock combines with the permeability structure to produce long-lived vent systems. At ridge axes, this results in the creation of large concentrations of hydrothermal minerals often deposited during repeated phases of activity at the same location.

#### **5.2.1.1. Current knowledge: Ridge Flanks and Old Ocean Basins**

Over the past three decades, considerable attention has been given to understanding mechanisms and consequences of hydrothermal circulation in the oceanic crust on ridge flanks. In addition to the integrated application of remote techniques of seismic reflection and refraction, coring,

heat-flow, pore-pressure, and seep-fluid sampling, chemical and physical studies of crustal fluid flow have benefited tremendously from DSDP and ODP drilling. Three locations that have been investigated extensively using this broad range of tools have become icons for crustal fluid-flow studies: North Pond on the Mid-Atlantic Ridge flank (DSDP Site 395), the Costa Rica Rift flank (DSDP Site 504 et al.), and the Juan de Fuca Ridge flank (ODP Sites 1023-1032). The experience gained at these sites provides us with a great deal of insight into the physics and chemistry of ridge flank hydrothermal circulation, as well as into the most efficient way that traditional and newly developed tools can be applied to the study of fluids in the crust.

Through these and other studies, the first-order hydrologic architecture of oceanic crust is now reasonably well established. Highest permeabilities are found in the uppermost extrusive layer, with values ranging from  $10^{-14}$  to  $10^{-9}$  m<sup>2</sup>. Davis et al. [2001] studied three-year records of fluid pressures and temperatures at four ODP sites on the northern Juan de Fuca Ridge and eastern ridge flank and observed hydrologic transients contemporaneous with earthquakes along the ridge axis, the Nootka transform fault, and within the Juan de Fuca plate. The rate at which the transients dissipate constrains the regional-scale permeability of the upper igneous crust to be of the order of  $10^{-10}$  to  $10^{-9}$  m<sup>2</sup>. Permeabilities are highest in young crust, and the extrusive layer has been found to host huge fluid, chemical, and heat fluxes. The pattern and vigor of thermal-buoyancy-driven flow in the extrusive layer appears to be strongly controlled by the topography of the layer. Discharge through the seafloor is often focused where basement is exposed at basement edifices. As sediments accumulate, they ultimately form a low-permeability barrier to fluid flow, and if sufficiently continuous and thick, they serve hydrologically to isolate the upper igneous crust from the ocean. Where sediments are discontinuous, fluid exchange between the ocean and crust can take place over distances of tens of kilometers via channelized lateral flow beneath the sediment cover. The deeper part of the igneous crust, which comprises dikes, sills, and intrusive rocks, is also characterized by low permeabilities, although faults, fractures, and joints are suspected to provide efficient pathways for locally focused deep flow. Based on the large difference between average heat flow observed through young seafloor and that predicted on the basis of the rate of lithospheric subsidence, it is inferred that huge volumes of water circulate through the crust of ridge flanks to remove heat by advection. The entire volume of the oceans may circulate through the oceanic crust in one million years or less. Associated with this advective exchange is a large chemical flux of elements such as calcium, magnesium, and carbon. Even lower limits of the estimated chemical fluxes are large relative to those from other sources.

#### 5.2.1.2. Scientific Issues

While the above picture is widely accepted as a good "working model" for fluid circulation in oceanic crust, much remains unknown or poorly quantified. More work is needed to extend it confidently through space and time, and hence to place solid quantitative constraints on the exchange of heat and chemical species between the crust and oceans, on the state of alteration of the crust when it subducts into the mantle, and on the nature of microbial activity within the oceanic crust. Outlined below are some specific scientific issues that need to be addressed.

1. Because they occur infrequently, few faults have been intersected by drilling, and hence their influence on crustal hydrogeology is not well documented.

2. Observations in middle- and old-age crust are required to assess how permeability, internal fluid flux, and ocean-crust fluid exchange vary with time, and to document how hydrologically inactive certain old, tectonically stable, and fully sedimented areas might be.
3. Observations at outer-trench flexural zones suggest that permeability can be "rejuvenated". How common is this, to what depth does the effect of fracturing extend, and how significant is the related alteration?
4. How does the permeability of sediments depend on sediment type and the state of compaction? Can permeable pathways through sediments be established during or after deposition that allow geochemically significant fluxes in otherwise well sedimented areas?
5. Over what distances can lateral fluid flow generate geochemically significant fluxes in partially sedimented regions? Hints from recent drilling have set lower limits of many tens of kilometers, but neither the mechanism nor the full extent is defined.
6. Microbiological activity is well established in sediments, particularly in young settings where chemical gradients are high. Activity is suspected in the upper igneous crust, but not well documented. Activity elsewhere is completely unexplored.

#### 5.2.1.3. Recommendations on Observational Tools and Research Strategies

Virtually all that is known about circulation has been inferred from observations at the seafloor, or from relatively shallow drilling of hydrothermal mineral bodies. Drilling into the igneous crust at mid-ocean ridges has proven to be extremely difficult because of the highly incompetent nature of rubbly or fractured young extrusive rocks. Problems with hole completion are also severe because the fractured rock that extends right to the seafloor is highly permeable, making holes difficult to case and cement. Addressing these issues requires improved capabilities. Use of nested casing strings and high-density muds to stabilize holes may open the door for successful drilling in the future. Once holes can be more reliably established, it will be necessary to design experiments for long-term monitoring and fluid sampling in order to document the processes that are known to be characterized by large variability over a broad range of temporal scales.

The research strategy involves work on two major fronts. First, work must be done in older ridge flank and ocean basin settings so that the basic principles that have been learned in younger settings can be generalized. Most detailed studies have taken place in settings less than 7 Ma old. A small number of "characteristic" sites spanning a broad age range should be defined and targeted for new detailed surveys and drilling. Second, at a few sites, deep drilling and observations will be required. In most cases explored to date, it has been found that the extreme vigor of circulation in the uppermost extrusive section effectively masks any physical or chemical signals arising from deeper crustal flow. While studies of hydrologic processes on mid-ocean ridge flanks and at ridge crests may differ in detail, there are many elements that are common to both. We highlight here the main study components.

Site Selection The most efficient approach must begin with choosing sites with care, with an emphasis 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.

Geophysical Imaging Before any drilling experiment can be planned, the hydrologic structure must be mapped in three dimensions using an appropriate combination of swath acoustic imagery and seismic reflection profiling. This task is made easy in those ocean crustal environments most suited to drilling because the first-order structure is established by the upper igneous rocks and the sediments that cover them. 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 lesser degree permeability, can be had from seismic velocity and gravity data. It is also important to integrate downhole geophysical imaging with all other information once a system has been drilled. Resistivity, porosity, seismic velocity, self potential, electrical resistivity imagery and acoustic imagery logs all provide valuable constraints on the nature and heterogeneity of formation parameters.

Fluid Chemistry Dissolved tracers of fluid flow can be divided into several broad categories depending on the chemistry of the fluid-solid reactions. Certain elements such as Mg and Sr are sensitive to basalt-seawater interaction. Mg reaction is sensitive to temperature, and the combination of changes in Sr concentrations and isotope ratios provide a tool for determination of the degree of basalt-seawater interaction. Other elements such as Cl, Br, and He are commonly assumed to behave conservatively in these reactions and can be used to determine mixing proportions between various water sources. Some dissolved components (SO<sub>4</sub>, NO<sub>3</sub>, H<sub>2</sub>S) are sensitive to reactions involving organic matter. Distribution of some radioactive elements provides chronometers as well as tracers for fluid origins. Concentrations of noble gases may also be used to trace flow paths. Clearly, a high priority must be given to obtaining pristine and large-volume formation fluid samples.

Crustal Alteration The combination of thermal budgets and the fluid chemical composition of hydrothermal vent fluids provides information on mass fluxes from the crust to the oceans but they may not provide the flux information from seawater to the crust. While alteration is heterogeneous in the crust and difficult to observe because current drilling techniques recover only a small fraction of the drilled material, the distribution and nature of alteration provides valuable information about the distribution and timing of flow. The distribution of alteration products reflect the distribution of oxidation/reduction reactions in the crust. The intensity of the alteration indicates at an order of magnitude level the volume of water required to generate the alteration of the crust. These solid interactions provide an integrated picture of flow, and when coupled with the instantaneous picture from fluid compositions they can constrain the evolution of the hydrogeologic systems.

Rates of Fluid Flow Constraints on thermal structure, fluid composition, and, by inference, rates of fluid flow can be gained efficiently through heat-flow measurements and core samples collected at a density appropriate for the expected scale of spatial variations. Where flow through the seafloor is suspected or identified, direct measurements of rates of flow and samples of fluids can be obtained using benthic-barrel devices that employ samplers driven by osmotic pumps, and flow meters that utilize mechanical, thermal, or chemical-tracer sensors. More direct techniques are needed, however, for determining intracrustal flow. New borehole tools or proxies are required to better assess rates of flow at depth.

Borehole Formation Testing The greatest challenge for marine hydrogeologic observations arises from the severe limit on the number of holes that can be drilled. Strong constraints are also imposed on the time available on site. Tests are 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.

Long-term Monitoring While formation parameters can be measured or inferred from observations made at the time of drilling, observations of the state of the formation is nearly impossible 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. 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. Long-term monitoring in sealed holes allows natural variations, associated with atmospheric, oceanographic (e.g. tides), and tectonic (earthquake stress change) loading, to be documented. These signals allow large-scale hydrologic and elastic properties of formations to be determined, and the regional strain 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. Furthermore, several opportunities for providing power and communications to borehole observatories may arise in the near future. These include planned fibre-optic cable links off Japan and spanning the Juan de Fuca plate. Such links will greatly expand the capabilities for long-term monitoring and allow hydrologic observations to be integrated with observations of crustal strain and seismicity.

### ***5.2.2. Subduction Zones***

The “subduction factory” initiative aims at understanding the fate of sediments, crust, and mantle, as they enter a subduction zone and the impact of their transformations on the subduction process [COMPLEX, 1999]. In the early 80s, deep-sea fluid seepages were found on the Cascadia accretionary complex [Kulm et al., 1986] and in the Nankai Trough and Japan Trench [LePichon et al., 1986]. This important discovery, and evidence from ODP Leg 110 of active fluid flow along the Barbados wedge decollement [Moore and Vrolijk, 1992; Moore et al., 1998], boosted the scientific interest for fluid flow in active margins. Although generally less spectacular than mid-ocean ridge vents, manifestations of fluid expulsion through the seafloor in subduction trenches such as mud volcanoes, carbonate pavements and chemosynthetic communities are now known to be a relatively common feature on continental margins. One core issue of the subduction process is the mass balance from mid-ocean ridges to arcs. To establish the fluid budget of subduction zones, we need to account for (1) the free and bound water going

into the trench and (2) the free water and dissolved solutes coming out through paths other than volcanoes. Drilling in or near the trench can provide the initial condition for the incoming material. If fluid pressure is measured, drilling near the trench also provides the seaward boundary condition of the flow system. Drilling at active margins will also provide insight on the deeper processes wherever deep fluids are able to migrate to accessible depths, along active faults for example.

#### 5.2.2.1. Current Understanding of Fluid Related Processes in Subduction Zones

Water enters the subduction factory not only as interstitial fluid but also as constitutive water in minerals and can be released at stages of increasing temperature and pressure. Fluids and volatiles are thus a vital component at all depths and they play a major role in subduction-zone processes. These processes include decollement formation and sediment accretion, fault zone mechanics and seismogenesis, mineralogical transformations, mantle alteration and, magmatism.

Processes involving fluids during subduction span a wide range of temperature and pressure, from shallow sediment deformation at a few hundred meters below seafloor in the trench to partial melting in the mantle at the depth of a hundred kilometers. Thus, the subduction factory may be viewed as a chain of interacting subsystems. Near the trench, compaction is usually considered the dominant driving force for fluid flow. Several processes contribute to high loading rates: fast sedimentation in trenches with turbidite, tectonic burial of sediments beneath the margin, and increase of deviatoric stress and total pressure as a consequence of compressive stresses in accretionary wedges. These loading processes contribute to the development of fluid overpressuring in the least permeable layers. At temperatures higher than 60-80°C, mineral dehydration becomes a significant fluid source, mainly from the smectite to illite transformation. Lateral transfer of fluids released from dehydration is documented along the decollement of Barbados wedge and may be generalized to other regions [Bekins et al., 1995]. In the temperature range of the seismogenic zone, 100-150°C to 350-450°C, diagenetic reactions and metamorphic transformation within the greenschist and blueschist facies will release or uptake fluids. Pressure-solution mechanisms are likely important and may affect the evolution of porosity and permeability.

Fluids released by dehydration of sediment and oceanic crust and migrating into the overlying mantle will strongly affect its mechanical properties within the stability field of serpentinites and, possibly, of talc [Peacock and Hyndman, 1999]. Minerals of the serpentinite group all have a lower friction coefficient than crust or unhydrated mantle and could result in stable sliding. In other words, fluids released in the downgoing plate may lubricate cold subduction zones not only by the effect of fluid pressure but by promoting mantle alteration.

The influence of the subducting sediment, crust, and lithosphere on the chemistry of arc magma has long been recognized. The crust is affected by partial melting only in some particular cases, notably in the subduction of very young oceanic crust. Metasomatization of mantle prior to melting (with transport of chemical elements by a fluid phase origination from the downgoing plate) is the most generally accepted explanation for regional variations in the composition of arc magmas.

All these processes should not be treated in isolation because they may be connected by upward fluid flow along the subduction plane. Observations at the toe of accretionary wedges suggest significant fluid flow occurs along the decollement zone, but the general importance of lateral fluid transfer between the systems defined above still needs to be assessed quantitatively.

#### 5.2.2.2. Scientific questions

Large scale migration of fluid, upward along the subduction plane, has been proposed to explain different types of observations in subduction trenches: mud volcanoes [Westbrook and Smith, 1983; Henry et al., 1996], high heat flow [Langseth et al., 1990; Foucher et al., 1990], and anomalous pore fluid geochemistry [Kastner et al., 1991; Bekins et al., 1995; Martin et al., 1996]. Specific questions related to these possible large-scale fluid migrations are:

- What is the nature of the high permeability conduits that allow large-scale fluid migrations?
- What are the relative contributions of decollement, faults, permeable sedimentary strata, and extension crack networks to fluid flow? Is the oceanic basement involved?
- What is the effect of fluid flow and transport on chemical fluxes in subduction zones?
- What is the fate of all waters entering a subduction zone, i.e., how much water leaves the system via volcanoes, takes part in metamorphic reaction, or subducts?

#### 5.2.2.3. Study strategy and recommendations

Strategies in studying active margins have been in part shaped by ODP technical limitations. For example, difficulties with hard rock drilling made sedimentary wedges better prospective targets than other types of margins that may be equally interesting from a scientific standpoint. Studies of subduction thrusts have been restricted to places where they could be reached at the depth of less than 1 km. The difficulty in drilling and instrumenting holes in overpressured formations with water as a drilling fluid limits current pressure measurements to the lower bound of the probable range. Riser-type drilling should remove at least part of these limitations, but measurement of formation pressure and determination of the state of stress in a tectonically active environment will not be an easy task. To investigate pathways of flow in subduction zones, we made following recommendations.

- Fluid flow along permeable sediment horizons, fractured oceanic basement, and along faults should be considered in a comprehensive framework.
- Investigations of subsurface flow should attempt tie manifestation of surface flow to deeper conduits to quantify water and chemical fluxes.
- Efforts should be made to determine if active faults act as drains for subducted fluids. The permeability of fault zones, and particularly of the main decollement, is a fundamental parameter for models of fluid in subduction zones.
- CORK deployment should be utilized not only for long-term passive monitoring but also for multi-well hydrogeologic testing. A controlled experiment using a drill-in packer near a CORKed hole would be an efficiently way to assess the true permeability of the decollement

zone with minimum drilling disturbance. Pressure variations caused by LWD operations at Site 949 were recorded at the CORKed hole, which yielded a reliable permeability measurement even though this experiment was unplanned and uncontrolled [Screaton et al., 2000]. However, this measurement is significantly higher than single-hole tests acquired over the same pressure range. Experience from the Barbados wedge decollement showed that two well tests would be a great improvement over single well tests.

### ***5.2.3. Seismogenic Zones***

More than 90% of seismic energy worldwide is released in subduction zone earthquakes. However, only a small portion of the plate boundary actually corresponds to the seismogenic zone; where the subducting and overriding plates are coupled to some degree so that elastic strain accumulates. The energy released by an earthquake is controlled by the rupture area, the amount of slip, and the drop in shear stress. Seismology and geodetic strain measurements reveal, however, considerable complexity in the manner in which energy is stored and released within the seismogenic zone. The seismogenic zone experiment (SEIZE) was conceived as a multidisciplinary program that will allow both direct sampling and monitoring of the upper and intermediate levels of the seismogenic zone through drilling a transect of riser and riserless holes.

#### **5.2.3.1. Previous modeling efforts in coupling fluid flow and mechanical processes**

The potential role of fluid pressure in subduction zone faults has been widely discussed. It remains to be explored how episodes of fluid flow relate to episodes of sliding along a decollement. Efforts have been made to understand the links between fluid pressure and mechanical behavior of the subducting and overriding plates. Numerical models are utilized in order to extend observations made at shallow regions of the subduction system to greater depths in a predictive way. Models partially coupling sediment compaction, advective solute and heat transport, and fluid flow have been developed for accretionary prisms at Barbados, Nankai, and Cascadia [Bekins et al., 1994 and 1995, Shi and Wang, 1994; Screaton and Ge, 1997, Cutillo et al., 2001, Saffer and Bekins, 2002]. Non-linear effects of fluid pressure on permeability have been considered in decollement zones [Henry, 2000]. These approaches have still yet to take into account the full coupling that occurs between the mechanical processes and fluid flow, including the interaction between strain and fluid pressure during different phases of the earthquake cycle. There are some modeling studies coupling mechanical and fluid flow processes in seismogenic faults [Rice, 1992; Segall and Rice, 1995; Miller et al., 1999, Ge and Stover, 2000]. These models treat faults as simple geometries, which may not be directly applied to modeling the seismogenic zone at convergent plate margins. Models coupling coseismic strain with fluid flow have been applied only recently to studies in a submarine setting. Screaton and Ge [2001] modeled deformation, coseismic pore pressure changes, and fluid flow of the Nankai subduction zone during faulting events. They suggested that the pore pressure changes due to coseismic deformation appear large enough to be observable. Their effect on fluid flow, however, will depend on their magnitude relative to the pre-existing excess pore pressures.

### 5.2.3.2. Scientific Issues

It is recognized that fluid flow and pressure distribution within the subduction thrust may be one of the most important but least constrained parameters that affect seismogenic zone processes. There are, however, fundamental uncertainties concerning the interactions between temporal changes in stress, strain, and fluid pressure, and their influence on the nature of the earthquake cycle.

1. What is the nature of the up-dip limit of seismogenic activity? Why is seismogenic fault weak? Why is the seismogenic zone heterogeneous? Lateral heterogeneity or depth dependent changes in fluid pressure distribution may be a cause for the change from aseismic to seismic slip at the up-dip limit and also complexities in slip distribution and strength on the subduction thrust.
2. What controls the earthquake cycle? Hypotheses have been proposed for how the earthquake cycle may be moderated by fluids in the system. For example, the fault-valving hypothesis suggests that the episodic stress build-up and release during earthquakes dynamically interacts with a hydrologic valving action on the fault. The valving action is driven by the build-up and release of fluid pressure due to mineral dehydration reactions and the change of fault permeability due to fault slip.
3. How do episodes of fluid flow relate to episodes of fault sliding? Observed pore fluid anomalies at the toe of some accretionary wedges are proposed to be episodic and generated by such a valving mechanism. The actual applicability of the episodic fault-valving models has yet to be tested.
4. What is the fault zone permeability and its temporal and spatial heterogeneity? How do pressures build before and how are they redistributed after an earthquake? What are the main fluid pathways, along the decollement or upward along splay faults?

### 5.2.3.3. Recommendations

The hydrologic objective of the seismogenic zone experiment are best met through a combination of different approaches, several of which have already been addressed in the SEIZE Detailed Planning Group report and we highlight some here along with our other recommendations.

***Better constrain the seabed boundary condition of the subduction system including seep and diffuse flow.*** The spatial and temporal variability in flow is a challenging issue that will require a combination of methods to be used to make it tractable. Surface mapping of fluid expulsion patterns needs to be undertaken utilizing both direct measurements of fluid flow using a benthic flux meter and proxies such as heat flow and pore water chemistry. Such measurements form important components of a broad suite of measurements that will be used to ascertain the scale and nature of the heterogeneity in the fluid flow patterns within the subduction system.

***In-situ long-term measurements of fluid pressure, temperature, and chemistry need to be conducted in representative critical localities within the forearc.*** The subsurface measurement

program will ultimately involve a transect of holes utilizing both the riserless and riser ships. The time-varying properties can be addressed by long-term monitoring of surface strain and seismicity patterns and utilizing an instrumented transect of holes and cold seeps at critical locations across the subduction system. Measurements of fluid pressure, temperature, strain, seismicity, fluid flux and chemistry at several positions within the subduction thrust and along seismically active faults will be required to determine the laterally varying nature of properties. These properties are likely to provide unique constraints on the dynamics of faulting and flow episodes within these systems. Instrumented CORKs would provide a real-time record of subsurface transient events manifested by temperature, pressure, and pore-water chemistry anomalies. At the very least, these records will establish the steady state or background hydrologic state. They can also record precursor, co-seismic, and post-seismic signals. Fluctuations of the measured parameters at the deeper sites can be compared with those at shallow sites. These measurements will enable us to investigate the time delay between events occurring in the seismogenic zone and at the toe of the margin. Fluid pressure monitoring additionally offers the possibility of determining fault zone permeability, both absolute and relative to the surrounding country rock. Fault zone permeability can be utilized in discriminating competing models for the earthquake process, some of which require low permeability to maintain high fluid pressures.

***Development of fully coupled hydrogeologic models that are applicable to seismogenic subduction settings.*** One of the major goals of studying the seismogenic zone is to understand the temporal relationships among stress, strain, and pore fluid pressure and chemistry throughout the earthquake cycle. Fully coupled models will be a vital component for both pre-drilling planning and post-drilling data synthesis. The two subduction systems: Costa Rica and Nankai, selected for seismogenic zone experiments have substantially different architectures and contrasting hydrogeologic environments. These margins could serve as the model testing ground. The Costa Rica margin is characterized as non-accretionary, having a forearc consisting of permeable fractured basement rocks, with a high convergence rate of approximately 87 mm/yr, a low thermal gradient, and relatively thin underthrust sediments of approximately 380 m of predominantly pelagic clays and carbonates. In contrast, Nankai forearc is dominated by the frontal accretion of turbidities, and underplating of low permeability finer grained clay rich Shikoku basin units; has a high heat flow, slow convergence rate, and a relatively thick incoming sedimentary section of greater than 1.2 km. These differences will lead to possibly significant differences in flow path, over-pressured regions, mechanical behavior of sediments, underthrust, and forearcs. Understanding of the nature of the earthquake cycle and fluid response to seismicity from these two systems will provide much insight into the coupled processes in seismogenic zones.

#### ***5.2.4. Coastal Zones***

Building a comprehensive understanding of the origin and dynamics of submarine pore waters requires a detailed look at the processes that operate at the boundaries. This section focuses on the processes that are active at the lateral boundaries of the domain, the world's coastal zones, where the classical land-based or terrestrial hydrogeology and the marine hydrogeology interact. Three aspects of the land-sea interaction at coastal zones can be distinguished that are particularly relevant to the hydrogeology of the marine realm (Figure 3):

1. the natural flow and chemistry patterns that arise under steady flow conditions (Figure 3a),
2. modifications of the flow and chemistry patterns due to natural and anthropogenic non-steady conditions in the coastal zone (Figure 3b and 3c), and
3. compaction-driven flow in response to sediment loading (Figure 3d).

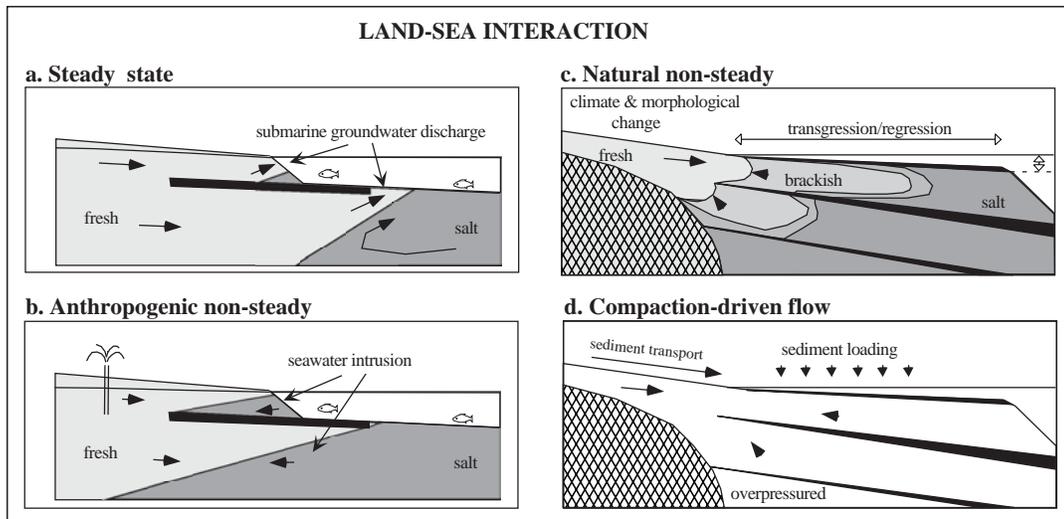


Figure 3. Land-sea interaction at coastal zones [Courtesy of Henk Kooi].

Furthering quantitative insight into the role of these aspects would necessarily be among the goals of a comprehensive marine hydrologic research program. Additionally, terrestrial hydrogeology can aid in understanding of submarine environments because submarine hydrogeologic structures are similar to onshore structures, and because patterns of terrestrial fluid flow are typical of some sub-sea bottom flows in similar geologic environments.

Data collected offshore can be critical aids in improving understanding of terrestrial systems. Submarine terminations of terrestrial aquifer systems are poorly known. Many of the terminations in island and coastal-zone settings are near-shore, often within 1 km. However, little is known about the distal end of terrestrial groundwater, and this region should be of significant interest to the IODP. There is little carefully collected offshore data on hydrogeology. Data collected by the hydrocarbon industry can be useful, but are obtained with a focus on oil and gas reservoirs that are generally located at relatively great depths. Data from shallower levels is often missing. Moreover, these data often are difficult to obtain due to proprietary concerns; thus, new data should be collected by IODP. New offshore data collection will be most effective when focused in a particular area to answer particular questions about local hydrology. Critical issues for terrestrial hydrogeology that can be aided by sub-sea data include seawater intrusion in aquifers, terrestrial aquifer water and solute budgets, and past climate and flow regimes.

#### 5.2.4.1. State of knowledge

Coastal zones are important because they are the regions in which fresh groundwater of meteoric origin and saline waters of marine origin meet. Under steady-state hydraulic conditions of sea level and recharge on land, the separation between these two water types generally takes the

form of a landward dipping interface or transition zone [e.g., Reilly and Goodman, 1985]. Consequently, a seawater wedge is often found to extend a considerable distance inland in coastal aquifers. The transition zone that forms the top of the wedge can be narrow or wide depending on the magnitude of hydrodynamic dispersion of the dissolved salts. For many decades, hydrogeologists have studied the fresh-salt transition zone, primarily with the aim of assessing fresh groundwater reserves and predicting seawater intrusion, the landward or upward movement of the saline water in response to groundwater exploitation practices [Bear et al., 1999]. Naturally, the focus has been on the prediction of fresh-salt relationships inland of the coast. A steady seaward flow of fresh water must exist that discharges into the sea by localized or diffuse seepage in the littoral zone or through the seafloor [Glover, 1959; Kooi and Groen, 2001]. Although this feature of submarine groundwater discharge has been known for a long time, concerted efforts have only begun in recent years to investigate the magnitude of this process in a systematic way [Burnett, 1999].

Non-steady hydrologic conditions cause adjustments in the groundwater flow field and chemistry distribution. The most extensively studied phenomenon of this type in coastal areas is seawater intrusion into coastal aquifers due to anthropogenic activities onshore such as pumping of fresh water [Bear et al., 1999]. Studies have focused on induced changes onshore; how far offshore the influence of these activities extends has yet been addressed. Although the impact of onshore activities on the flow field will rapidly diminish with distance offshore, the relative influence may still be quite large because natural flow rates offshore tend to be small.

Natural hydrologic conditions also change in coastal areas although at a much slower pace than man-induced changes. When viewed on sufficiently long time scales, coastal zones are very dynamic. Sea-level change, erosion and sedimentation can cause major shifts in the location of the coastline in the course of several thousands of years. For instance, during the Holocene coastlines migrated landward over distances of up to several hundreds of kilometers. Naturally, groundwater systems attempt to follow these changes [Kooi et al., 2000]. Although indications are still scarce, there is compelling evidence that in many areas, groundwater systems have not been able to keep up with these changes, leading to the development of transients in salinity patterns and flow fields, sometimes far offshore. These ground-water bodies may be defined as paleowaters in the sense that they are not part of currently active flow systems, but formed in the past under hydrological conditions different from those of today. They may be considered as relics of the land-seafloor connection from the geological past. Observations concerning submarine groundwater discharge and offshore fresh-brackish paleo-waters are detailed in Section 6.4.1.

#### 5.2.4.2. Major scientific questions

The following five key unsolved scientific questions relate to fundamental understanding of coastal marine hydrogeological systems.

1. How far offshore do continental flow systems extend, what are the controls on the extent, and what do such systems imply for the associated pore-water salinity and chemistry distribution in marine sediments?

2. What is the influence of anthropogenic changes in coastal areas on groundwater flow and chemical patterns offshore?
3. What is the distribution of fresh and brackish paleo-groundwaters offshore that are related to former low sea levels?
4. What is the role of compaction-driven flow in shallow parts of continental shelves and other shallow seas and what is its interaction with continental flow systems?
5. How does mixing of fresh and sea water affect chemical fluxes in coastal systems?

Related issues include:

- the relationship of offshore fresh and brackish groundwater occurrences to gas hydrates,
- the significance of submarine groundwater discharge and fresh-brackish paleowaters for early diagenesis,
- distinction of submarine ground-water discharge from fluid venting due to deformation such as occurs at active margins, and
- quantification of seepage contributions by tidal pumping.

The following three issues relate to the practical relevance of understanding of hydrogeologic understanding of the coastal zone for terrestrial systems.

1. What are the implications of coastal zone hydrogeology for onshore groundwater quality particularly regarding seawater intrusion in aquifers?
2. What are the implications of coastal zone hydrogeology for onshore groundwater quantities available for coastal fresh-water supply?
3. What are the implications of coastal zone relic fluids for understanding former climates and flow regimes?

#### 5.2.4.3. Recommendations on general approach and data collection

We envision a general approach that includes a major effort in three aspects: obtaining data, integrated modeling, and a coastal-zone hydrogeology-focused leg.

***To obtain data from coast to shelf edge at depths less than 1 km.*** Alternate platform capabilities are required for this purpose. The data to constrain the current flow regime and flow rates are considered important. They include accurate pressure measurements in combination with detailed recording of vertical fluid-density distribution. Including pressure measurements in low-permeability strata and deep confined aquifers is particularly important to detect compaction-generated flow contributions. Other data include seepage measurements at the seafloor, vertical temperature measurements, permeability measurements at core and formation scales, geomorphology and biota distributions to map areas of fluid discharge.

Data to constrain paleohydrologic conditions include full chemical analyses, with environmental isotopes, in both high- and low-permeability strata, resistivity and porosity logs, noble-gas recharge temperature analysis on fresh/brackish pore waters, temperature data, independent paleoclimate, oceanographic, morphologic, and sea-level data. Data required to constrain compaction-driven flow models are: geotechnical properties of sediments such as compressibility, and porosity measurements on sediment samples.

***Integrated process modeling*** It is essential to invest in both pre-cruise and post-cruise modeling. Pre-cruise models can generate working hypotheses that should provide guidance in the design of a drilling and measurement campaign, and post-cruise to serve as a framework of data integration and testing. The pre-cruise modeling should at least include a study of onshore hydrogeological data. It should also include an assessment of offshore conditions based on an inventory of hydrocarbon industry and other relevant data. Post-cruise modeling integrating chemical and hydraulic data will provide constraints on the steady or unsteady nature of the system and the role of compaction-driven flow. Modeling may be dominantly two-dimensional vertical cross-sections perpendicular to the coastline or three-dimensional in nature depending on local and regional conditions and on scale.

***A leg primarily devoted to coastal-zone hydrogeology.*** This leg may be combined with other objectives such as sedimentology; gas hydrates, or climate change.

### ***5.2.5. Carbonate Platforms***

The relatively large volumes of fluids known to circulate through many carbonate platforms drive significant water-rock interaction due to the permeable and reactive nature of carbonate sediments. These processes are also an important influence on the chemistry of the atmosphere and the oceans, regulating climate, and controlling the fate of atmospheric carbon dioxide. Understanding fluid flow and water-rock interaction is important for the effective exploitation of carbonate platforms as hydrocarbon reservoirs, and also waste repositories for industrial waste, sewage and CO<sub>2</sub>.

Carbonate rocks and sediments are characterized by a highly heterogeneous pore network, with a strong scale-dependence of permeability, as a result of a combination of depositional and diagenetic processes. Therefore even with limited hydraulic driving forces, fluid fluxes in carbonate platforms, and consequent water-rock interaction, can be significant over both short and long time scales. The interactions between large-scale fluid flow, diagenesis, porosity and permeability remain poorly understood, particularly in the marine realm. It has recently emerged that much of the carbonate diagenesis previously attributed to near-surface meteoric processes actually takes place in marine-dominated fluids.

#### **5.2.5.1. State of knowledge**

Carbonate platforms are unusual in terms of both the range of driving forces for fluid flow, which may operate singly or interact, and also the importance of the time-dimension in controlling boundary conditions and thus flow (Figure 4). In attached platforms, topographic head is the overriding driving force for fluid flow, with discharge of meteoric waters inducing reciprocal circulation of underlying seawater. Such flows also operate within exposed parts of isolated platforms, but generally extend to only shallow depth. In addition, small-scale differences in sea-surface elevation, generated by wind, storm, and ocean currents, can also drive shallow flow across reefs, tidal flats or islands. Fluid flow by thermal convection will be particularly active in platforms where surrounding oceans are deep (and thus cold) and/or platform cores are subject to a high heat flux. While thermal circulation occurs in all platforms

on a depth scale of kilometers independent of sea-level, density contrasts due to thermal gradients are small compared with those generated by salinity gradients such as evaporation of seawater or dissolution of evaporites. Such reflux circulation can also extend to considerable depth and is not limited to brines, but may be significant with an only marginal increase in salinity, and can continue after brine generation ceases.

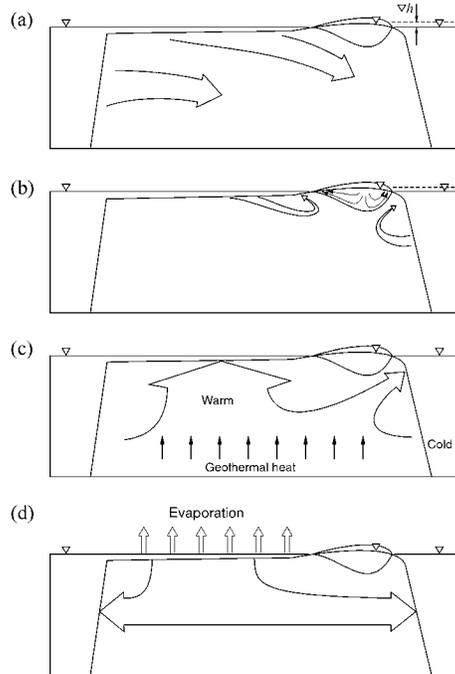


Figure 4. Conceptual models of the potentially important driving forces for large-scale circulation of groundwater within carbonate platforms [Whitaker and Smart, 1993].

In few platforms will these drives operate singly, and the interactions between different drives will depend upon boundary conditions that can vary over geologically-short time scales. Important controls include the scale of the carbonate platform, whether it is attached to a continental source of meteoric water, and the interplay between relative sea-level and platform geometry. In addition diagenesis will be strongly influenced by fluid flow and resultant changes in permeability will affect subsequent flow

Much of our understanding of flow in carbonate platforms is based on the onshore and/or shallow parts of these flow systems, and relatively poorly constrained numerical modeling. Previous deeper investigations by the ODP and others confirm both the active nature of the hydrological systems in a range of platform types, and the utility of geochemistry and temperature as tracers for flow. However, as yet they have offered only tantalizing insights into the driving forces, patterns and rates of flow. This is partly because of the lack of hydrogeological expertise and technologies. As of the present day, neither downhole packer tests (with the exception of the failed wireline packer experiment during Leg 133), nor any CORK experiments have been performed on any carbonate drilling legs. Furthermore, the critical shallower parts of flow systems within carbonate platforms remain largely unexplored.

#### 5.2.5.2. Major scientific questions

Carbonate platforms are an important link between onshore data and that from deeper sequences the offshore. Establishment of a long-term hydrogeological monitoring system for carbonate platforms requires inclusion of an alternative, shallow-water drilling platform. Hydrogeological investigations in these areas in the IODP offer an opportunity to address the following major scientific issues.

1. What are the relative scales and fluxes of flow systems resulting from different driving forces? What are the major controls on flow in response to the different drives? How do the different drives interact to control fluid flow?
2. What is the nature of the scale-dependence of permeability at depth within carbonate platforms? What role do fracture and karstic conduits play in governing flow, and how does this interact with storage in the aquifer matrix?
3. What are the nature of the feedbacks between fluid flow, diagenesis and porosity-permeability?
4. How might fluid flow respond to changes in boundary conditions through time, including sea level and climatic variations?

#### 5.2.5.3. Recommendations

Some of the failure in the past to understand flow in carbonate platforms has been a result of technological limitations such as inadequate drilling support in shallow waters and the problems of retrieving pore fluids from cemented sections and under hydrostatic pressure. To effectively address the scientific issues, we recommend future efforts be made in the following areas.

***Shallow water drilling*** Alternate platforms are used for drilling in shallow water across the platform top, and extending down the marginal slopes into the basin. We recommend developing the capability for larger diameter boreholes with off the shelf borehole fluid sampling technologies, including packers and geochemical tools.

***Data collection*** Temperature, fluid chemistry, fluid pressure, and formation permeability are essential to investigations in carbonate platforms. We recommend the use of technologies to optimize downhole measurements of temperature and fluid sampling. Installation of packed intervals within CORKed holes for long-term monitoring and formation testing to characterize and investigate interactions between units dominating flow and storage.

***Modeling*** is viewed as central both in experimental design, and as a means to examine the effect of temporal perturbations of the boundary conditions of the flow system. Flow modeling will require coupled fluid-flow, heat and solute transport codes, while reaction-transport models can provide insights into feedbacks between flow, diagenesis and porosity-permeability.

***A leg primarily devoted to carbonate platform hydrogeology*** The general approach is illustrated by a plan of a hypothetical hydrogeological leg across the Great Bahama Bank detailed in Section 6.2. Alternatively a leg on an attached platform would also provide insights into coastal zone hydrology.

### ***5.2.6. Flow Systems Supporting the Deep Biosphere***

Studies over the last 15 years have definitively established that large and diverse microbial populations are active below the seafloor. Although fundamental questions such as the maximum depth and temperature for viable organisms remain open, perhaps the most compelling question for hydrologists is the mechanism of supply of nutrients to this subsurface population. It is important to recognize that new mechanisms by which microbial life may be maintained are being continuously discovered. At this point, both heterotrophic organisms that consume deeply buried ancient carbon and chemolithotrophic organisms that harness geochemical energy of reactive rocks have been documented below the seafloor. However, abundant microorganisms do not exist everywhere in the subsurface, making it clear that a better understanding of the ecology of subsurface ecosystems is needed to predict the abundance and significance of the subseafloor biosphere.

Numerous features of subseafloor hydrologic environments exert significant influence on microbial community structure and on the biochemical processes mediated by these communities. Examples of important environmental influences include pore-water chemistry, permeability, pore size, mineralogy, temperature, and fluid flow rates. In some subseafloor environments relatively, stagnant hydrologic conditions over geologic time spans may foster microbial populations adapted to very slow rates of energy supplied from recalcitrant carbon sources. In other environments, vigorous flow driven by topography, compaction, or density contrasts may drive significant fluxes of energy supplies through high permeability zones. In both cases, a coordinated interdisciplinary approach is required to understand the many physical and chemical aspects controlling the resulting microbial ecology. One important goal of IODP investigations should be to foster such an approach. Eventually it should be possible predict the expected microbial activities in sub-seafloor environments on the basis of broad hydrologic and geologic categories.

#### **5.2.6.1. State of knowledge**

Recent reviews of the microbial communities in the deep subsurface [Krumholz, 2000] and of bacterial populations in subseafloor sediments [Parkes et al., 2000] provide a foundation for IODP studies in this field. Both articles emphasize the importance of understanding the environmental conditions that foster deep microbial communities. For example, Krumholz explains that heterotrophic populations in deep sediments flourish at interfaces where low permeability organic-rich shales are adjacent to high permeability sands carrying an electron acceptor such as sulphate (Figure 5). Parkes explains that fortuitous conditions for heterotrophic growth at depth may also result from density-driven brine excursions into carbon-rich sediments or from thermal maturation of recalcitrant hydrocarbons releasing favorable carbon sources such as acetate. In each of these examples, the carbon and electron acceptors must be transported through the pore fluids to the microbial populations. Another key observation is that sharp chemical transitions, where different compositions of pore waters mix, are frequently important in maintaining a viable habitat. Thus, understanding site hydrogeology is critical to evaluation of subsurface microbial ecologic conditions.

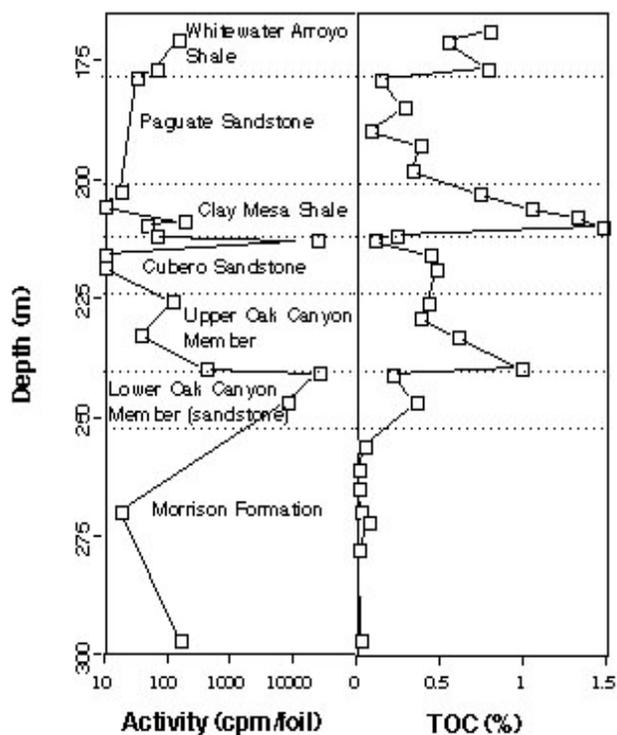


Figure 5: Relation between depth and sulfate-reduction activity and total organic carbon content at the Cerro Negro site near Seboeta, New Mexico [Krumholz, 2000].

Nevertheless, very few studies have documented the effect of hydrogeologic parameters on microbial populations. The most comprehensive studies have been of microbial populations in contaminant plumes [see Haack and Bekins, 2000, for a review]. Several studies of contaminant plumes have documented the development of a sequence of redox zones and accompanying variation in microbial physiologic processes comparable to those found below the seafloor. From these studies, it is now well established that sharp redox gradients exist in the subsurface over vertical scales less than one meter. These gradients result in concomitant changes in subsurface microbial populations over comparable scales. Thus, in locations with active fluid flow and associated solute transport, very low rates of transverse mixing in the subsurface can maintain sharp geochemical gradients fostering small-scale microbial habitat in the subseafloor environment. Results from contaminant plume studies also highlight the importance of transient hydrologic effects driving changes in microbial growth rates and shifting communities over time and space.

#### 5.2.6.2. Major scientific goals

- Identify the major ecological niches for sub-seafloor microorganisms.
- Determine how solute transport by pore fluids contributes to the maintenance of sub-seafloor microbial communities.
- Determine how the combined effects of fluid flow and microbial processes affect global geochemical budgets and diagenesis.

### 5.2.6.3. Approach and example setting

It is essential that a coordinated interdisciplinary approach be used to identify the hydrologic settings of the various deep biosphere habitats. For each setting it will be necessary to characterize the gradients in pore water chemistry, temperature, solid phase chemistry, and fluid flux. These must, in turn, be related to the associated changes in microbial populations. In each subseafloor setting, the approach should be closely tied to a conceptual model of the subsurface microbial ecology and the hydrologic environment that it thrives in.

A conceptual model of the subsurface microbial ecology is an idealized picture of the microbial populations, the energy sources and growth substrates for the organisms, and how they are supplied. A key aspect of this model is a description of the fluid flow system together with the postulated origin and fate of microbial energy sources and products. Gradients in physical and chemical properties of the environment such as temperature, fluid chemistry, and mineralogy that are postulated to result in a shift in microbial population must be described. In particular, contrasts in permeability can strongly affect flux rates, so the conceptual model should describe the expected differences in microbial populations between high and low permeability areas. The sample plan should then be carefully tied to this conceptual model. It is especially important to identify how sharp transitions in properties can be identified during drilling and targeted for microbial characterization. For example, transitions may be identified on the basis of geophysical logging, temperature, physical property changes, or pore water chemical gradients.

A conceptual model of the fluid flow system is an integral part of any program investigating the role of heat and mass flux in maintaining microbial populations. It forms the basis for a model of solute transport coupled to biotic and abiotic reactions. Eventually model results will provide important quantitative estimates on the role of the deep biosphere in mediating global geochemical cycles. The drilling plan design must include the necessary measurements to test the conceptual model of the flow system. A minimum plan must include pore pressure measurements sufficient to establish the regional pore pressure gradient and superimposed local variations. In many cases, long-term monitoring may be required to determine the importance of temporal variability in pressure, temperature, or chemistry. Currently, long term monitoring is also necessary simply to establish baseline pressures due to the extreme perturbations caused by drilling disturbances. Ideally, new tools for measuring pressure while drilling or by probing the formation ahead of the drill bit could lessen the need for establishing CORKed holes in some environments. In general, for solute transport investigations, characterizing permeability contrasts is more important than determining absolute values. This may be initially accomplished through physical property and logging observations.

### ***5.2.7. Gas Hydrates***

#### 5.2.7.1. Objectives

Gas hydrates are an ice-like form of water and low-molecular weight gas (e.g., methane) stable at the pressure-temperature conditions common in continental margin marine sediments and permafrost regions. The Gas Hydrate PPG report [2002] identifies as one of the fundamental

objectives of gas hydrate research the need to establish the distribution of gas hydrate and to delineate the dynamics of gas hydrate deposits. A fluid focused study can assist in addressing some important issues outlined by the gas hydrate community:

- Is the amount of methane sufficient to permit hydrate accumulation?
- How does gas hydrate dissociation affect pore pressures?
- Is transport of gas in and out of the hydrate stability zone dominated by advection or diffusion?  
If by advection, does methane migrate primarily in the dissolved or free gas phase?
- To what degree can the boundary between free gas and gas hydrate phases be out of equilibrium?
- How does gas hydrate alter the physical properties of sediments?

#### 5.2.7.2. State of knowledge

As shown in Figure 6 [Ruppel, 2001], the distribution of free gas and gas hydrate is controlled by flow regimes and the sources and sinks for methane. An important factor that distinguishes gas hydrate reservoirs from other marine hydrogeologic settings is the interdependence of hydraulic parameters and the presence or absence of free gas/gas hydrate. For example, free gas and gas hydrate may locally reduce permeability by clogging pore spaces. At the same time, an inherently low permeability formation will generally have more widely disseminated gas hydrate, while higher permeability zones (e.g., faults, some types of sediments) accumulate more massive hydrates.

Gas hydrate formation and stability are often viewed as a function of only pressure and temperature although the amount, composition, and solubility of hydrate-forming gases also play a critical role in determining the thickness of free gas, gas hydrate, and dissolved gas zones in hydrate reservoirs [Xu and Ruppel, 1999]. Field observations [e.g., Macdonald et al., 1994; Trehu et al., 1999; Tryon et al., 1999], laboratory and seafloor experiments [e.g., Brewer et al., 1997; Tohidi et al., 2001], and modeling studies [e.g., Rempel and Buffett, 1997; Xu and Ruppel, 1999] underscore the fundamental link between rapid fluid advection and the formation and concentration of gas hydrate. Taken together, these studies imply that an understanding of the hydrologic processes responsible for supplying and concentrating gas will be required to unravel hydrate system dynamics. Relatively little effort has been made to acquire the data needed to understand fluid flow in these settings at multiple spatial and temporal scales and from a process-oriented approach.

#### 5.2.7.3 Recommendations

There is emerging evidence that free gas as well as dissolved gas migrates through these environments. To predict the dynamics of free gas migration will require techniques developed for studying multiphase flow systems. A conceptual model for fluid and gas flow is important for analysis of gas hydrate provinces. Sufficient field measurements are necessary to test the conceptual model and to provide constraints on the driving forces for flow, pore pressure gradients, and hydraulic parameters such as permeability and storativity. Pressures should be measured at depth well below the base of the hydrate stability zones. It is important to assess varying flow pathways in heterogeneous permeability systems.

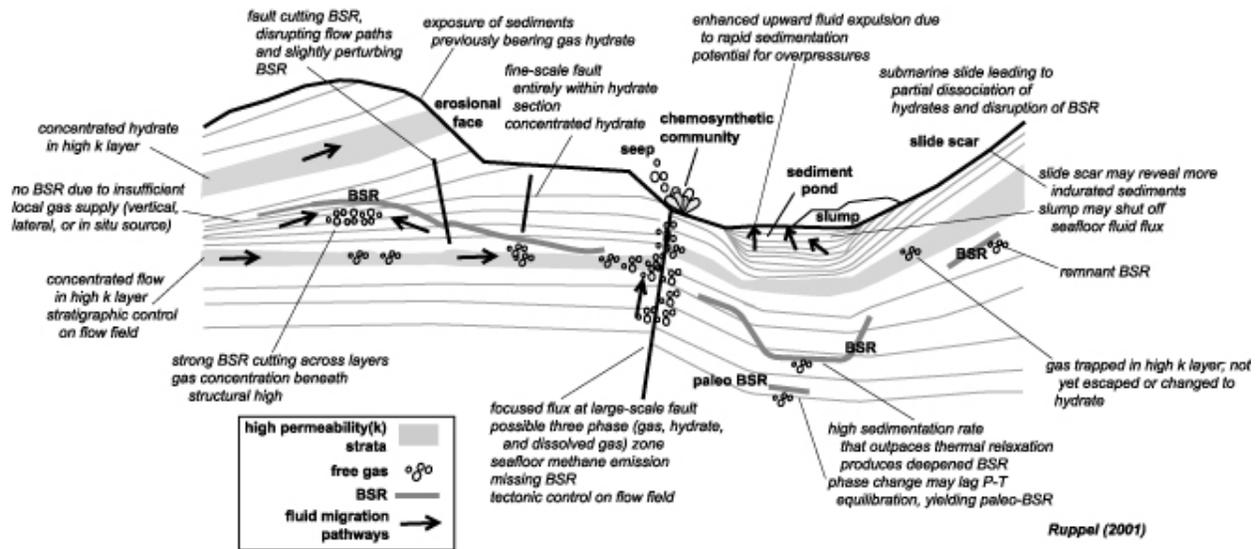


Figure 6. Schematic hydrogeologic framework for a simplified single-gas (methane) hydrate reservoir [Ruppel, 2001].

### 5.3. Collection of Routine Hydrogeologic Data on All Legs

To fulfill the objective of establishing global hydrogeologic observation stations, we recommend that future efforts make use of non-hydrogeology focused legs. This will be a cost-effective effort that offers the potential for collection of basic data to build up a broad-based hydrogeological database. This section identifies specific parameters that form the foundation for studying sub-seafloor fluid flow systems, which serves as a guide for opportunistic data collecting during non-hydrogeology legs. The detailed specification of the parameter measurement also benefits fluid-focused legs.

Some state parameters such as fluid chemistry and formation temperature are more suited to such opportunistic measurement than others such as stress and pore pressure that are easily disturbed by transients associated with drilling. With existing technologies almost all will require a reconsideration of the traditional priorities of the ODP, which focus on complete recovery of core. In addition some carry a time burden, which should be factored into planning of each leg.

For critical parameters including temperature and pressure a minimum downhole measurement frequency is suggested. However, for all parameters measurement frequency needs to be appropriate to the scale of down-hole variations. A complex permeability structure will require more frequent measurements, and any known or revealed heterogeneity such as a fault will need to be specifically targeted.

#### 5.3.1 Formation Temperature

Because of the importance of temperature measurements for interpretations of fluid flow as well as for chemistry, microbiology, and other processes, we recommend the development of a temperature and pressure tool for consolidated sediment. Prior to the routine availability of any new tool for more consolidated formations, temperatures should always be taken where packers

are set and open-hole temperatures from logging runs should be evaluated for evidence of fluid inflow. Temperature measurements are essential from the seafloor downwards in all holes. Even a few good data points provide invaluable information for the hydrogeological as well as wider community. Where holes are re-entered, temperature should be logged to aid identification and characterization of fluid flow through any open fractures. It is recommended that one scientist per shift be assigned the responsibility for temperature measurements in addition to the scientist's other responsibilities.

The ADARA APC or similar tools should be used at shallow depth, requiring every coring device to include a temperature sensor. This will be easier following a redesign of the piston coring and temperature sensor to incorporate new and rechargeable technology. A minimum of 1 per 3 cores is suggested. Below the maximum depth of piston coring the DVTP or equivalent should be at least once per 3 cores, and more frequently where fluid flow is suspected. Both ADARA and DVTP tools must therefore be routinely available, requiring regular maintenance, availability of spares, calibration and training of personnel responsible for their use. Protocols for care of temperature equipment and for the procedures for temperature measurements should be updated to reflect the current equipment and should be available to scientists online.

### ***5.3.2. Pressure***

Within partially consolidated material, formation pressure should be estimated routinely using the DVTP with pressure capability or similar tools in parallel to temperature measurements at a suggested minimum vertical frequency of 1 per 3 cores. Pressure measurements should be the responsibility of the scientist responsible for temperature measurement on the shift. This will require regular maintenance, availability of spares, calibration of the DVTP pressure sensors and training of personnel responsible for their use. Protocols for care of pressure equipment and for the procedures for pressure measurements should be updated to reflect the current equipment and should be available to scientists online.

Pressure at the bit should be measured, included in the database, and examined for evidence of any loss of circulation or fluid ingress. In addition riser drilling mud weight records should be examined, although this provides only a proxy of average total stress over the uncased length of the hole.

For stable holes, deployment of packers should be considered to determine formation pressure on legs with a hydrogeological component. Drillstring packers have been successfully deployed on the non-riser ship, but require a pipe trip. The feasibility of other packer systems, e.g. wireline, with less time costs should be investigated for the future drilling program.

Within all suspected overpressured intervals, core samples should be taken for consolidation tests. Long-term fluid pressure history should be estimated using void ratio-effective stress relationships from consolidation tests and physical property data.

### ***5.3.3. Fluid Composition***

At present many legs include geochemical analysis of interstitial fluids by squeezing of recovered cores. However, this requires early sacrifice of sections of core and thus other priorities may limit the vertical frequency of sampling. We recommend a minimum vertical resolution of 1 sample per 3 cores to determine the structure of the dissolved constituent profile, and higher resolutions where large gradients are expected.

Where packers are set, fluids should be sampled whenever possible. Where holes are re-entered, electrical conductivity of borehole fluids should be logged to aid identification and characterization of fluid flow through any open fractures. Where temperature or drilling pressure at the bit indicates possible zones of rapid fluid flow, opportunistic sampling in the open hole using downhole samplers should be undertaken. Where fluid pressures at depth exceeds local hydrostatic, often resulting in outflow of water at the seafloor, any formation water produced at the seafloor should also be sampled. We support the development of sampling tools for in-situ pore water collection. Selection of sites should be done wherever possible with the goal of intersecting locally super hydrostatic formation pressures.

#### ***5.3.4. Permeability and Porosity***

Matrix permeability in both vertical and horizontal directions should be determined routinely. We suggest that samples are taken from each representative lithology. Due to the time requirements of permeability measurements, it may be not expected that this could be accomplished shipboard. Bases using standardized testing technologies should be established for post-cruise measurements at in-situ pressure conditions, or this measurement should be conducted at a central facility with staff time budgeted. Important issues to be considered in the development of this methodology are to establish the necessary sample sizes and the degree to which situ pressures and fluid compositions must be reproduced during testing.

On legs with a hydrogeological component, LWD technology provides valuable information on in-situ properties. We recommend the increased availability of this technology to supplement existing shipboard measurement of porosity and other physical properties on cores, which is of particular importance where recovery is likely to be low

#### ***5.3.5. Fluid Flux***

A new tool to measure flow within the borehole needs to be designed for deployment in open-holes, possibly as part of logger string. This tool should be used wherever rapid fluid flux is inferred. On legs with a hydrogeology focus where packers are set, the use of point dilution techniques should be considered, potentially using temperature as a tracer. Where pressure and permeability allow rapid inflow of formation waters large-volume water samples should be collected for determination of groundwater age.

#### ***5.3.6. Stress***

Hydrofracture tests are a standard method for determination of least principal stress. We recommend that these tests be conducted in settings where stress determinations are valuable

such as in seismogenic zones. Use of these tests would be greatly benefited by development of wireline packer systems.

### 5.3.7. Pragmatic Considerations

Pragmatic considerations require that acquisition of data on non-hydrogeology focused legs should not require significant additional ship time, although suggested investment in equipment and manpower could have significant benefits. We recommend that relatively simple hydrogeological measurements (Type I, Table 2) become routine on most of the non-hydrogeology focused legs, and a case must then be made on a leg-by-leg basis for their exclusion rather than for their inclusion. For legs with a hydrogeological component, acquisition of additional (Type II) measurements should become recommended practice. There must be a requirement for inclusion of an assessment of the hydrogeology in all proposals, and these issues should be considered by the IODP review. A summary of our recommendations for these two types of legs is given in Table 2.

Table 2. Summary of Type I hydrogeological measurements recommended as routine on non-hydrogeological legs and Type II hydrogeological measurements recommended on legs with a hydrogeological component.

Parameter	Type I	Type II
Temperature	Fully supported ADARA & DVTP and new tool for consolidated material	Measurement in packed-off intervals Open-hole logging
Pressure	DVTP or similar Examination of drillers logs	Measurement in packed-off intervals Consolidation tests in suspected overpressured intervals
Fluid Composition	Core squeezing, EC logging of open holes WSTP sampler in producing holes Sampling in open holes and of any formation water produced at seafloor	Sampling of packed-off intervals Development of in-situ sampling tool
Permeability and porosity	Preserved whole-round core samples collected for post-cruise permeability measurement at elevated pressure Down-hole geophysical logging Physical properties measurement of porosity	Testing of packed-off intervals Pressure-history reconstruction for overpressured intervals
Flux	New tool for measuring flow in producing holes	Testing of packed-off intervals Dating of formation water
Stress		Hydrofracture tests

### 5.4. Developing, Improving, and Maintaining Tools

Technologies and tools are a crucial component of any successful hydrogeologic study. We summarized in Section 4.4 the status of current tools and technologies used in ODP hydrogeologic studies. Areas we strongly recommend IODP invest future efforts in are as follows.

***Developing expanded packer capabilities, such as a multi-set bottom-hole-assembly packer.*** Improved capabilities are needed to allow estimation of natural formation pressure, permeability, and stress. These are all important parameters that are difficult to obtain in any other way. Premature technology and lack of experience plagued previous attempts. Industrial packer designs and materials have improved greatly and much experience has been gained in the fifteen years that have elapsed since early failures. It is critical that IODP be equipped with reliable packer capability.

***Improving shipboard low-flow pumps and real-time downhole pressure monitoring tools.*** To carry out experiments with packers of any type, improvements are needed to better control and monitor pressures and flow delivered to packers and to the formation. Present capabilities are adequate in strong, high-permeability formations such as the oceanic crust. This is not the case in weak, low-permeability material such as accretionary prism sediments, where determinations of pressure, permeability, and stress are badly needed.

***Improving the capability and strategy for downhole water sampling.*** The water-sampling temperature probe (WSTP) has been flawed for years by the large and uncontrolled differential pressure between the formation and sample chamber, the unreasonably large volume expected from the formation, and the large diameter and irregular cross section of the probe tip. It may never be possible to obtain a sizeable volume of interstitial pore fluid from low-permeability sediments, although continuing attempts with improvements of the newer Fissler tool may prove fruitful in modest permeability material. The much simpler task of fluid sampling in producing holes will most certainly continue to be desired, so maintaining downhole fluid sampling capabilities is important, however moot in-situ sediment pore fluid sampling might be. While the debate continues on whether integration of fluid sampling, temperature, and pressure capabilities should be again attempted, it may be wise to keep the tools separate.

***Enhancing the ability to recover fluid samples from the pressured core sampler.*** Recovering fluid samples without depressurising a sample remains a challenge. Improvements could be made to the manifold subassembly of the pressure core sampler by using a different closure design if a larger diameter drill pipe were adopted by IODP. This would have advantages on other fronts as well, perhaps the most important of which would be larger volume core.

***Developing and improving temperature measurement tools.*** The next generation of temperature tools for piston coring need to allow more rapid determinations of temperature through faster time response and greater thermal isolation from the massive part of the core cutter and easier servicing through greater battery lifetime and simplified data retrieval. A goal should be set to acquire temperature data with every APC core with no significant loss of time. Furthermore, it is necessary and important for IODP to be capable of measuring temperature at depth greater than current DVTP's range of hundred meters.

***Establishing new apparatus for measuring electrical conductivity on the ship.*** Diffusivity of sediments is a critical parameter for estimating chemical fluxes by diffusion through a porous medium. Formation diffusivity can be estimated from electrical conductivity measurements on the working half of sediment cores. A calibrated device with a digital read-out should be built and maintained for use in the shipboard corelab.

***Improving tool maintenance and management*** Existing temperature tools, APC and DVTP, function well in soft sediments and should be routinely used on all legs to better understand the role of fluid flow in heat transport. To facilitate routine use, several new procedures are required. The tools should be calibrated annually for the range of temperatures expected. A full set of spare parts including a spare data logger should be carried on the ship. Guidelines specifying ideal conditions for deployment and strategies for problematic formation conditions should be developed. For example, the DVTP data from deployments in shallow water and shallow depths are often excessively noisy. The guidelines for the DVTP should describe the basic geometry of the tool, the mechanism for locking into the drill bit, distance the tool projects beyond the drill bit, and the dimensions of the telescoping section that isolates the tool from the ship's heave. The guidelines should also cover deployment issues such as force limits, required distance of insertion, problems with hole stability, use of pumps, and recommendations for use of heave compensation. The software for processing the temperature data from the ADARA and DVTP should be standardized and modernized to run under Windows with a direct link to Excel. The temperature data and fitted temperature values should be included in the Janus database.

A prototype tool for measuring in situ pressures called the DVTP-P was developed by modifying the DVTP to add the capability of measuring pressure. It was successfully used on Leg 190 and is now part of the standard suite of downhole tools. Successful use of DVTP-P requires similar formation conditions and deployment guidelines to those recommended for the DVTP. The standard deployment sequence should include a 5 minute stop at the base of the borehole to measure the hydrostatic pressure. Software for extrapolating the observed pressure decay to obtain an estimate for formation pressure should be developed and maintained on the ship.

## **5.5. Pre- and Post-Cruise Modeling Studies**

An important part of establishing an initial conceptual model is the development of a water budget of seafloor vents. Diffuse discharge may be more difficult to identify because manifestations in the way of gas hydrate accumulations, seafloor mineralization, and seafloor biological communities are rare. In some settings the development of other budgets, e.g., heat, carbon, or sediment, will be necessary. Heat flow rates, chemical concentrations, and other data, e.g., the presence of a BSR, may provide important constraints on flow directions and exit points. Modeling is initiated as a guide and it is anticipated that the model will be changed as new information becomes available. A conceptual model of a particular type setting is quantified by the introduction of known geology, boundary conditions, initial conditions, and driving forces. In many sub-seafloor investigations, the geometry of the system is reasonably well constrained by seismic investigations. In contrast, flow system boundaries may be difficult to identify. From seismic information and knowledge of the geologic setting, hydrostratigraphic units, which are geologic units of similar hydrogeologic properties, can often be defined. Ranges of values for hydrologic parameters like permeability can be identified from previous drilling results, if any, or from the literature pertaining to similar areas.

We recommended that pre-cruise hydrogeologic modeling be carried out early in the investigative process, perhaps even before writing a proposal for a drilling leg. For very modest cost, pre-cruise modeling can give the scientist a conceptual understanding of the

hydrogeological system. Modeling can be of help in formulating hypotheses and defining investigative strategies, e.g., drilling locations, when only limited data are available. The pre-cruise modeling exercise can also narrow down possible scenarios by eliminating those deemed to be unfeasible. The results of a modeling effort should not preclude drilling at a particular site, however, if there are other compelling reasons to suspect that there may be scientific payoff. It is likely that most of the modeling effort will be in developing the conceptual model, rather than on complex numerical solutions. Modeling studies can often be accomplished by means of analytical solutions to relatively simple boundary-value problems. However, if more complex hydrogeological features are needed one may have to develop numerical models.

Post-cruise modeling is an effective means to synthesize data obtained during the cruise and is done to demonstrate the state of knowledge following a drilling leg. This can be accomplished by revising a pre-cruise model or by developing a completely new model. Such modeling endeavors are often an integral part of reporting the results in the open literature. Post-cruise modeling can also be used to demonstrate where understanding of processes occurring in a given setting is lacking and point the way for future investigations.

## **5.6. Encourage Larger Hydrogeological Community Involvement**

We recommend holding future hydrogeology-focused workshops as a way of informing and encouraging participation of the interested hydrogeology community.

We recommend staffing hydrogeologists on all relevant IODP cruises and making a good-faith effort in nurturing hydrogeologists who were not previously involved in ODP experiences, encouraging more research legs devoted to fluid flow studies, and supporting one or more fluid flow analyst or modeler for each of the type settings described in this report.

We also encourage bringing scientists with hydrogeology expertise into as many scientific advisory panels and committees as appropriate. Evaluation of proposals should be conducted by a multi-disciplinary panel that includes land-based hydrogeologists and marine geologists.

To implement the recommendations outlined in this report, it would be prudent to provide necessary funding for hydrogeologic studies. We recommend that IODP pay special attention to the needs of developing new tools for hydrogeologic measurements, and of pre- and post-cruise modeling studies in order to achieve specific hydrogeologic objectives.

## 6. Appendix

### 6.1. Coastal zones (supplement to Section 5.2.4.)

This section elaborates on the brief summary of the state of knowledge of marine hydrogeology of coastal zones. Observational evidence and insights from process modeling are discussed concerning a) submarine groundwater discharge b) offshore paleowaters and c) compaction-driven flow in coastal zones and continental shelves. Also, an illustrative example design of a hydrogeological leg devoted to the study of fresh-brackish paleowaters in the continental shelf of Suriname (South America) is presented.

#### *6.1.1. Seaward continuation of continental groundwater systems*

Under steady-state conditions, seaward flow of fresh groundwater causes discharge into the sea by localized or diffuse seepage in the littoral zone or through the seafloor [Glover, 1959]. Although this feature of submarine groundwater (SGD) discharge has been known for a long time, concerted efforts have begun in recent years to investigate the magnitude of this process in a systematic way [Burnett, 1999; [kellia.nioz.nl/loicz](http://kellia.nioz.nl/loicz)]. Primary attention in this work is presently directed towards elucidating the influence of SGD on marine ecology through its delivery of fresh water, nutrients and pollutants to estuaries and seas. However, SGD is also intimately related to groundwater flow and pore water chemistry in sediments below the seafloor. At present, relatively little is known about the seaward continuation of continental ground-water flow systems. Nonetheless, there are several observations that suggest that the seaward influence of fresh-water flow systems can be quite extensive. In the following, a review of these observations is given.

#### Submarine springs

Submarine springs are the most spectacular manifestations of ground-water discharge to the sea. Often, they can be recognized by eye (boils, different water color); in other cases they are detected indirectly, by anomalous salinity, electrical conductivity and temperature of seawater. Some submarine geomorphological features such as karstic solution forms, slumps resulting from ground-water sapping and circular depressions (pockmarks from gas release) on flat seafloors sometimes are also taken as indirect evidence for SGD [Robb, 1990; Harrington, 1985]. Submarine springs were already exploited as a source of water supply in ancient times. Kohout [1966] and Zektzer et al. [1973] provide reviews of many of the known submarine springs. The coasts of the Mediterranean Sea, Black Sea, Persian Gulf, Florida, Yucatan (Mexico) and the Caribbean are well known for this phenomenon. Submarine springs are also reported near Hawaii, Samoa, Australia, Japan, Norway and Chile.

Submarine springs appear to be mainly associated with karst regions where highly pervious conduits allow efficient transport of fresh water far into the offshore. One of the largest known springs occurs 4 km off Crescent Beach, Florida with an estimated discharge of 42 m<sup>3</sup>/s [Kohout, 1966]. Outflow of fresh or brackish water has been suggested to occur over a 50 m deep depression in the seafloor as far as 200 km off the coast of Florida at a water depth of 510 m, based on observations made by the submersible ‘Aluminaut’, [Manheim, 1967]. Although

the suggestion that this flow is driven by hydraulic heads onshore seems rather implausible, convincing evidence that fresh-water flow can extend far into the offshore was provided during the JOIDES drilling project in 1965; in the test hole J-1B, located 40 km offshore, a fresh-water head of 9 m above sea level was measured in the Eocene Floridan aquifer system at a depth of about 250 m below sea level, which is considerably higher than the fresh-water head of about 6 m corresponding to a hydrostatic seawater column to that depth [Kohout et al., 1988].

### Submarine diffuse seepage

Though diffuse seepage probably is the more common mechanism of SGD, it is also more difficult to detect. Submarine seepage may be observed and quantified by means of seepage meters [Simmons, 1992; Cable et al., 1997] or mass balances of tracers with contrasting concentrations in seawater and ground water like radon, radium, methane, barium and TDS (e.g., Bugna et al., 1996; Cable et al., 1996; Moore, 1996; Chanton et al., 1996). Remarkably, high seepage rates have been measured with these methods. Cable et al. [1996] found average summer seepage rate of 20 to 70 mm/day in an area of 21 by 30 km in the north-eastern Gulf of Mexico using  $^{222}\text{Ra}$ . Bugna et al. [1996] arrived at similar rates of 5 and 20 mm/day using methane. Moore [1996] reported rates of 5 mm/day for an area of 20 by 320 km along southeastern coast of the USA based on a  $^{226}\text{Ra}$  balance. Shaw et al. [1998] reached the same conclusion using barium. The results of the latter two studies compare favorably with rates of 5 to 20 mm/day found with seepage meters along the coasts of North and South Carolina [Simmons, 1992]. Guglielmi and Priour [1997] carried out a mass balance study on TDS in the Mediterranean Sea south of Nice. They determined an average seepage rate of 10 mm/day for an area of 1.6 by 2.0 km in front of the coast. If the submarine seepage reported in the above studies originates from the continent, the aquifers must carry very high ground-water flows of at least 20 to 1400  $\text{m}^2/\text{day}$ . These flows would require very high hydraulic head gradients. For instance, for an aquifer with a very high transmissivity of 4000  $\text{m}^2/\text{day}$ , gradients of 0.005 to 0.350 would be required which, in most cases, are unreasonably high. A large part of the inferred seepage may, therefore, represent recirculated seawater associated with subtidal pumping as suggested by Simmons [1992] and Cable et al. [1996].

### Indications from modeling

Glover [1959] was the first to explicitly model the offshore distribution of fresh groundwater in a coastal aquifer. By making a large number of assumptions - sharp interface, no flow in the saltwater domain, uniform and isotropic aquifer permeability, total fresh water discharge below the sea – he was able to derive a simple expression

$$x = 20 \frac{Q}{K},$$

that relates the width of the sub-sea seepage face,  $x$ , [L] to the fresh water discharge,  $Q$ , [ $\text{L}^2/\text{T}$ ] and aquifer hydraulic conductivity,  $K$ , [L/T]. Inspection of this expression shows that, even for very favorable conditions, the fresh-water seepage face will not extend much further than several hundreds of meters into the sea. Meisler et al. [1984] used a numerical approach to calculate the location of a steady-state sharp interface for conditions that are representative for the New Jersey

continental margin. Their results showed that the seepage face can extend far into the offshore if a strongly anisotropic permeability exists. For a ratio of horizontal to vertical permeability of 30,000 – representative of sand-shale layering - they found the fresh-water domain extends some 60 km offshore and the fresh-water layer at the coastline to be about 1,000 m thick.

Kooi and Groen [2001] recently applied both sharp-interface modeling and variable-density flow and transport modeling to a problem in which a high-permeability aquifer is overlain in the offshore by a low-permeability aquitard. They showed that sharp-interface models such as those discussed above significantly overestimate the offshore extent of the fresh-water domain because input of salt from the sea through the seafloor by diffusion and unstable convection assume an important role. Even in this case, occurrence of relatively fresh pore waters up to several tens of kilometers offshore is deemed likely under favorable conditions.

### ***6.1.2. Offshore fresh and brackish paleowaters***

Natural changes in hydrologic conditions in coastal areas tend to occur at a much slower pace than man-induced changes. Nonetheless, when viewed on sufficiently long time scales, coastal zones are very dynamic. Sea-level change, erosion and sedimentation can cause major shifts in the location of the coastline in the course of several thousands of years. For instance, during the Holocene coastlines migrated landward over distances of up to several hundreds of kilometers. Naturally, ground-water systems attempt to follow these changes. Although indications are still scarce, there is compelling evidence that in many areas, ground-water systems have not been able to keep up with these changes, leading to the development of transients in salinity patterns and flow fields, sometimes far offshore. These ground-water bodies may be defined as paleowaters in the sense that they are not part of currently active flow systems, but formed in the past under hydrological conditions different from those of today. They may be considered as relics of the land-seafloor connection from the geological past. In the following, evidence for these transients is briefly reviewed.

Nantucket island (USA) – Atlantic Ocean Kohout et al. [1977] describe a borehole at Nantucket island, 70 km off the Atlantic coast at Cape Cod (Massachusetts, USA) traversing a 457 m sequence of Quaternary and Tertiary clastic sediments upon basement rocks. Fresh ground water (< 1000 mg/l TDS) was found to a depth of 158 m below sea level, followed by a zone with alternating layers of fresh, brackish and saline water down to 350 m. In the underlying basal sand layers below 350 m, salinity values again became very low (< 2000 mg/l TDS). The heads in the upper and lower fresh ground waters are 3.6 and 7 m above sea level, respectively. Kohout et al. [1977] state that the upper fresh water represents a lens of recently formed fresh water floating on saline water. They consider fresh ground water at depths exceeding 222 m to be paleo-water of Pleistocene age.

New Jersey (USA) – Atlantic Ocean A transect of 5 boreholes (Atlantic Margin Coring Program) perpendicular to the Atlantic coast of New Jersey (USA) near Barnegat Light showed that groundwater with salinities less than 5000 mg/l TDS extends 100 km offshore and to depth of 200 to 300 m below sea level [Hathaway et al., 1979; Kohout et al., 1988]. Close to the coast, almost potable submarine ground water is found (800 mg/l TDS). Modeling of the steady-state fresh-salt distribution shows that present hydrologic and sea conditions are insufficient to

account for the presence of the distal offshore fresh and brackish waters [Meisler et al., 1984; Kooi and Groen, 2001].

Paramaribo (Suriname) – Atlantic Ocean Wells in the coastal plain around Paramaribo in Suriname and resistivity logs of several offshore oil exploration wells show that meteoric ground water with chloride concentrations lower than 1000 mg/l extends about 50 km from the coastline [Groen, 1998]. This ground water is found between 100 to 250 m below msl. Moreover, pre-pumping hydraulic heads indicate stagnant or even landward hydraulic gradients.

IJmuiden (Netherlands) - North Sea Pore water samples from a very shallow well drilled in the clayey Brown Bank formation 50 km west of IJmuiden show that chloride concentration decreased from 20,000 mg/l at the seafloor to 10,000 mg/l at a depth of 5 m, suggesting the presence of even fresher water at larger depths [Post et al., 2000]. Modeling of Cl and <sup>18</sup>O vertical profiles shows that these patterns can be explained by downward diffusion of seawater into a fresh-water body since the transgression of the area about 8 ka BP.

Fresh-brackish ground water occurrences in the offshore environment that may represent paleowaters, but for which evidence designating it as this type is not as conclusive as in the above-mentioned cases, have been documented for the Atlantic Ocean at Georgia/Florida [Manheim, 1967; Kohout et al., 1988], at Port Harcourt, Nigeria (Shell, unpublished data), for the Strait of Taiwan at the Penghu Islands, for the Java Sea at Jakarta, Indonesia [Geyh and Sofner, 1989], and for the Chinese Sea at Shanghai [Wang, 1994]. Hine et al. [1999] reported brine waters at the outer shelf and shelf edge in the Great Australian Bight (ODP-Leg 182) and propose that they formed during the Pleistocene low sea level stands within extensive evaporative ponds. These waters, therefore, can be designated as saline offshore paleo-waters.

Kooi et al. [2000] recently used numerical modelling to study the transient behaviour of the salinity distribution in coastal areas during transgression. They found that Holocene transgression rates were often sufficiently high to cause the fresh-salt transition zone to lag behind coastline migration. For permeable sediments, salinisation occurs relatively quickly by vertical intrusion of seawater plumes (density fingering). However, only relatively minor low permeability clay layers suffice to greatly reduce such salinisation rates and to preserve low salinity waters far offshore for very long periods of time.

### ***6.1.3. Compaction-driven flow***

Loading associated with sediment deposition in coastal areas induces compaction-driven flow of pore water in the underlying sediments. Hence, sediment transport from the continent by fluvial systems and deposition in deltas and in the offshore environment provides an indirect way in which terrestrial processes are connected to sub-sea hydrology.

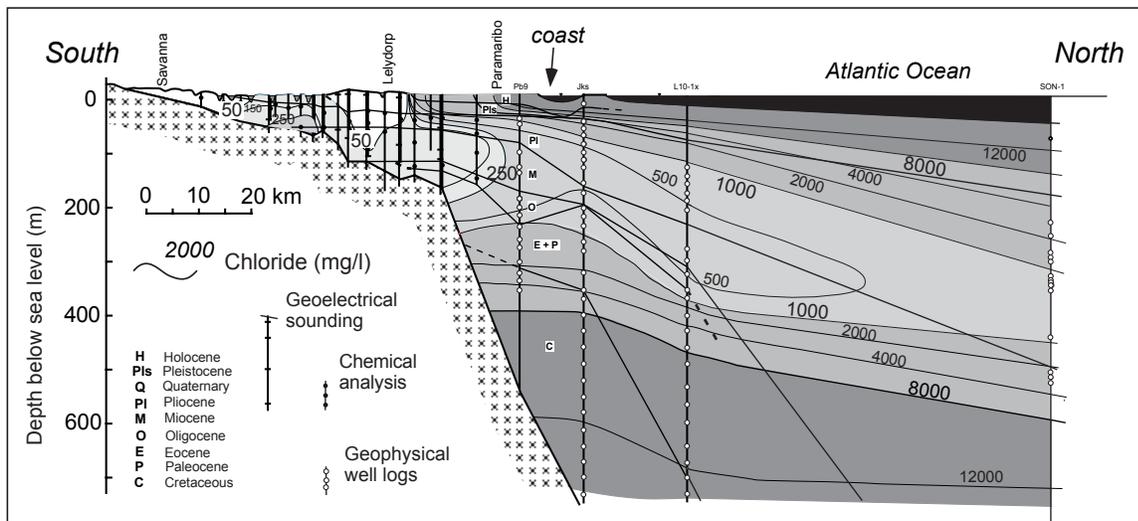
Over the years, numerous studies have addressed the role of sediment loading in the generation of high pore fluid pressures in deep confined parts of sedimentary basins. Other studies have used numerical or analytical methods to investigate the role of compaction-driven flow relative to other flow mechanisms in shallower parts of sedimentary basins. For instance, Person and Garven [1994] illustrated how the compaction-dominated domain in the central part of a

continental rift-basin expands towards the basin flank as flank topography decreases over time. Kooi [1999] showed that very high sedimentation rates are required to significantly alter the topography-driven flow field in a semi-confined aquifer that is subject to a fresh-water head of only 1 m onshore. However, apart from these theoretical predictions, observational data that would document the role of compaction-driven flow at shallow parts of sedimentary basins are still lacking.

#### 6.1.4. Example setting

An interesting location to study offshore paleowaters is the continental margin off Suriname (South America). The following two figures serve to illustrate a hypothetical (rough) design of a hydrogeological leg in this area that would meet the general approach and data acquisition criteria outlined in chapter 5. The first figure summarizes results of an onshore hydrogeological study augmented with chloride data inferred from offshore oil-industry well-log data [Groen et al., 2000]. The chloride data together with hydraulic data onshore suggest virtually stagnant conditions and the presence of fresh/brackish paleowaters far offshore. The second figure summarizes a series of proposed boreholes together with measurement to be obtained in them in addition to standard measurements such as temperature profiles, logs, seismic studies, sediment samples etc. (distribution of aquifer/aquitard units is fictitious). This design of a hydrogeology leg would be suited to address the following:

1. constrain the present offshore flow field and hydraulic/geological structure.
2. provide more insight into the offshore water quality distribution.
3. explain the genesis of the offshore water quality distribution in relation to climate change, sea-level change and geological structure of the margin.
4. constrain the role of compaction-driven flow in this setting with high Holocene sedimentation rates.



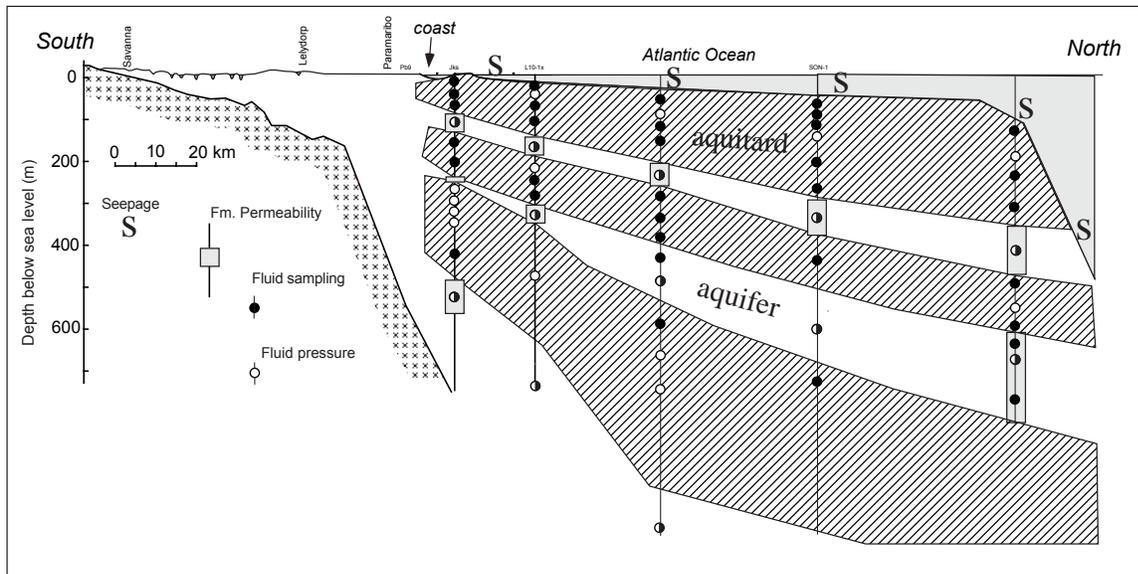


Figure 7.

## 6.2. Carbonate Platforms - Ideal Drilling Transect (supplement to Section 5.2.5.)

The following is a broad template for hydrogeological investigations of carbonate platforms.

1. Formalize conceptual models of possible platform-scale fluid flow systems. Establish a hydrostratigraphy for the platform, based on detailed seismic investigation and previous drilling. Numerical rather than analytical solutions will probably be required due to complexity of the systems (several interacting drives, mineral-fluid interactions, and 2 or 3 spatial dimensions plus the critical time dimension).
2. Develop drilling strategies to best test alternative hydrogeological models. Critically the platform should be investigated in its entirety, which will generally require shallow water drilling using alternative platforms.
3. Focus drilling program on characterization of formation temperature and composition of fluid in the matrix and open fractures/conduits, flow velocity and direction, permeability (vertical and horizontal) and porosity including matrix and fractures/conduits, with cross-hole experiments to determine the properties of a larger volume of rock. These investigations will involve interruption of drilling, re-entry of holes and/or loss of core.
4. Establish long term observatories, which include thermistor and pressure sensor strings and water samplers, with testing at multiple levels and investigation of matrix and fractures/conduits within packered intervals.
5. Couple subsurface investigations with additional data from onshore hydrogeological studies (for exposed or attached platforms), seepage meters and satellite-borne sensors for shallow water temperature and tidal head.
6. Compare field results with preliminary numerical simulations, refine hydrostratigraphy (including incorporation of heterogeneities), and estimates of current- and paleo-boundary conditions. Modeling will involve full coupling of fluid flow, heat and solute transport, with potential for reactive transport modeling.

A proposed hydrological leg on the Great Bahama Bank (GBB) exemplifies application of the approach detailed above.

The extensive, flat-topped platform is sedimentologically and hydrologically isolated and comprises a thick (>5 km) sequence of shallow-water carbonates and evaporites. The GBB provides the basis for the ideal drilling program to investigate fluid flow in carbonate platforms for the following important reasons:

1. A number of holes already drilled by academic and industry projects as well as ODP on the margin and slopes of the GBB, have yielded temperature profiles, rock and fluid samples which indicate fluid circulation and water-rock interaction;
2. Studies of the surficial and deep carbonate geology of the platform, together with seismic studies, provide a reasonable understanding of the geological framework within which fluids circulate;
3. Several generic modeling studies of the large-scale circulation within carbonate platforms have used the morphology, dimensions and boundary conditions of the GBB., and suggest the potential for significant fluid flow from a number of drives;
4. The extensive nature of the platform means that flow can initially be considered in 2-spatial dimensions (a section perpendicular to the bank margin). This initial simplification is particularly important given the critical role of the fourth dimension (time) in controlling drives for circulation.

More geological investigations have been carried out on GBB than any other carbonate platform. These include 2 ODP legs off the sediment-draped western margin and the Bahamas Drilling Project (BDP) which drilled 2 holes some 20 km from the platform margin in <10 m of water. However, it remains unclear what drives fluid flow within the GBB, how much water is moving and what the circulation pattern might be. Potentially important drives include

**Topographic/elevation head.** The shallow hydrology of the emergent islands such as Andros on the eastern GBB is relatively well known [Whitaker and Smart, 1997], with meteoric circulation (maximum depth 45 mbsl) entraining reciprocal flow of seawater. While currently only affecting the eastern side of the GBB, during sea-level low-stands the entire platform would be emergent potentially creating a very extensive meteoric-driven circulation. In addition the oceanographic context of the platform may be of hydrological significance [Whitaker and Smart, 1990], with the possibility of subsurface flow in response to the head difference (average 76 cm) set up across the Straits of Florida by the Gulf Stream [Maul, 1986].

**Geothermal convection.** Little is known of the distribution of groundwater temperatures, although cool temperatures at shallow depth beneath Andros Island [Whitaker and Smart, 1993] indicate removal of geothermal heat by shallow circulation of cooler ocean-derived waters. In addition the discharge of cold water of near seawater composition from marginal submarine springs [Whitaker and Smart, 1990, 1993] and inverted thermal profiles in deep marginal test wells [Walles, 1993] are suggestive of thermal convection.

**Reflux.** At present the GBB is flooded to shallow depth (<6 m), with restricted platform-top circulation giving seasonally elevated salinity (locally exceeding 46 ‰). These water have the potential to reflux [Simms, 1984], and have been identified in deep (c 100 mbsl) sinkholes beneath Andros Island and discharging from submarine springs off the east coast [Whitaker and

Smart, 1993; Whitaker et al., 1994]. Significantly higher salinity waters (<62 ‰) have also been detected in holes on the western slopes of the GBB during Legs 101 [Austin et al., 1986] and 166 [Swart et al., 2000], possibly representing residual brines from Pleistocene reflux events currently discharging from the platform [Jones et al, 2002].

The flow system within the GBB is likely to be a complex product of a number of drives, some of which are critically dependent upon relative sea-level. These operate within a porosity-permeability network that is not only locally highly heterogeneous, but also shows large-scale patterns, within progradation and infilling of older troughs and diagenetic modification by meteoric and modified seawater. The number, distribution and types of holes drilled to date on the GBB, and the types of measurements made and samples collected remain inadequate to characterize the flow system. Important questions about the drives for, patterns and rates of fluid circulation, and their consequences for carbonate diagenesis and geochemical cycling within the GBB remain unanswered. An investigation targeted at the hydrology of the platform from the basal slopes into the shallow platform interior thus offers great potential.

### **Specific Drilling Plan**

**Shallow Water Drilling:** Using a jack-up drilling rig we will drill up to six holes on GBB along the Western seismic line across the top of the GBB to the western coast of Andros Island. Tentative locations of these holes are shown in Figure 7, although precise locations will be confirmed by an extensive seismic survey. It is critical to acquire good temperature profile during drilling, and measurements of pressure while drilling should be attempted. The drilling program at all of these sites will be optimized to acquire these downhole measurements and to collect fluid samples. We do not rule out the possibility of drilling dedicated holes for fluid sampling. Once high flow zones have been identified a limited number of packer tests could be performed within and between these intervals. In addition core-scale permeability will be measured routinely. In order to preserve the wells for later experiments, well heads will be installed so that access to the wells would be possible for later experiments which should include rate of recovery from transients associated with drilling, and assessment of post-recovery fluid pressure and fluid composition.

**Deeper Drilling:** A series of holes would be made parallel to the existing ODP sites 1003-1007. These will enable assessment of spatial variability of sedimentology and geochemistry, but their primary objective is to permit detailed downhole temperature and pressure measurements. This series of holes would be extended into shallower water (100 m) to fully characterize the platform margin. Measurements and experiments will be as described above for shallow water drilling, although technologies may differ as much of the work will be in unconsolidated or poorly consolidated sediments, while on the platform the sequence will be completely lithified. CORKs will be installed in a subset of the sites to permit subsequent sampling of fluids and aquifer testing.

**Additional technologies:** A network of relatively low-cost seepage meters [Tyron et al, 1999] will be deployed over the slope of the GBB to enable measurements of the chemistry and flux of any diffuse discharge. Groundwater studies should be coupled with high-resolution sea-surface satellite altimetry and measurements of ocean currents and atmospheric pressure to constrain modern boundary conditions. These measurements should be made over 2 annual cycles.

**Modeling:** We consider numerical modeling of equal importance as the field program. The critical contribution of the modeling is to permit investigation of the effects of temporal variations in boundary conditions particularly sea-level and platform-top salinity. Short-term perturbations may have long-term consequences on groundwater flow, and the current groundwater system may be the product of a complex history of changing boundary conditions. Two phases of numerical simulation modeling will be undertaken using a fully-coupled model of fluid flow, heat and solute transport [Jones et al., 2000] in 3D (two spatial dimensions over time). Prior to drilling the model will be employed in experimental mode, with roughly constrained boundary conditions and rock properties, to determine the potential interactions between the different driving forces and identify optimal sites for drilling. Data obtained during drilling and from subsequent borehole observatories may then enable refinement of this model. Subsequent incorporation of reactive-transport will enable modeling of carbonate diagenesis, including porosity feedbacks.

### **6.3. Fluid Flow in Continental Margins (supplement to 5.2.4. and 5.2.5.)**

It has long been recognized that significant amounts of fluid migration (liquid and gas phases) take place in the margins of passive continental margins and isolated carbonate platforms. However, the magnitude of such flow and hence its geochemical significance remains largely unknown. At the time of COSOD II for example, it was estimated that approximately 100 km<sup>3</sup>/yr fluids was discharged from the ocean crust through passive continental margins as a result of gravity flow. This estimate compares with an estimated total of 584 km<sup>3</sup>/yr of fluids through ocean ridges and the flanks of ocean ridges and 1 km<sup>3</sup>/yr through accretionary prisms. While such estimates were recognized at the time of COSOD II as being inadequate, it is now believed that discharge to the coastal zone in some areas may be significantly higher than previously realized. In addition several other mechanism of fluid flow in continental margins have been recognized leading to realization that the COSOD II estimate of fluid discharge through passive margins may be in error by an order of magnitude or greater. If true such fluxes would (i) exceed those estimated through all other types of systems combined, have (ii) significant impact upon the geochemical cycling of critical elements in the lithosphere and biosphere, and (iii) change our estimates regarding the residence time of important geochemical parameters.

An additional important aspect of flow along continental margins is encroachment of saltwater into potable water sources. The location of boundary between salt and fresh water is poorly constrained because of the lack of drilling in shallow shelf areas. This boundary is likely to migrate through time as a result of natural climatic variations that occur at different time scales (e.g. seasonal, glacial-interglacial cycles) as well as from anthropogenic causes. Understanding of mixing between continental and marine ground water will require measuring the location and characteristics of the boundary.

#### ***6.3.1. Evidence of fluid Flow in Continental Margins***

It has long been recognized that gravity induced discharge of continental occurs along passive continental margins [Sotelo and Gieskes, 1978; Couture et al., 1978; Suess von Huene et al.,

1988; Kastner et al., 1990]. Such waters can be essentially meteoric or saline, arising from the evaporation of closed water bodies. In addition to continental margins, circulation of fluids occurs within carbonate platforms both on the scale of the smaller atolls and guyots as well as larger carbonate bodies such as Great Bahama Bank [Leg 166, Eberli, Swart, Malone et al., 1997] and the Queensland Plateau, N.E. Australia [Davies, McKenzie, Palmer-Julson, et al., 1991].

Evidence of fluid flow in continental margins and carbonate platforms can be expressed in many different forms. In the case of the Ocean Drilling Program where direct measurements of fluid movement are not available, evidence of fluid flow is derived mainly from geochemical indices as well as gradients in temperature and certain chemical properties of the porewaters.

One of the more spectacular examples of fluid flow in a carbonate platform is provided by evidence from Leg 133 which drilled the Queensland plateau off the eastern coast of Australia [Davies, McKenzie, Palmer-Julson, et al., 1991]. In this particular example clear unequivocal evidence of modern seawater being advected through the platform was provided by existence of porewaters deep within the platform with modern  $^{87}\text{Sr}/^{86}\text{Sr}$  values. The presence of underpressure was further confirmed by the measurement of temperature on the borehole during logging which suggested bottom seawater was being drawn into the hole.

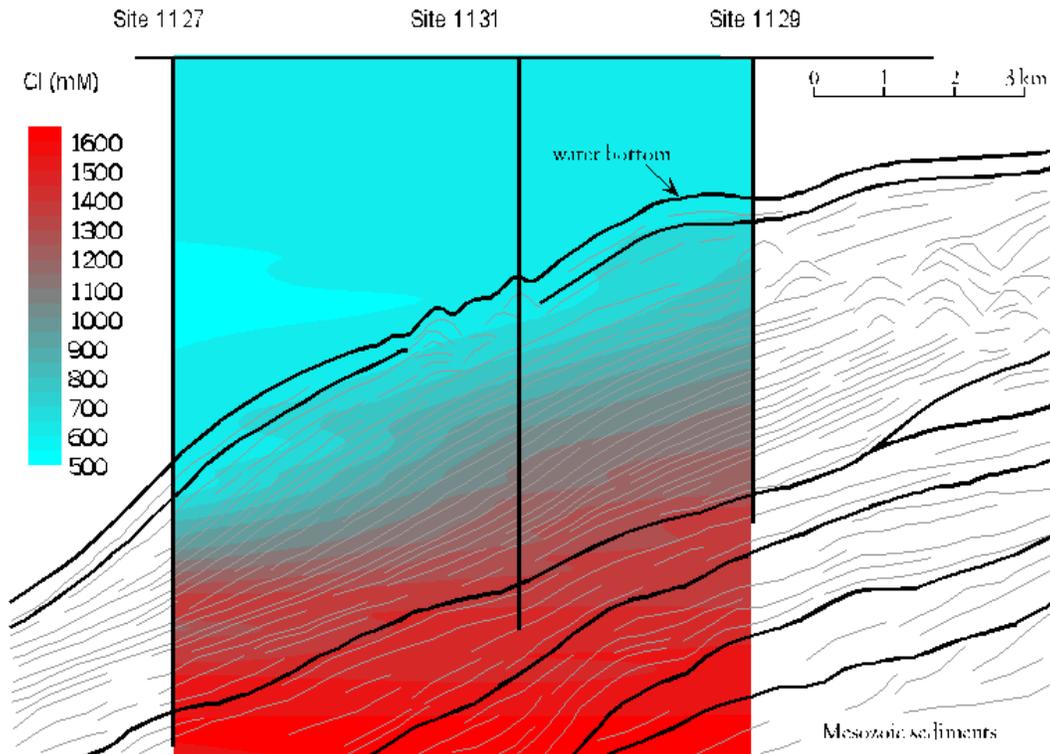
Fluid flow associated with continentally derived fluids is evident from sites drilled along the southern margin of Australia, in the Great Australia Bight. At these sites the presence of high salinity fluids, up to three times the salinity of seawater were present at a constant depth below the sea surface (Fig. 8). The constant depth of these waters and their cross cutting relationships relative to the sedimentary architecture suggests that the waters were emplaced under the influence of gravity, perhaps during a previous sea-level lowstand.

### ***6.3.2. Mechanisms of Fluid Flow***

Numerous mechanisms exist which can produce fluid movement or migration through sedimentary deposits. These mechanisms, described below operate over a range of time periods and change in importance with time. Sea-level changes are particularly important in this regard.

Gravity or Topographic Induced Flow Gravity induced flow is perhaps the most powerful mechanism for inducing flow in continental margins. It arises simply as a result of the higher elevation of land on the adjacent continents, which allows water falling on the land to attempt to find a common level by discharging through the sediment on the adjacent shelf. The magnitude of the flow is therefore directly related to many factors, most of which are poorly constrained. Some of these factors include the elevation of the adjacent land on the continent, the amount of freshwater present that is in turn related to climate, and characteristics of the aquifers such as porosity and permeability. As a result of the driving force of this mechanism, even small differences in elevation can produce large amounts of fluid discharge depending on connectivity of the aquifers. While compositions of the fluids involved in this mechanism are usually fresh, cases can arise when fluids become saline through evaporation or the dissolution of preexisting evaporites [Suess, von Huene, R. et al., 1988]. Such is the case in the example shown in from Leg 182 and in Leg 112 [Suess von Huene et al., 1988; Kastner et al., 1990]. Evidence of such

flow can be provided by the salinity of fluid (low salinity or high salinity) and the nature of the fluid body relative to the sedimentary architecture. Although gravity induced flow can occur during both highstands and lowstands of sealevel, significantly higher rates of flow probably take place during lowstands, when large portions of the continental shelf are exposed. As in the case of the example from Leg 182, fluids emplaced during lowstands can then diffuse out of the sediments into the marine environment during high stands.



Concentration of Chloride in western transect

Figure 8. Concentration of chloride in the eastern transect from Leg 182 on the S. Australian continental margin. High salinity fluids are believed to derived from shallow evaporative lakes that developed on the adjacent continental margin during a sea level lowstand.

Geothermal Flow Geothermal convection is related to the difference in temperature between the continental margin and the adjacent seaway. Typically, a difference of 50°C at a depth of 1000 meters is more than sufficient to set up thermal instabilities which cause water in the margin to rise drawing additional fluids through the sediments which lie on the slopes of the margin or platform. Recognition of geothermal convection can be achieved by examining geochemical and geothermal profiles in the porewaters and sediments. In regions of the platform characterized by active recharge, there will be an isochemical porewater profile indicating the recharge of water into the sediments. Similarly, *in situ* porewater temperature will indicate an absence of a geothermal gradient suggest the influx of bottom waters.

Reflux of Hypersaline Fluids During certain periods of geological time continental margins and carbonate platforms are only barely submerged leading to formation of hypersaline fluids. These

fluids, by virtue of their greater density can sink into the platform and penetrate through the sediments. The reflux of hypersaline fluids usually takes place during sealevel highstands when the driving force is principally the density difference between the fluids and the water within the platform.

Compaction The fluid movement and expulsion of fluids during compaction contributes fluids to the overlying seawater. This mechanism is not one of recycling and is essentially a one-way transfer of fluids.

Mineralogical and phase transformations Generation of overpressure is common in thick sedimentary sections along continental margins from mineral dehydration reactions and conversion of solid organic matter to liquid and gaseous hydrocarbons. This overpressuring creates pressure gradients that can drive flow.

Clathrates The presence of gas hydrates within passive and active margins are produced in response to fluid movement and in turn can induce fluid flow through decomposition related to climate and sea-level change.

### **6.3.3. Fluid Flow Targets and Some Technology Issues**

The understanding of fluid flow in passive continental margins and carbonate platforms can be integrated with other studies that target sedimentary architecture and geochemical fluxes. Our strategy will be to examine a transect across targeted passive and carbonate margins obtaining samples using a variety of platforms including land drilling, shallow water drilling, JR type drilling, and riser drilling. Initial transect will examine fluid flow in 2-D, with the ultimate goal of 3-D and 4-D studies.

At least some of the failure to understand flow in such environments in the past has been a result of technological problems such as the inadequate drilling support in shallow water and the problems of retrieving pore fluids from cemented sections and under hydrostatic pressure. Solution to these problems include:

- Alternate platforms for drilling in shallow water;
- Larger diameter boreholes with off the shelf borehole fluid sampling technologies, including packers, geochemical tools;
- Legacy holes with CORKS and *in situ* water monitoring and sampling;
- Pumping tests using geothermister strings, PEEPERS, and flow meters.

### **6.3.4. Previous Ocean Drilling Studies**

Carbonate sediments are currently being deposited in many low-latitude carbonate areas at present, as well as in cooler waters. Previous ODP investigations of carbonate platforms have focused on four areas, the Bahamas (Legs 101 and 166) [Austin et al., 1986; Eberli, et al., 1997; Swart et al., 2000], the NW Pacific Atolls and Guyots (Legs 143 and 144) [Paull, 1993] and Australia's Queensland Plateau (Legs 133 and 194) [Davies, et al., 1991] and Eucla Shelf (Leg 182 and proposal 565-Full) [Shipboard Scientific Party, 2000]. These sites span large- and small-scale, attached and isolated platforms, and warm- and cool-water carbonates, although ramp

systems, such as the Campeche Bank, Mexico, remain an obvious omission. This work has provided exciting sedimentological and paleoenvironmental results, and offered tantalising insights into processes controlling fluid flow in carbonate platforms. These derive largely from studies of the geochemistry of pore fluids, which consistently indicate active hydrological circulation.

**Queensland Plateau** Several sites were drilled during Leg 133, which demonstrated the presence of confined aquifers with waters showing chemical similarities. Perhaps the most dramatic evidence of fluid flow was experienced at Site 812. This site penetrated the submerged Queensland plateau and demonstrated a significant degree of under pressure in the platform which was drawing water through the cemented limestone. The active fluid flow was evident in a large section of unconsolidated Miocene aged sediments, which contained modern seawater as evidenced by its  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio and seawater like concentrations of minor and major elements. In addition during the logging of Site 812 [Elderfield et al., 1993; Swart et al., 1993] (Figure 9) the geothermal profile indicated that water was being drawn into the platform (Figure 10). In addition to Site 812, Sites 814, 813, and 811 showed indications of lateral continuity of geochemically similar units [Davies et al., 1991]. These units could be correlated using seismic data and sharp changes traced across sequence boundaries. Such difference indicates the lateral movement of fluids confined by semi-permeable sequence boundaries. Clearly, the geochemical and geothermal data from these sites indicates large-scale circulation within the Queensland Plateau. However, the driving force of such flow remains uncertain and considering the extent of the Queensland Plateau, what was drilled during Leg 133 must be considered only the tip of very large regional circulation system.

**Atolls and Guyots** Evidence of circulation by normal seawater was provided by geochemical evidence from pore fluids taken from Site 865 and 866 [Paull et al., 1993]. Pore water samples showed evidence of the flushing of the rocks by fluids with near normal seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  and oxygen isotopic ratios. In the case of atolls and guyots the case for circulation driven by geothermal convection processes is more persuasive. These bodies originally possessed high temperature cores that would setup large temperature differences between the atoll or guyot and the adjacent seaway driving water through the sediments.

**Bahamas** Three separate drilling programs investigated the fluids within and on the flanks of the Bahamian platform. The Bahamas Drilling Program (BDP) retrieved fluids from two cores drilled on the platform itself [Swart et al., 2001]. As the two holes were drilled in approximately 10 meters water depth, drilling was accomplished using a jack-up barge. In addition most of the rocks drilled were of a hard cemented nature, which precluded the squeezing of sediments to obtain pore fluids. Instead water samples were retrieved by pumping during hiatuses in drilling and by using a bailer after logging. In spite of these constraints formation fluids were obtained which were substantially different from surface seawater [Swart et al., 2001] suggesting that active diagenesis is taking place within the carbonate platform in the absence of the influence of meteoric fluids. These workers also concluded that active the chemical analyses of the fluids suggested active flow within the platform. The evidence which they presented was (1) the presence of fluids with Sr-isotope compositions that reflect mixtures between modern seawater and  $\text{Sr}^{2+}$  derived from the dissolution of older carbonates, (2) the absence of geochemical gradients in the upper interval of one of the wells, despite the presence of fluids with low- tritium

concentrations, and (3) the presence of minerals such as celestite that require the movement of large amounts of seawater to provide the necessary reactants for its formation. Additional evidence of circulation within the platform was provided during the drilling of the second hole when an overpressured zone was encountered at a depth 677.2 m forcing water out of the top of the drill rig.

A second drilling program was initiated on an extension of a seismic line that massed through the two sites on the Great Bahama Bank. This led to Leg 166 of the ODP and had the mission to investigate possible geochemical and geothermal signatures, which might suggest the movement of fluids through the sediment, draped margin of Great Bahama Bank. A series of seven holes was drilled, five on the extension of the seismic line and two in a more southerly position on Great Bahama Bank where the nature of the platform margin was expected to produce a different type of fluid movement. Perhaps the most arresting finding of this drilling is the presence of a zone in the upper 50 m in which there is an absence of geothermal and geochemical gradients. The presence of this zone shows that there is active advection of fluids in this interval, although the mechanism remains unknown.

Additional information on fluid flow was obtained during Leg 101, the inaugural leg of the ODP. During this leg sediments were penetrated which possessed  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios close to modern values, suggesting the penetration of modern seawater to great depths within the sediments. In addition, this unit possessed fluids with high salinities and elevated oxygen and hydrogen isotopic compositions. The interpretation of these data is that these are fluids with modern  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, sourced on the nearby Bahama Banks where high salinities and elevated oxygen isotopic compositions are common. They penetrate into the platform by virtue of the greater density of the fluids.

**Great Australian Bight** Leg 182 drilled a series of holes on the margin of the Southern Margin of the Australian continental shelf. It was anticipated that we might find some evidence of topographic driven flow as a result of the regions proximity to a large landmass. Instead it was determined that fluids permeated the sediments with salinities in excess of 90, almost three times seawater values. It is postulated that these fluids were driven into the adjacent sediments under the influence of a topographic head during previous periods of low sea-level. This proposed mechanism emphasizes the dynamic nature of fluid flow processes, which change as a function of sea-level.

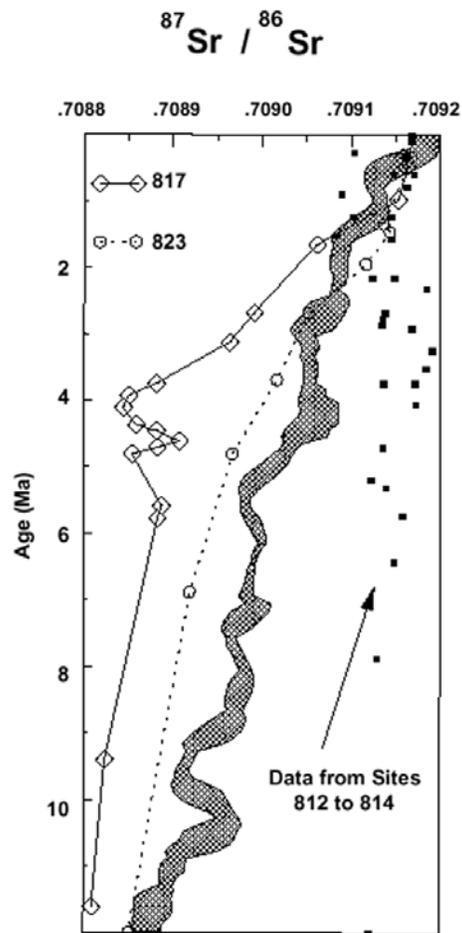


Figure 9. Sr-isotopic composition of pore waters collected from various sites drilled during Leg 133 of the ODP. The Sr-isotopic composition of the sediment is represented by the shaded curve. Sites exhibiting little fluid movement are represented by 817 and 823 that exhibit normal behavior of the Sr-isotopes with increasing depth. Sites 812 and 814 exhibit more radiogenic Sr-isotopic values reflecting the flow of modern seawater.

## Temperature Gradient from Site 812 obtained during logging

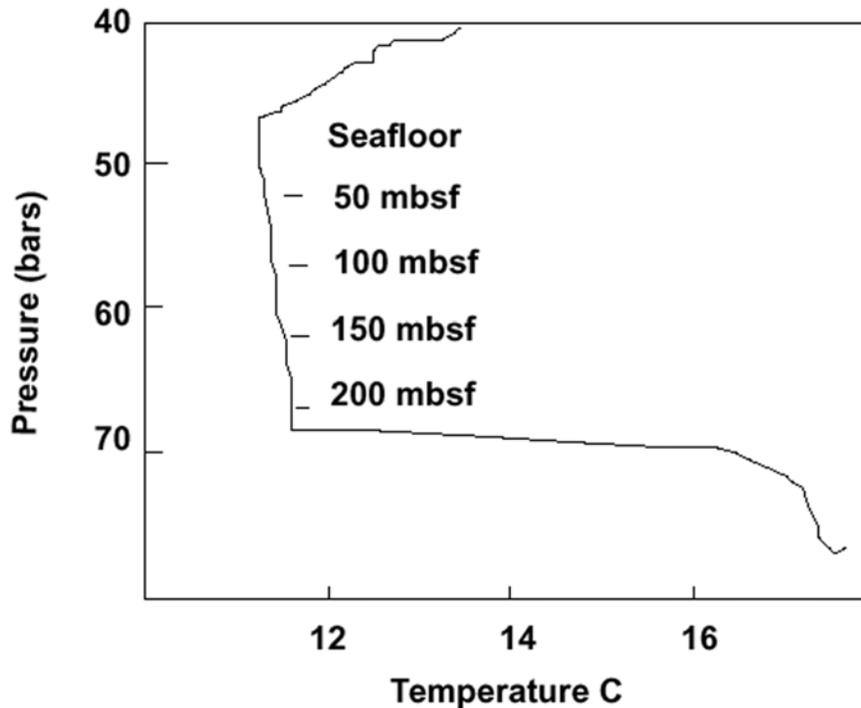


Figure 10. Temperature profile in Site 812 after logging exhibiting substantial downflow into the formation caused by underpressure.

### 6.4. Hydrogeology PPG Members, ESSEP Liaison, Goals, Mandate, Timeline, Meetings

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## **Overall Goal**

To define and prioritize the main problems in submarine hydrogeology in terms of their overall global significance. This PPG should summarize our current understanding of the processes and effects of fluid flow in different submarine hydrogeologic environments, and explain how studies of these environments will relate to those of analogous subaerial formations.

## **Mandate**

Identify the most cost-effective field and modeling strategies for studying submarine fluid flow and its effects on physical, chemical, and biological systems.

Develop strategies for handling critical issues such as the influence of geological heterogeneity on heat and solute transport.

Assess the requirements for site surveying, pre- and post-drilling hydrogeologic studies, and the use of long-term observatories.

Identify future needs for either novel approaches or new adaptations of land-based methods to seafloor environments, and promote the development of these methods by PPG members and other interested parties.

Encourage involvement of the continental hydrogeologic community, with the dual purpose of broadening the interest in submarine hydrogeologic processes and increasing the human resources and skill base needed for scientific advance.

Encourage and nurture the development of drilling proposals.

## **Meetings**

### 1. April 9-10, 2000, University of Colorado, Boulder, USA

Participants: all PPG members and ESSEP liaison, Barbara Bekins, guests: Kevin Brown (Scripps), Adam Klaus (Texas A&M), Roger Morin (USGS), Elizabeth Sreaton (Univ. Florida)  
Reported by Shemin Ge to SSEPs, May, 2000, Cambridge, UK

### 2. September 23-24, 2000, Ecole normale superieure, Paris

Participants: all PPG members except Earl Davis and ESSEP liaison, Barbara Bekins, guests: Kevin Brown, Dave Goldberg (Lamont), Warner Bruckmann (JOIDES)

### 3. February 25-26, 2001, University of Miami

Participants: all PPG members and EESEP liaison, Elizabeth Sreaton, guests: Keir Becker (Univ. Miami), Barbara Bekins (USGS), Kevin Brown (Scripps), Carolyn Ruppel (Georgia Tech), William Moore (Univ. North Carolina)  
Reported by Shemin Ge to SCICOM, March 2001, Shanghai, China

## **6.5. Acknowledgment**

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