Marine hydrogeology: recent accomplishments and future opportunities

A. T. Fisher

Abstract Marine hydrogeology is a broad-ranging scientific discipline involving the exploration of fluid–rock interactions below the seafloor. Studies have been conducted at seafloor spreading centers, mid-plate locations, and in plate- and continental-margin environments. Although many seafloor locations are remote, there are aspects of marine systems that make them uniquely suited for hydrologic analysis. Newly developed tools and techniques, and the establishment of several multidisciplinary programs for oceanographic exploration, have helped to push marine hydrogeology forward over the last several decades. Most marine hydrogeologic work has focused on measurement or estimation of hydrogeologic properties within the shallow subsurface, but additional work has emphasized measurements of local and global fluxes, fluid source and sink terms, and quantitative links between hydrogeologic, chemical, tectonic, biological, and geophysical processes. In addition to summarizing selected results from a small number of case studies, this paper includes a description of several new experiments and programs that will provide outstanding opportunities to address fundamental hydrogeologic questions within the seafloor during the next 20–30 years.

Résumé L'hydrogéologie marine est une large discipline scientifique impliquant l' exploration des interactions entre les fluides et les roches sous les fonds marins. Des études ont été menées dans les différents environnements sous-marins (zone abyssale, plaque océanique, marges continentales). Bien que de nombreux fonds marins soient connus, il existe des aspects des systèmes marins qui les rendent inadaptés à l'analyse hydrologique. De nouveaux outils et techniques, et la mise en oeuvre de nombreux programmes multidisciplinaires d'exploration océanographique, ont aidé à pousser en avant l'hydrogéologie marine ces dix dernières années. La plus part des études hydrogéologiques se sont concentrées jusqu'à présent sur la mesure ou l'estimation des propriétés à la sub-surface des fonds marins, et des travaux complémentaires ont mis en valeur les mesures de flux, local ou global, de termes « sources » et « pertes », et des liens quantitatifs entre l'hydrogéologie, la chimie, la tectonique, la biologie, et les processus géophysiques. Cet article vise à résumer des résultats sélectionnés parmi un petit nombre d'études, et à décrire plusieurs nouvelles expériences et programmes, qui sont autant d'opportunités pour répondre aux questions fondamentales relatives aux fonds marins, posées ces dernières 20-30 années.

Resumen La hidrogeología marina es una disciplina científica de amplios alcances que involucra la exploración de interacciones fluido-roca por debajo del fondo del mar. Se han llevado a cabo estudios en centros de expansión del fondo del mar, lugares en medio de una placa, y en ambientes de placa y margen continental. Aunque muchos sitios en el fondo del mar son remotos, existen aspectos de estos sistemas marinos que los hacen particularmente adaptables para análisis hidrológico. Nuevas técnicas y herramientas desarrolladas, y el establecimiento de varios programas multidisciplinarios para exploración oceanográfica, han ayudado a impulsar la hidrogeología marina hacia delante durante las ultimas décadas. La mayor parte del trabajo hidrogeológico marino se ha enfocado en la medición o estimación de propiedades hidrogeológicas dentro del subsuelo superficial, pero trabajo adicional ha enfatizado mediciones de flujos globales y locales, términos de fuente y sumidero de fluidos, y vínculos cuantitativos entre procesos hidrogeológicos, químicos, tectónicos, biológicos y geofísicos. Además de resumir resultados seleccionados de un número pequeño de estudios de caso, este artículo incluye una descripción de varios programas y experimentos nuevos que aportarán oportunidades excepcionales para dirigir preguntas hidrogeológicas fundamentales dentro del fondo oceánico durante los siguientes 20-30 años.

Received: 18 March 2004 / Accepted: 9 November 2004
Published online: 25 February 2005

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Introduction

Marine hydrogeology is the study of fluid–rock interaction below the seafloor (Fig. 1). Processes of interest in-

 DOI 10.1007/s10040-004-0400-y

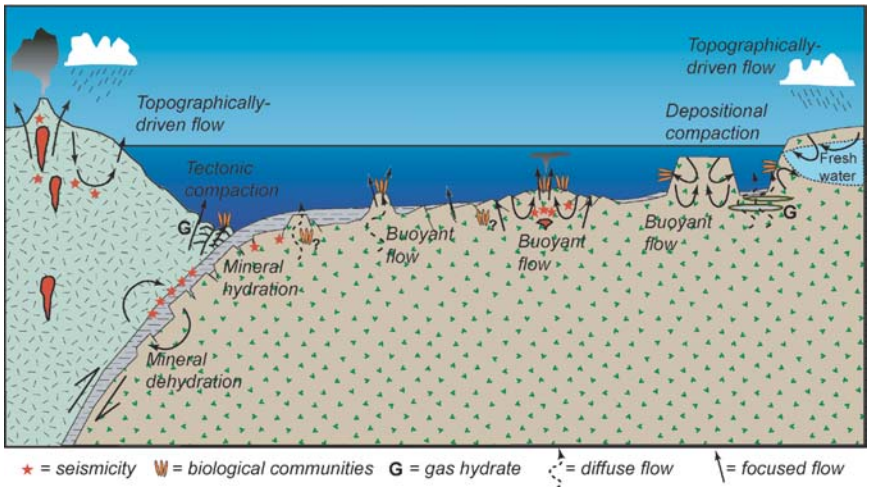

Fig. 1 Cartoon showing characteristic marine hydrogeologic systems that may occur throughout the global ocean. Fluids flow within the seafloor in many settings, several of which are described in the text. Modified from (Ge et al. 2002)

clude: vigorous fluid circulation resulting from heating (both lithospheric and magmatic), alteration of the oceanic lithosphere and chemistry of flowing fluids as a result of water–rock reactions; establishment and maintenance of subseafloor microbial ecosystems; diagenetic, seismic, and magmatic impacts resulting from fluid flow along plate-boundary faults; creation of ore and hydrate deposits both on and below the seafloor; and exchange of fluids and solutes across continental margins, influencing the extent and quality of near-shore water and biological resources.

Parameters of interest to seafloor hydrogeologists include: fluxes of fluid, heat, and solutes; the magnitude and dynamic behavior of driving forces; the nature of source and sink terms; storage properties; and relations among these parameters and between fundamental properties and the processes listed above. Hydrogeologic systems are present below the seafloor worldwide, from seafloor spreading centers where new tectonic plates are created, to mid-plate regions where seamounts provide high-permeability connections between the lithosphere and the overlying ocean, to subduction zones where older plates plunge into the asthenosphere to be recycled, to continental margins where enormous lateral gradients drive fluid between terrestrial and marine reservoirs (Fig. 1). Although many of these regions, features, and properties have drawn the attention of individual researchers for the last several decades, there is growing appreciation that marine hydrogeology comprises a distinct, fundamentally important Earth Science discipline. Marine hydrogeology has global implications; functional understanding of the planet's groundwater systems cannot be claimed if the two-thirds of them that lie below the seafloor are ignored.

There are two primary messages that this paper is intended to convey. First, this is an exciting time for marine hydrogeologic studies, when newly available data, observational tools and techniques, conceptual and quantitative models, access to remote environments, and a willingness to embrace multidisciplinary approaches leave the science poised to make major advances. There are going to be especially good opportunities for marine research elucidating links between hydrogeologic, tectonic, magmatic, and biological processes during the next 20–30 years.

Second, numerous hydrogeologic topics important to those working in a wide range of environments, including those on land, can and should be addressed within the seafloor. These topics include: strategies for developing continuum-modeling approximations for heterogeneous (often, fractured), strongly anisotropic aquifers; incorporation of complex and uncertain geological information into conceptual and quantitative models of coupled flows; and the apparent scaling of hydrogeologic phenomena.

Because space is limited, and several recently and soon-to-be-published review articles and books (cited throughout this paper) cover these topics in considerable detail, the focus of this paper is on a small number of field and programmatic examples. This paper begins with a brief overview of tools and methods and a summary of basic research goals, then considers work that has focused on two main classes of marine hydrogeological environments: those within igneous rock (at spreading centers and in mid-plate locations), and those within sedimentary environments (along continental and plate margins).

Marine hydrogeologic tools and methods

Multibeam swath-mapping systems, which became widely available to marine geologists in the 1980s, have revolutionized the study of seafloor and subseafloor hydrogeologic environments. These tools, including banks of transmit and receive transducers that are hull-mounted or towed behind research platforms, allow rapid collection of high-quality topographic and back-scatter (energy reflection) data, typically at speeds of 0.5–10 kts. The data produced during these surveys vary in swath width from a few hundred meters to a few kilometers, depending on water depth, transducer depth, and resolution requirements. Many Earth scientists (and the public at large) are surprised to learn that there are more detailed

 DOI 10.1007/s10040-004-0400-y

maps of the Moon, Mars, and other objects in our solar system than exist for most of the seafloor. Earth's ocean is vast, covering >2/3 of the planet's surface, and much of the seafloor is remote or commonly experiences sea conditions that make mapping difficult. In addition, typical survey speeds and expedition length restrictions (generally $\leq$30–50 days), limit how much area can be covered during a single voyage. Most effort has focused in the last 20 years on plate- and continental-margin environments. Seafloor topographic maps having spatial resolution $\leq$100 m exist for less than 10% of the seafloor; maps with a resolution equivalent to the standard USGS 7.5-min quad exist for less than 1% of the seafloor. Global seafloor topographic maps have been created using satellite gravimetry and along-track depth data from ships, but typical resolution is on the order of $\sim$3–4 km (Smith and Sandwell 1997).

Imaging the geologic environment below the seafloor is accomplished mainly by seismic reflection, which produces vertical profiles of geophysical structure. Seismic surveys commonly comprise grids of intersecting profiles; if these surveys include a dense enough set of parallel and crossing lines, processing in three dimensions can result in a much more detailed and accurate view of subseafloor conditions. Such surveys are particularly valuable in locations where geological structures are complex, non-horizontal, or involve subtle differences in rock properties, but they are also time-consuming, expensive, and computationally challenging. Tomographic techniques have been applied to several seafloor settings, particularly across seafloor spreading centers. Several of these studies have led to assessments of the thermal state of the lithosphere, which is strongly influenced by the fluxes and flow paths of circulating fluids (e.g., Cochran and Buck 2001; Dunn and Toomey 2001; Sohn et al. 1997; Toomey et al. 1988).

The Deep Sea Drilling Project (DSDP) was developed through the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) and operated a customized drilling research vessel during 1968–1983. The DR/V *GLOMAR Challenger* used a dynamic "thruster" system to hold the platform on station, could operate in water up to 7 km deep, and penetrate another 2 km below the seafloor. Although the scope of DSDP research was necessarily broad, and focused initially on topics such as testing the theory of plate tectonics, later expeditions included investigations of fluid flow in oceanic sediments and rocks (mainly within young igneous crust and near subduction zones).

The DSDP ended in 1983 and was succeeded by the Ocean Drilling Program (ODP), which leased and modified another platform, DR/V *JOIDES Resolution*. ODP at-sea operations ran during 1985–2003, extending scientific drilling to higher latitudes, more remote areas, and greater water and subseafloor depths. ODP greatly extended studies of marine hydrogeology begun during DSDP, particularly with in-situ measurements and experiments and the establishment of long-term seafloor observatories. Nevertheless, it is important to note that seafloor boreholes generally yield a one-dimensional (subvertical) view of crustal conditions; long-term and cross-hole experiments give a more spatially complex understanding, albeit one with fewer direct constraints.

Hydrogeologists working on land have conducted aquifer tests for more than a century, but tests were not attempted in deep seafloor boreholes until the latter part of DSDP (Zoback and Anderson 1983), and methods were substantially improved during ODP (Becker 1986; Becker and Davis 2004). Borehole packer tests in the seafloor have been relatively short in terms of pumping time, have virtually all been restricted to single-hole experiments (testing only the near-borehole region), and have not been particularly effective at delineating the distribution of properties. The development over the last 15 years of pressure-tight, subseafloor observatories ("CORKs") comprises a major advance in marine hydrogeologic studies (Davis and Becker 2002b; Davis et al. 1992a). These systems allow thermal, pressure, and chemical disturbances associated with drilling to dissipate, and provide monitoring and sampling points for subsequent experiments. CORK systems have been used in the past mainly for passive monitoring and sampling in single holes, but there are plans to use these systems for controlled, cross-hole testing.

Our understanding of marine hydrogeologic processes has benefited greatly from the use of several indirect (proxy) tools to estimate flow rates and directions. Perhaps the most important of these is subseafloor heat flow measurements (e.g., Fisher et al. 2001; Langseth and Herman 1981; Williams and Von Herzen 1974). The use of heat flow to estimate fluid fluxes, either on a regional or global basis, starts with calculation of the conductive lithospheric heat flow, based on well-established models for plate evolution (e.g., Parsons and Sclater 1977; Stein and Stein 1992). Conductive lithospheric cooling curves are compared to data sets of observations, and the difference between the two is often attributed to advective heat extraction. It may seem surprising that (a) such an indirect approach is necessary, and (b) that measurements of seafloor heat flow are sufficiently accurate for this purpose. The indirect approach is needed because the heat capacity of seawater is very high, and the ocean is essentially an infinite heat sink, so direct detection of thermal anomalies in the water column is difficult except where there is focused fluid venting. The vast majority of seafloor fluid flow occurs in areas that are far from volcanic heat sources (Fig. 2), and the temperature differences between most subseafloor fluids and bottom water tend to be small. Even a few tens of meters above high-temperature ($\geq$350°C) hydrothermal vents, the water column thermal anomaly is generally a few tens of mK or less (e.g., Baker and Massoth 1987; Murton et al. 1999).

Methods to determine subseafloor temperatures and thermal gradients in shallow marine sediments have become increasing sophisticated, and mK resolution is now routine. The high heat capacity of water, which makes direct measurement of fluid outflow difficult, also makes detection of subseafloor flows and seafloor seepage pos-

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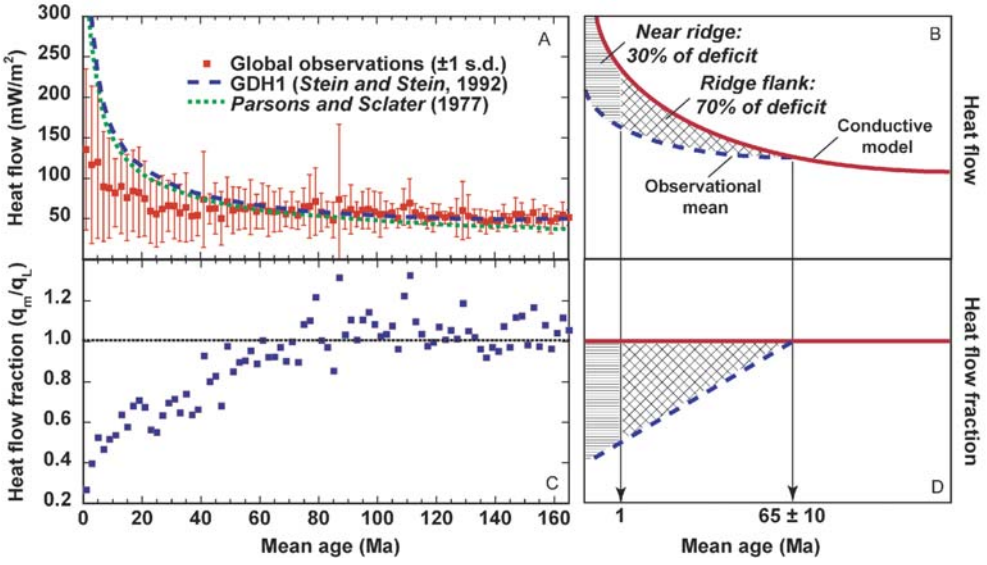

Fig. 2 Summary of global seafloor heat flow data set, with implications for hydrothermal fluxes. **a** Compilation of global data set, binned in 1-m-year intervals. *Squares* are means, and *vertical bars* indicate ±1 SD. *Curves* indicate widely accepted models of conductive lithospheric cooling. **b** Cartoon of data illustrating the magnitude of the typical heat flow anomaly, which varies as a function of age. Integrated over the area of the seafloor, about 30% of lithospheric heat flow is "missing" in the compilation of conductive data, and this heat is thought to be advected from the crust by flowing water. Most of this advection takes place on ridge flanks, within seafloor greater than 1 Ma in age. **c** Mean of binned measurements divided by conductive cooling lithospheric predictions, illustrating that observations are typically well below the mean until an average crustal age of about 65 Ma. **d** Cartoon of relation shown in part **c**. Figure modified from Stein et al. (1995)

sible using heat flow measurements, often co-located on high-quality seismic data (e.g., Davis et al. 1989; Fisher 2004).

Temperature logs in open boreholes also have been used to estimate rates of flow to or from the formation (e.g., Becker et al. 1985). These are perturbation experiments, since the ambient formation fluid is replaced by cold seawater (the primary drilling fluid used during scientific ocean drilling), leading to long-term flow to or from the formation, depending on the magnitude and sign of the pressure differential. Temperature logs can also be helpful in delineating relatively narrow regions within which fluid flows; in combination with packer tests and geophysical logs (density, formation microscanner, resistivity), thermal data can provide detailed hydrogeologic insight.

Measurements of subseafloor pore-fluid chemical data can also help to identify regions where subseafloor fluid flow occurs. The challenge is to find naturally occurring tracers that are conservative, or reactive in ways that are well understood, and to collect appropriate samples at sufficient resolution. Geochemical data have been used in both hard rock and soft rock seafloor settings to identify likely fluid pathways (e.g., Baker et al. 1991; Bekins et al. 1994; Gieskes et al. 1990; Kastner 1982; Mottl et al. 1994). Collection of pristine pore fluids from unconsolidated sediments is fairly routine, at least within layers that are not extremely sandy, but there continue to be serious challenges in extracting uncontaminated fluids from hard rock, where the most important hydrogeologic conduits are likely to be regions that are not represented by core. Similarly, it is difficult to recover pristine formation fluids from open boreholes. The drilling process causes considerable invasion of the formation surrounding a borehole by drilling fluid (typically surface seawater), and the most permeable regions are likely to be the most contaminated. If the drilling fluid is denser than formation fluid, a common occurrence in many settings, "run away" invasion can be initiated during drilling and the borehole may not recover for many years (e.g., Becker et al. 1983; Gable et al. 1989; Guerin et al. 1996). In the petroleum industry and in many applications of environmental hydrogeology on land, holes are produced or purged for days to months prior to collection of chemically useful samples. This approach is not practical within most open boreholes on the seafloor, but the recent development of CORK observatories has profoundly improved opportunities for collection of pristine fluid samples (e.g., Jannasch et al. 2003; Wheat et al. 2004a). Geochemists also sample pore fluids in sediment close to uppermost basement and in areas of upward fluid seepage, to get estimates of basement fluid compositions (e.g., Mottl and Wheat 1994).

Both thermal and chemical data from shallow subseafloor depths can be used to estimate subvertical seepage rates (Langseth et al. 1988; Wheat 1990), with chemical data being about three orders of magnitude more sensitive to seepage (Fisher 2004; Wheat et al. 2004b). In addition, seepage meters developed for work in the shallow and deep ocean (Suess et al. 1999; Taniguchi et al. 2003; Tryon et al. 2001) allow direct measurements of local seepage rates at the seafloor, demonstrating the importance of flow heterogeneity and transience.

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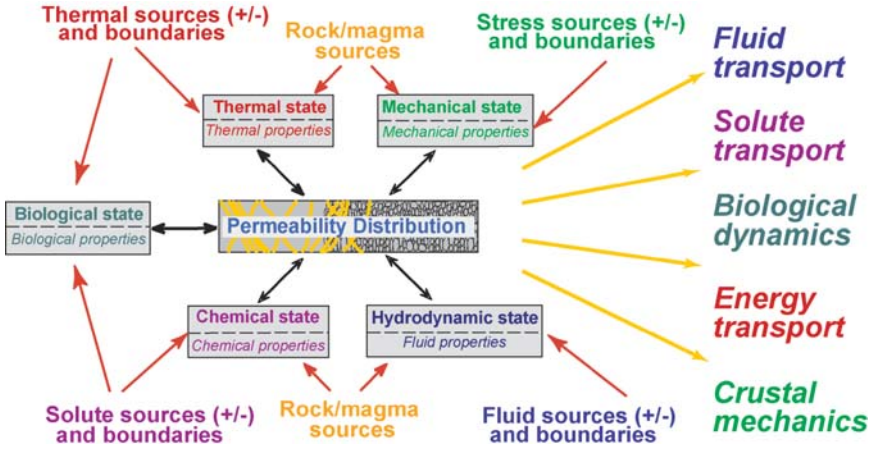

Fig. 3 Relations between properties that can be readily measured (*gray boxes*) and processes of greatest interest to marine hydrogeologists (on the right of *yellow arrows*). Various sources and sinks contribute to the measured conditions (*red arrows*), and there are feedbacks between conditions (*black arrows*), all of which are influenced by the nature of seafloor permeability distribution. Whether the crust hosts flow that occurs dominantly within intergranular pores or fractures will profoundly influence how these conditions, sources, sinks, and feedbacks impact critical processes. Figure modified from Wilcock and Fisher (2004) and Becker and Davis (2004)

Seafloor hydrogeology: goals, accomplishments, and opportunities

Marine hydrogeologic studies focus on four main topics: (1) properties controlling fluid flow and storage and the nature of flow paths, (2) driving forces, (3) fluxes, and (4) sources and sinks. The first topics are perhaps the most fundamental, since they address the basic physics of flow phenomena, and help us to determine how the parameters that we can readily measure lead to the processes we care most about (Fig. 3).

The first set of topics is readily addressed with measurements on the seafloor and in boreholes (e.g., Carson and Screaton 1998; Davis et al. 2000; Fisher 1998), although there are considerable difficulties related to the transient nature of flow processes, heterogeneity, scaling, anisotropy, and coupling between heat, fluid, chemical and biological systems. The second and third topics have also received considerable attention in the last several decades, but the techniques and interpretive methods remain more developmental (e.g., Baker et al. 1996; Davis and Becker 2002a; Elderfield et al. 1999). The fourth topic has been addressed mainly through computer modeling, since fluid production and uptake often occur over geological timescales (e.g., Bekins et al. 1994). The summary and case studies that follow focus mainly on measurements related to hydrogeologic properties and flow paths, and to a lesser extent, driving forces, fluxes, fluid sources, and the relations between these parameters.

As summarized by Ingebritsen and Sanford (2004), some aspects of marine systems are fundamentally different from equivalent systems on land, whereas other aspects are remarkably similar. Most groundwater systems on land can be analyzed by consideration of differences in total head assuming constant fluid density. In contrast, practically all marine hydrogeologic studies require consideration of fluid density, particularly because permeabilities are often very high and driving forces are surprisingly small. Within these systems, a gradient in potential will coincide with the primary fluid flow direction only if both: (1) permeability is either homogeneous or is anisotropic with the dominant flow direction coinciding with the steepest gradient (Hubbert 1956), and (2) variations in fluid density occur only in the vertical direction, such that surfaces of equal density correspond to surfaces of equal pressure (Hickey 1989; Oberlander 1989). Neither of these conditions is likely to be met in most seafloor systems, which are highly heterogeneous and anisotropic and contain fluids having densities that vary laterally as well as vertically. As a result, the basic definition of fluid "head" (energy per unit weight of water) breaks down, and fully coupled solutions (heat–fluid, solute–fluid, heat–solute–fluid) are generally required. In addition, static and steady-state analyses can be misleading; dynamic, transient models are generally required.

Within terrestrial hydrogeologic systems, the shallowest rocks tend to be the most permeable, and permeability tends to decrease with depth below the land surface. This trend is broadly consistent with seafloor sediments and basement rocks when considered separately, but most marine sediments have permeabilities that are 3–7 orders of magnitude *lower* than those of shallow basement rocks (e.g., Becker and Davis 2003; Bryant et al. 1974; Davis et al. 1997; Fisher et al. 1994; Spinelli et al. 2004). One of the most ubiquitous causes for lateral variations in head on land is topography, with many elevated regions hosting sites of recharge and relatively high water table levels. In contrast, the seafloor is nominally a hydrostatic boundary, with three extra complexities. First, variations in pressure, temperature, and salinity yield differences in seawater density on the order of 1–2% over a depth range of 0–4 km (a typical depth of the abyssal seafloor). In addition, seafloor aquifers ex-

 DOI 10.1007/s10040-004-0400-y

perience considerable high-frequency variations in pressure at the upper boundary as a result of ocean tides and other processes. Finally, buried basement highs below the seafloor can lead to conductive refraction of heat, resulting in significant lateral fluid temperature, density, and pressure gradients.

Although the deep seafloor can be considered to be a constant-temperature boundary, there can be significant local differences in bottom water temperatures, particularly in shallow marine settings. Phase separation and segregation are important processes in geothermal areas on land and in the seafloor as well, and the presence of varying amounts of salt in subseafloor fluids fundamentally changes phase relations and can lead to very complex patterns of flow (e.g., Bischoff and Rosenbauer 1989).

Despite these complexities, there are many advantages to studying fundamental hydrogeologic processes in the seafloor. The seafloor is geologically active, generating large, natural perturbations on human time-scales. The first-order boundary conditions (relatively constant pressure, temperature, and fluid chemistry) tend to be more stable than those applied to crustal-scale systems on land. Because of limited anthropogenic influences, the signal-noise ratio within the seafloor can be very high, particularly in mid-plate areas. As described below, bulk permeability in oceanic basement tends to be high, fluxes are large, and subtle changes in water properties can be tracked over great distances.

The upper oceanic crust comprises the largest continuous aquifer on Earth, permitting hydrogeologists to assess processes and properties over enormous lateral scales (at least tens of kilometers). In many systems on land, changes in basic rock types and modes of emplacement greatly limit lateral continuity. Marine seismic surveys allow first-order, subsurface features to be mapped in considerable detail, on a continuous basis, along regularly spaced grids of lines. Running similar surveys on land is very difficult because of topography and urbanization, and data quality is often less that of conventional high-resolution, seafloor surveys. The introduction of differential-GPS and dynamic positioning on many research vessels allows scientists to return to particular locations with 5 to 10-m positioning confidence, and submersibles, remotely operated vehicles, and other tools allow detailed investigation of small features. It is generally not necessary to secure discharge or injection permits for aquifer testing in the deep ocean since the fluids pumped typically have a chemistry very close to that of seawater. Much of the seafloor is considered to be located in "international waters," although permission must be secured to work in territorial waters of other countries, a task routinely completed by ship operators with the assistance of scientific investigators and the investigator's Department of State.

Studies of seafloor basement hydrogeology

Many kinds of geological, geophysical, and geochemical research have important implications for the hydrogeology of the oceanic crust, including studies of seismicity (Golden et al. 2003; Johnson et al. 2000a; Wilcock et al. 2002), the distribution of diffuse versus focused flow at spreading centers (Converse et al. 1980; Schultz et al. 1992), relations between venting, magmatism, and crustal structure (e.g., Baker et al. 1989; Haymon 1996; Haymon et al. 1991; Kelley et al. 2001a), and the distribution of subseafloor ecosystems (Cowen et al. 2003; Kelley 2002). Space limitations preclude discussion of these and many additional topics, but the interested reader is directed to several excellent compilations and reviews, and references cited therein (e.g., Cary et al. 2004; Davis and Elderfield 2004; Halbach et al. 2003; Humphris et al. 1995). After a brief consideration of global hydrogeology, the rest of this section focuses on a limited set of case studies that include a range of geological settings and techniques.

Global considerations

Fisher (1998, 2003, 2004), Becker and Davis (2004), and Davis and Becker (2004) summarize studies of seafloor basement hydrogeology over the last 30 years, with an emphasis on work occurring on ridge flanks, kilometers to hundreds of kilometers from seafloor spreading centers. Mottl (2003) and Johnson and Pruis (2003) synthesize and update studies completed over the last several decades in which global hydrothermal heat and mass fluxes were estimated on the basis of thermal and chemical anomalies.

Mature oceanic crust is generally 6–8 km thick and is constructed of irregular layers. In early studies, seismic velocities and structure were used to infer basic crustal composition and mode of emplacement, and models were confirmed and refined through sampling and analysis of rocks from the seafloor and from ophiolites (e.g., Houtz and Ewing 1976; Moores and Vine 1971). From the top-down, the igneous ocean crust comprises extrusive basalt (pillows, flows, breccia) and intrusive basalt (sheeted dikes), underlain by gabbro. The Moho separates these rocks from peridotitic mantle rocks. Although alteration patterns in seafloor boreholes and ophiolites indicate that water–rock interaction is pervasive, it is also highly heterogeneous and (on average) decreases in extent with depth below the seafloor (Alt et al. 1998; Gillis and Robinson 1988). Exceptions to these depth-dependent alteration trends occur mainly in magmatically active areas such as spreading centers, where elevated permeability channels may penetrate to several kilometers below the seafloor.

The upper few kilometers of crust formed at slow- to fast-spreading ridges (half-spreading rate of ~10–60 mm/year, respectively) is nominally similar in gross structure, but primary emplacement and modification processes differ significantly as a function of spreading rate (e.g., Karson 2002; Mutter and Karson 1992; Sinha et al. 1998). It was shown recently that ultra-slow spreading seafloor (<5 mm/year) has a profoundly different crustal structure, with a broad, diffuse region of crustal construction, and rocks commonly associated with the deep crust and upper mantle exposed at the seafloor (Dick et al. 2003). Several studies have also suggested that there is an influence of

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the rate of crustal accretion and mode of modification on the extent and nature of water–rock interactions (e.g., Bach and Humphris 1999; Fisher et al. 2003b; Kelley et al. 2001b), but quantifying specific causal relations will require additional work.

The global oceanic crustal fluid reservoir has a mass comparable to that of water in ice caps and glaciers (Johnson and Pruis 2003). Although often considered peripheral to Earth's hydrologic cycle, seafloor hydrothermal circulation results in global mass fluxes comparable to that of rivers: $\sim 0.2–2\times10^4$ km^3/year (Mottl 2003). This flux is sufficiently large that the entire volume of the global ocean is recycled through the seafloor about every 100–500 k/year. In fact, this estimate is likely to be an extreme lower limit of actual hydrothermal fluxes for several reasons. First, the estimate is based largely on the global seafloor heat flow deficit, but regional observations demonstrate that circulation within oceanic crust often continues well beyond the average 65 Ma age at which the mean heat flow anomaly disappears (e.g., Noel and Hounslow 1988; Von Herzen 2004) (Fig. 2). Flow at greater ages may not extract as much lithospheric heat as that through younger seafloor, but it certainly has important chemical and biological implications. Second, tens of thousands of seamounts distributed around the world are likely to induce a global flux comparable in mass to that through ridge flanks and spreading centers (Harris et al. 2004).

Most seafloor hydrothermal circulation occurs far from volcanically active areas, at low temperatures, where the primary driving force is buoyancy that results from heating at the base of the crust. Detection is theoretically easiest in areas close to recharge sites where thermal suppression is greatest (e.g., Langseth and Herman 1981). Unfortunately, recharge often occurs where bare rock is exposed at the seafloor, and thermal measurements at these sites are difficult. In some cases, one can sample pore fluids at the base of thin sediment layers close to sites of recharge, but these tend to look very similar (or identical) to regional bottom water. As in hydrogeologic systems on land, quantification of recharge processes has been and continues to be a great challenge.

Basement permeability

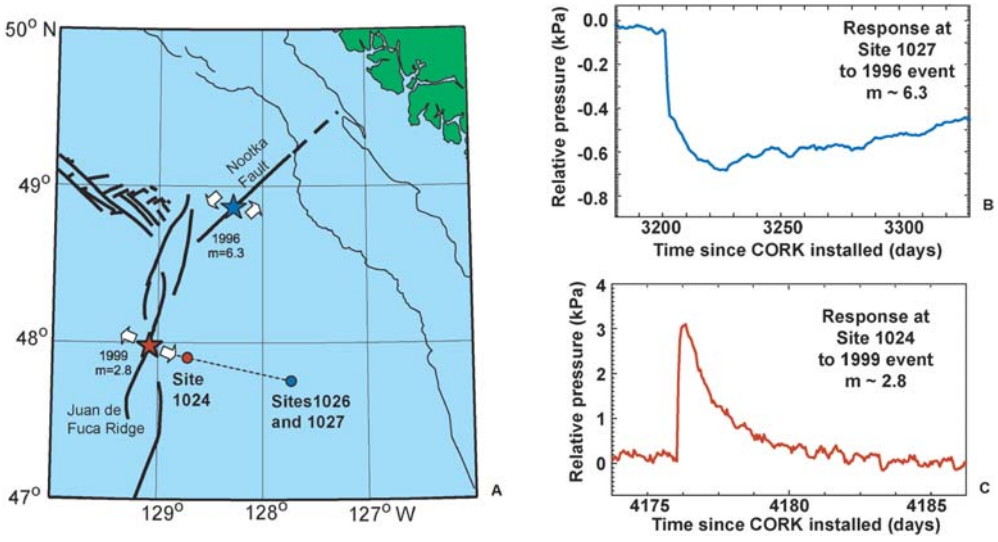

Fig. 7 Detection of tectonic events in CORK observatories. **a** Locations of CORKs at Sites 1024 and 1027, at either end of the ODP Leg 168 transect. Numerous seismic events were detected in these CORKs, as well as CORKs in Middle Valley (Fig. 6). **b** Pressure response in basement at Site 1027 to a strike-slip event along the Nootka Fault. **c** Pressure response in basement at Site 1024 to an extensional, largely aseismic, event near the Endeavour segment of the Juan de Fuca Ridge. Pressure response following tectonic perturbation suggests very high basement permeabilities (Davis et al. 2001)

tially isothermal, requires that the hydrothermal basement be extremely permeable.

An estimate of the large-scale basement permeability was made for this region based on application of a simple model for aquifer response to pumping (Theim 1906). Holes 858G and 857D are considered to be observation wells located 50 and 1,600 m, respectively, from the vent field, idealized as a single large "pumping well." Based on the temperature-corrected head difference between the observation points, and a reservoir thickness of 10–1,000 m, the bulk permeability in the basement necessary to supply fluid to the vents is 10^{-12} to 10^{-10} m^2, with the higher permeability value corresponding to the thinner aquifer (Fig. 6d). A value of 10^{-10} m^2 was estimated independently for a 5 to 10-m-thick interval based on packer and flow-meter experiments (Fig. 4; Becker et al. 1994).

Considerable hydrogeologic work has also been completed along the eastern flank of the Juan de Fuca Ridge, a well-studied off-axis region hosting several distinct hydrothermal systems (Fig. 7). Basement topographic relief in this area produced barriers to turbidites that flowed from the nearby continental margin, resulting in the accumulation of thick sediments on young seafloor. Oceanic basement is exposed to the west, near the active spreading center, and the sedimented seafloor is relatively flat to the east, except over widely spaced seamounts.

ODP Leg 168 completed work along a transect of ten sites in this area, on 0.9–3.6 Ma seafloor. Four sites were instrumented with CORK observatories and have been revisited several times to service instruments, collect fluid and biological samples, and download pressure and temperature data (Cowen et al. 2003; Davis and Becker 2004; Davis et al. 2000; Wheat et al. 2004a). At the eastern end of the drilling transect, two observatories were installed 2.2 km apart, into a buried basement ridge-trough pair (Fig. 7). The buried-ridge CORK, at Site 1026, penetrated 250 m of sediment and 20 m of uppermost basement, whereas the buried-trough CORK, at Site 1027, penetrated 600 m of sediment and 40 m of basement. Under purely conductive conditions, upper basement temperatures at Site 1027 would have been about 50°C warmer than those at Site 1026, but measurements indicate that uppermost basement at these sites is practically isothermal. This condition requires vigorous fluid convection in the basement, and the relatively small pressure gradients detected between the two CORKs suggests that effectively basement permeability must be very high (Davis and Becker 2002a; Davis et al. 1989, 1997; Spinelli and Fisher 2004).

These observatories have been used to estimate hydrologic properties on the basis of responses to tidal loading (Davis and Becker 2004; Davis et al. 2000; Wang and Davis 1996), yielding permeability estimates on the order of 10^{-10} to 10^{-9} m^2. The observatories have also recorded transient fluid pressure "events" associated with seismic activity more than 100 km from the instruments (Davis et al. 2001). After filtering CORK pressure records to remove the influence of barometric pressure changes and tides, distinct signals remain that correlate with independently detected seismic events along plate-boundary faults. An October 1996 event along the Nootka Transform Fault led to an abrupt decrease in fluid pressure at Site 1027, followed by a gradual rise back to background values (Fig. 7b). A June 1999 event near the spreading axis of the Juan de Fuca Ridge lead to an abrupt rise in fluid pressure at Site 1024, followed by a slow decay of the pressure perturbation (Fig. 7c). This last observation is interpreted to have been associated with an episode of seafloor spreading along the ridge crest 20 km to the west.

DOI 10.1007/s10040-004-0400-y

The stresses associated with spreading events are thought to be transmitted through crustal rocks, and the gradual decay of pressure depends on the hydrologic properties of the upper crust (Davis et al. 2001).

Hydrogeologic models have played a fundamental role in interpretation of pressure, temperature, and geochemical data from ridge flanks, but it has been challenging to reconcile results constrained by different observations. For example, Elderfield et al. (1999) used observations of pore fluid chlorinity, sulfate, and ^{14}C age to estimate rates of lateral fluid flow along the western end of the ODP Leg 168 transect. Pore fluids were collected from sediments just above basement, and assumed to be in equilibrium with underlying basement fluids. Based on the spacing between sites and a plug-flow model for solute transport, lateral fluid flow velocities in the upper basement were estimated to be ~2 m/year, with net transport from west to east, a direction consistent with seafloor heat flow data (Davis et al. 1999). Assuming an effective porosity in the upper basement aquifer 1–10%, lateral specific discharge would be 0.02–0.2 m/year. Stein and Fisher (2003) investigated this hydrogeologic system using pressure and thermal observations and a transient, coupled model of fluid and heat flow. They found that fluid could be forced to enter the basement close to the ridge crest to the west and then to flow to the east, as inferred from seafloor heat flow data, but when models were started with a hydrostatic initial condition, the fluid tended to flow in the opposite direction. This occurred because heat flow into the base of the model domain was greatest at the western end, closest to the ridge. However, once rapid flow was initiated from west to east, through use of temporary, forced-flow boundary conditions, a "hydrothermal siphon" was established, and the small difference in basement pressure below cool and warm columns of water (recharge and discharge sites, respectively) continued to move fluid from west to east even after forcing was discontinued.

The models revealed an inconsistency between thermal and chemical data: thermal models required lateral fluid flow rates 10–100 times greater than those based on chemical tracers. This discrepancy was reconciled through consideration of dispersive mixing and diffusive loss of solutes during lateral flow (e.g., Bethke and Johnson 2002; Goode 1996; Sanford 1997). Consideration of heterogeneity and flow channeling within upper oceanic basement rocks, and the likely interaction between primary flow paths and more stagnant crustal regions, suggest that corrections of at least 10–100, and possibly as great at 1,000–10,000, are required for proper interpretation of geochemical tracer data (e.g., Bartetzko et al. 2001; Fisher 2004; Fisher and Becker 2000; Stein and Fisher 2003).

A related conundrum arose during modeling of hydrothermal circulation within the sediment-covered basement aquifer surrounding ODP Sites 1026 and 1027, at the eastern end of the drilling transect. Thermal homogeneity in the uppermost basement requires vigorous fluid circulation, but it does not allow assessment of convection geometry or direction. One might suppose that the fluid flow direction could be determined from differences in fluid pressure measured in CORKs, but observed pressure differences are extremely small (Davis and Becker 2004). One set of steady-state models of similar geometries, but much lower permeabilities, predicted that fluid should flow up along the edges of buried basement highs, and then flow downward into the center of these features (Davis et al. 1997; Wang et al. 1997). Later transient models with higher permeabilities (Spinelli and Fisher 2004) show that the preferred direction of fluid flow depends on both the model initial condition and the distribution of permeability in the basement. Models having the greatest permeability concentrated within narrow channels were much less sensitive to initial conditions, and when permeabilities consistent with other estimates were used, the dominant flow direction was always *up* through basement highs and *down* on their edges. These transient models with heterogeneous permeability distributions also were better able to match both the magnitude and the signs of very small pressure and temperature differences observed in subseafloor observatories (Fig. 8).

It has been known for some time that regions of basement exposure provide fluid entry and exit points on otherwise sediment-covered ridge flanks (e.g., Davis et al. 1980; Johnson et al. 1993; Villinger et al. 2002; Williams et al. 1974), but the importance of seamounts in facilitating long-distance lateral flow and efficient advective cooling of the upper oceanic lithosphere has been emphasized by several recent studies. Fisher et al. (2003a) showed that two seamounts separated spatially by >50 km comprise recharge and discharge points for ridge-flank hydrothermal circulation (Fig. 9). Heat flow data around the margins of the two seamounts show strongly contrasting thermal conditions in the uppermost basement. The larger of the two seamounts, which recharges bottom seawater to the crust, helps to cool upper basement rocks to a distance of several kilometers from the area of basalt exposure. In contrast, a smaller seamount that is the associated site of hydrothermal discharge is surrounded by crust that is warmed by hydrothermal fluids flowing rapidly towards the exposed basement. Once the system is running, it can be maintained by a hydrothermal siphon, with rapid fluid flow driven by differences in pressure at the base of warm (discharging) and cool (recharging) columns of pore fluid. Additional evidence that fluid flows between these two seamounts comes from regional pore fluid chemistry data, and from consideration of fluid mass balance and the difficulty of recharging crustal fluids through thick, low-permeability sediments (Fisher et al. 2003a). Interestingly, although fluid flow is relatively rapid in a geological sense (estimated velocities are on the order of hundreds to thousands of meters per year), this flow system is spatially restricted and so is inefficient in mining lithospheric heat on a regional basis.

In contrast, a vast area in the eastern Equatorial Pacific Ocean has anomalously low seafloor heat flow (Vacquier et al. 1967). Recent studies of 18–24 Ma seafloor of the Cocos Plate in this area (Fisher et al. 2003b; Hutnak et al.

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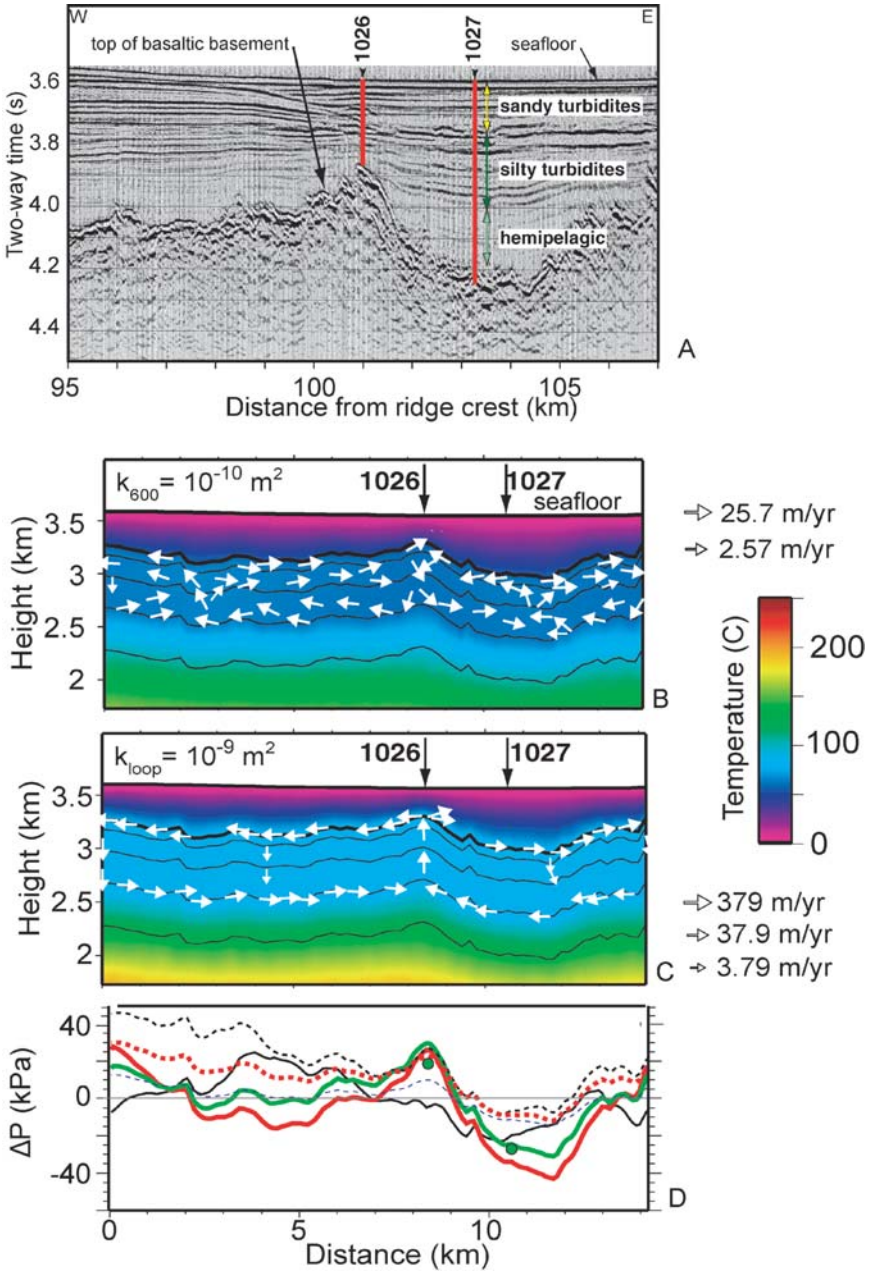

Fig. 8 Results from transient, coupled heat-fluid flow models of hydrothermal circulation in basement around ODP Sites 1026 and 1027 (Spinelli and Fisher 2004). **a** Seismic profile across the sites, with lithologic interpretation based on drilling results. CORK observatories were installed at Sites 1026 and 1027. **b** Temperature contours and fluid flow vectors after the system reaches a dynamic "steady-state" (convection oscillates, but the thermal field becomes quasi-stable). Only a small fraction of flow vectors are shown for clarity. Modeled fluid flow move either up or down within the basement high at Site 1026, depending on the bulk permeability in basement and initial conditions. The permeability value assigned to the upper 600 m of basement is within the range required by earlier models and based on analysis of formation tidal response. **c** When the greatest permeability occurs within thin channels, nominally representing normal faults associated with abyssal hill topography and other heterogeneities, circulation stabilizes and the flow direction is always up below Site 1026 (buried basement high). Note much more rapid flow rates in this case. **d** Comparison between modeled (*lines*) and observed (*green dots*) pressure differences relative to ambient hydrostatic. The best fit to the data was achieved with a model in which permeability was higher within thin channels (10^{-10} m^2, *thick red line*; 10^{-9} m^2, *thick green line*). *Dashed lines* are homogeneous permeability distributions, whereas the *thinner solid line* indicates permeability in narrow zones of 10^{-11} m^2 (*black*)

2004) show that seamounts just seaward of the Middle America Trench allow hydrothermal fluids to extract ~70% of lithospheric heat over and area of 1,000's of km^2. Seamounts are common on this part of the plate, with typical lateral spacing of 20–50 km. An adjacent part of the plate appears to experience little or no advective heat loss. The boundary between hydrogeologically active and inactive parts of the plate is remarkably abrupt,

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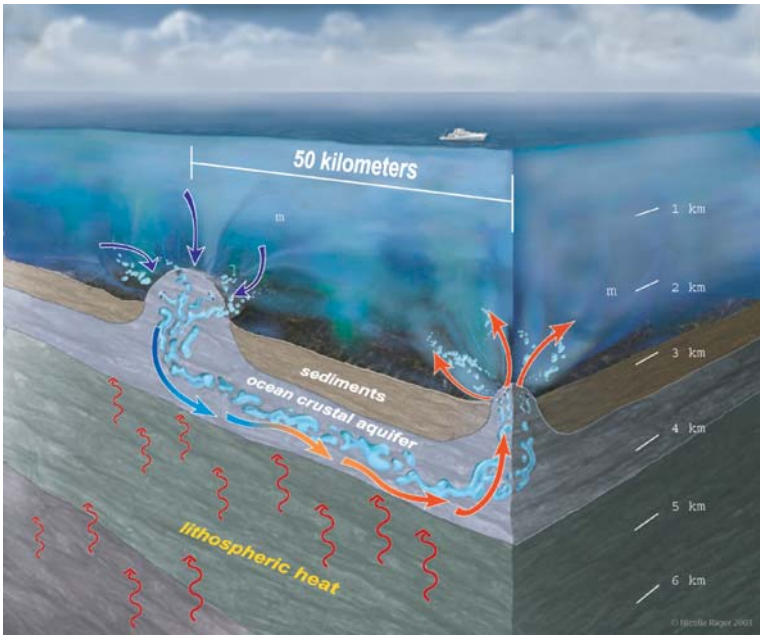

Fig. 9 Cartoon showing hydrothermal circulation on a ridge flank between basaltic seamounts separated by 50 km, as described by Fisher et al. (2003a, 2003b). Water and crustal depths are approximately correct, but the cartoon is vertically exaggerated. Lithospheric heat rises from below the crustal aquifer, generating lateral differences in fluid density. Seamounts allow fluids to bypass the low-permeability sediment cover found throughout most ocean basins on seafloor older than a few to a few tens of millions of years in age, and thus may be responsible for the bulk of hydrothermal circulation occurring within the seafloor. Additional details are described in the text. Original artwork by Nicolle Rager, modified by the author

suggesting that hydrothermal circulation on the cool side of the plate extends to shallow basement depths. Why two similarly aged parts of the same plate experience such different dominant mechanisms of heat loss is not immediately clear, but it may result from differences in crustal construction processes, which could impact permeability distributions in basement (Fisher et al. 2003b). Ongoing observational and numerical studies should help to determine the crustal conditions under which seamounts can have a regional hydrogeologic influence, how circulation is initiated, and why some seamounts host hydrothermal recharge but others host discharge.

Studies of seafloor sediment hydrogeology

Seafloor hydrogeologic studies in sedimented settings present unique challenges. Sediments tend to have much lower permeability, and greater compliance, than do basement rocks, leading to a considerably lower hydraulic diffusivity. Because of their unconsolidated nature, many sedimentary environments are modified greatly by drilling and sampling operations, leading to difficulties in separating experimental and natural perturbations. Although they can be mechanically soft, sediments in many hydrologic systems can be fractured as a result of excess fluid pressure conditions. Despite these complexities, hydrologic studies in sedimentary marine systems continue to generate exciting and unexpected results.

Active margin hydrogeology

Subduction zones at active margins have received considerable attention. In some of these systems, sediments near the top of the subducting plate are transferred to the overriding plate during subduction, leading to the formation of an accretionary complex. These sediments often provide a record of coupled hydrologic, thermal, and chemical processes. The Barbados accretionary complex has been visited for scientific ocean drilling several times (Biju-Duval 1984; Mascle et al. 1988; Moore et al. 1998; Shipley et al. 1995). One goal of these expeditions has been to understand processes controlling deformation, with an emphasis on the décollement, the low-angle, plate-boundary fault separating the accretionary wedge of the Caribbean Plate from the subducting sediments and basement of the North American Plate (Fig. 10). The earliest drilling expeditions to this area concentrated on coring and sample analysis, in part because borehole measurements were extremely difficult within unstable formations. Later attempts to set an inflatable packer in an open borehole within a "critically tapered" wedge proved unsuccessful, but hydrologic tests were finally completed through screened and perforated casing set across the décollement (Fisher and Zwart 1996, 1997).

ODP Holes 948D and 949C were drilled into the toe of the accretionary complex, in areas previously interpreted on the basis of seismic reflection surveys as having unusually high porosity (Shipley et al. 1994). Logging data through the décollement confirmed this interpretation (Bangs et al. 1999; Moore et al. 1995). Packer tests in these holes were complicated by unstable hole conditions and changes in background pressure during testing. After in-situ testing was completed, the cased holes were fitted with CORK observatories. Formation pressures during

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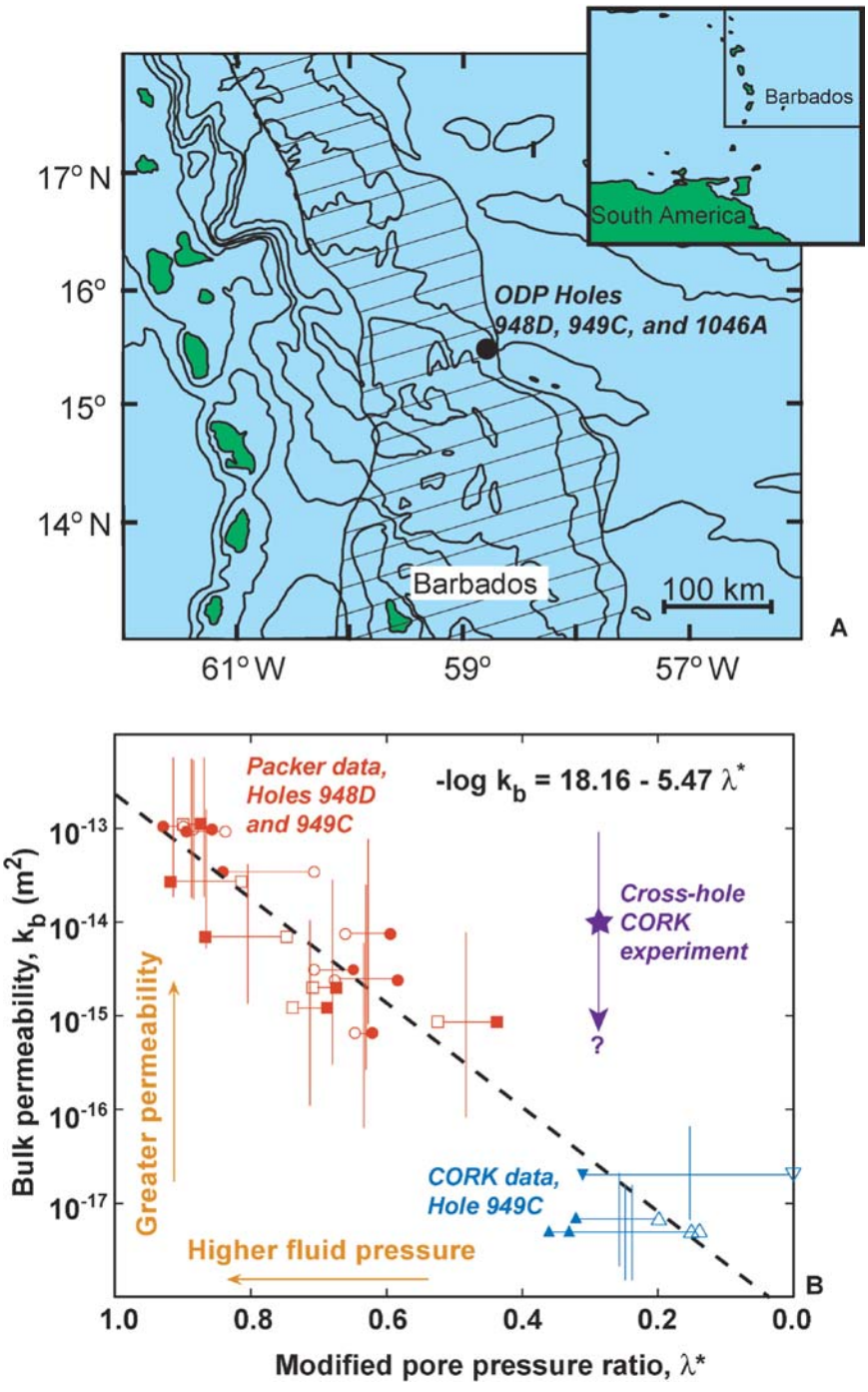

Fig. 10 Permeability versus effective stress relations near the toe of the Barbados accretionary complex. **a** Location map showing the accretionary complex (*shaded*) and locations of ODP drilling sites near the front of deformation. Holes at these sites were drilled through the accretionary wedge and into the décollement, the major plate boundary that separates the North American and Caribbean Plates. **b** Compilation of permeability estimates from packer and CORK experiments (Fisher and Zwart 1996, 1997; Screaton et al. 1997, 2000). *Different symbols* represent results from independent tests, and *vertical bars* indicate range of bulk permeability indicated by each test. *Open symbols* indicate conditions at the start of each test, whereas *filled symbols* indicate conditions at the end of each test. In general, the data suggest that there is a consistent (semi-log) relation between bulk permeability and the modified pore pressure ratio, $\lambda^* = \frac{P_{\text{meas}} - P_{\text{hydrostat}}}{P_{\text{lithostat}} - P_{\text{hydrostat}}}$. The equation shown on the figure indicates the empirical relation between bulk permeability and modified pore pressure ratio, based on all observations shown except those associated with the uncontrolled, cross-hole experiment

and soon after drilling had appeared to be in excess of hydrostatic, but it could not be demonstrated that this did not result from "charging" of the formation during drilling. The CORKs were revisited by submersible 18 months later, both to evaluate pressure conditions after the disturbance due to drilling had dissipated, and to conduct additional active hydrogeologic tests (Becker et al. 1997; Foucher et al. 1997; Screaton et al. 1997). During this visit, overpressured Hole 949C was subjected to hydrologic tests by opening and closing the fluid sampling valve and allowing excess fluid pressure to vent at the seafloor. CORK records during a later drilling expedition provided an additional test of sediment properties between two boreholes, based on estimates of excess pressures generated while drilling nearby (Screaton et al. 2000).

Collectively, packer and CORK tests yield a range in décollement permeabilities, from 10^{-17} to 10^{-13} m^2 (Fig. 10b). At the low end of this range, the borehole results are consistent with laboratory tests of fine-grained material recovered from this area (Taylor and Leonard 1990), suggesting that these values may represent back-

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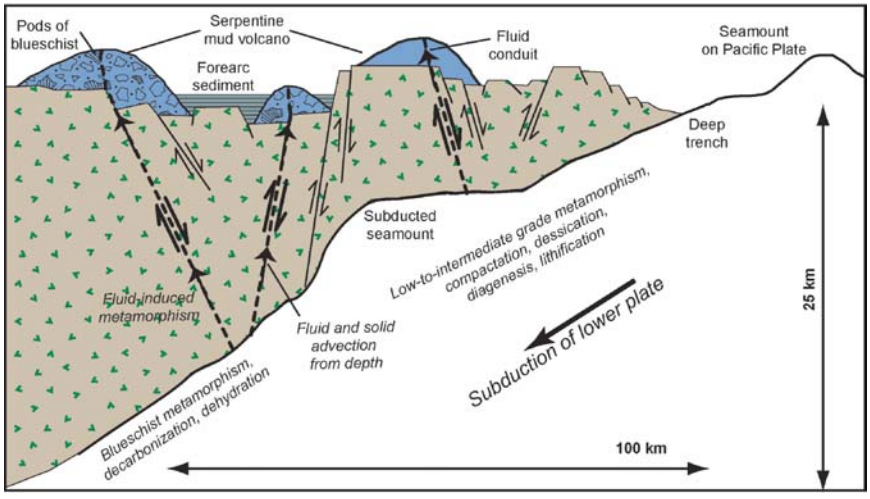

Fig. 11 Geologic and hydrogeologic setting and processes within the Mariana Forearc, western Pacific Ocean (Fryer et al. 1999). At this nonaccretionary subduction zone, the underthrust plate releases heat, solutes, fluids, and mass that rise through faults in the overriding plate and emerge at the seafloor, providing a unique window into processes occurring at depths up to 25 km below the seafloor

ground, intergranular permeabilities. At the higher end, permeabilities are close to those suggested by steady-state numerical models of large-scale fluid flow and accretionary wedge dewatering. The highest-quality packer and single-hole CORK test results suggest a dependence of formation permeability on pore fluid pressure, with differences in permeability of five orders of magnitude as fluid pressure varies from hydrostatic to lithostatic (Fig. 10b). This result is intriguing because it may help to explain how excess fluid pressures and fluid flow are coupled through non-linear changes in formation properties. The cross-hole test resulted in greater apparent permeability at low pore fluid pressures than suggested by the trends deduced from the other tests (Screaton et al. 2000). More work is needed to determine dynamic relations between fluid pressure and permeability in similar settings.

Thermal and modeling studies have yielded additional hydrogeologic constraints on this accretionary system (e.g., Ferguson 1993; Fisher and Hounslow 1990; Henry 2000; Langseth et al. 1990; Screaton et al. 1990; Stauffer and Bekins 2001). Permeabilities similar to those estimated from packer and CORK observations are consistent with steady-state numerical models that result in sufficient subsurface flow and seafloor seepage so as to explain thermal and chemical observations, and to generate superhydrostatic fluid pressures at depth. Several of these studies also suggest that hydrologic conditions within the accretionary complex, and particularly along the décollement, are likely to be highly transient with regard to driving forces, excess fluid pressure, fluid flow, and heat and solute transport. In addition, modeling suggests that flow within the accretionary complex is likely to occur "along strike," subparallel to the deformation of the accretionary wedge, as well as "across strike" (Cutillo et al. 2003; Screaton and Ge 1997).

Many subduction zones are bounded by neither an accretionary complex nor any other form of subduction wedge. Hydrogeologic investigation of these nonaccretionary subduction zones is difficult because water depths are great and there is a less complete geological record of subduction. On the other hand, fluids that rise from the lithospheric-boundary fault or the underthrust plate in these settings are also less likely to be modified during ascent than those passing through a thick subduction wedge. The Mariana forearc in the western Pacific Ocean is one of the best-studied nonaccretionary margins. Work has focused on a long arc of nonvolcanic seamounts, features created by rising diapers of serpentinite and other rock types having origins deep within the Earth (Fryer et al. 1992, 1999; Mottl et al. 2003). The tops of many of these seamounts are sites of focused fluid seepage, creating carbonate and brucite chimneys, and supporting chemosynthetic communities of micro- and macrofauna (Fig. 11). The chemistry of muds and fluids recovered by conventional coring and ocean drilling, including samples that were created under blue schist conditions (high pressure, low temperature), suggests that mass fluxes originate at depths up to 25 km below the seafloor. Pore fluids from these seamounts have unusual chemistries, including extremely low chlorinities and pH >12. The active nature of forearc tectonics is certain to play a role in creation of nonvolcanic seamounts in this setting, since faulting through the overriding plate creates conduits along which fluids, rocks, heat and solutes are transported, but quantitative relations between seismic activity, near-surface faulting, and hydrologic processes remain to be delineated.

Passive margin hydrogeology

There is growing interest in terrestrial-marine interactions along continental margins for several reasons (e.g., Buddemeier 1996; Moore 1996; Parnell 2002). Water managers in coastal hydrologic basins are under increasing pressure to develop, maintain, and protect limited resources. Many coastal basins have large and growing human populations and also host economically important agriculture or industries that require large amounts of water. Understanding how extractions in excess of annual recharge will impact the quantity and quality of available water requires assessment of interactions between terrestrial and marine environments. Unfortunately, determina-

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tion of fluxes between terrestrial and marine aquifers is difficult, at least as challenging as determination of recharge rates. The movement of groundwater into offshore environments can have either positive or negative influences on water quality in estuaries and lakes and on continental shelves and slopes, depending on water chemistry (Burnett et al. 2003; Cherkauer and Nader 1989; Phillips and Lindsey 2003; Spinelli et al. 2002). Groundwater fluxes on continental margins can contribute to creation of hardgrounds and other conditions supportive of healthy fisheries. There are also important relations between slope stability and groundwater pressure and flow, and between fluid flow and the formation and maintenance of large gas hydrate deposits along continental margins. Hydrogeologists must also understand how geological and hydrogeologic conditions have influenced each other in the past, and how conditions today may differ.

It has long been known that pore fluids within sediments along some continental shelves are unusually fresh relative to overlying seawater (Kohout et al. 1988). Person et al. (2003) investigated current and past hydrogeologic conditions on the continental shelf and slope offshore of Cape Cod and Long Island. It was hypothesized that a combination of Pleistocene sea level low-stands, with associated subglacial recharge and flushing of meteoric water through shallow aquifers, might be responsible for the presence of extensive regions of fresh water below the continental shelf in this area. Relatively fresh fluids currently extend seaward tens of kilometers from the present-day shoreline, much farther than can be explained by current hydrologic conditions. Seismic data and results from drilling of several exploratory wells were used to generate computer models of coupled fluid, heat and solute transport, and various boundary conditions were tested (Fig. 12).

The critical test for model "success" was the ability to match pore-fluid salinity profiles from deep wells. This requirement was satisfied only when elevated fluid pressures and high recharge at the base of a Pleistocene ice-sheet were imposed on the landward side of the simulations, and a postulated offshore submarine canyon allowed use of a hydrostatic boundary condition at the seaward edge of a shallow aquifer unit (Fig. 12). The results of this work have implications for water management in this and similar settings. One (more positive) view might be that there are fresh water resources available for extraction along many continental shelves, but another (more cautious) consideration is that hydrologic conditions that led to the filling of groundwater aquifers in the past no longer exist in many areas, requiring that water be mined to satisfy current and future needs.

Drilling along the New Jersey margin has provided insights as to how excess fluid pressures and fluid flow are coupled on the Mid-Atlantic continental shelf and slope. Drilling extended through 650 m of Oligocene to Holocene sediments in 640 m of water (Fig. 13). Sediment porosities were found to be anomalously high, leading to an interpretation that pore fluids were overpressured relative to hydrostatic (Dugan and Flemings 2000, 2002; Dugan et al. 2003). Fluid pressures below the Miocene-Pliocene boundary (Fig. 13b) were calculated to be within 95% of lithostatic values. The creation of fluid overpressures requires application of stresses at a rate that is sufficiently high so that fluid cannot escape rapidly enough to maintain hydrostatic conditions (e.g., Neuzil 1995). In passive margin settings, this can result from generation of hydrocarbon or other diagenetic processes, from topographic forcing associated with an adjacent continental area, or through rapid sedimentation of fine-grained material. The latter process, along with the focusing of flow during Pleistocene sea-level low stands, is thought to be responsible for occurrence of excess pressures in this area today (Dugan and Flemings 2000, 2002).

Two-dimensional modeling of coupled sediment deposition and mechanics and fluid flow suggests that excess fluid pressures should be expected to develop within relatively permeable Miocene sediments below a cap of lower-permeability Pliocene sediments. Specific discharge at the seafloor above the shallow part of the section is relatively slow, <0.05 mm/year, but considerably greater values are calculated near the toe of the Miocene strata, >5 mm/year (Fig. 13c). Local fluxes could be even greater, depending on the nature of permeability heterogeneity and distribution of subsurface pathways. These fluxes are geochemically significant and could support seep communities without requiring a direct connection between continental (meteoric) waters and the continental slope. The models also suggest that the continental slope in this region may be broadly overpressured, a state that could lead to rapid (even catastrophic) slope failure and the creation of submarine canyons with a small change in effective stress. Excess fluid pressure, and slope instability, migrate seaward over time in these simulations.

Future opportunities

The preceding discussions of tools, methods, and case studies include several common themes. First, marine hydrogeology as a discipline is wide open. There are many first-order problems that remain unresolved, in large part because the environments of interest are remote and, until recently, technological limitations precluded making basic observations. Second, many of the tools and methods are indirect, with thermal and chemical tracers used commonly as proxies for parameters of direct interest (rates of fluid flow, global fluxes, etc.), and numerical models constrained by limited observations. As in all such studies, establishing ground truth through direct observation is essential for testing interpretations based mainly on indirect methods. Third, major research initiatives have played critical roles in fostering marine hydrogeologic studies. As described below, several new initiatives will continue to present exciting hydrogeologic opportunities during the next 10–20 years.

In the mid- to late-1990s, the U.S. National Science Foundation (NSF) convened a series of workshops to identify future directions for oceanographic research in the new century. One of these meetings included a working group whose primary focus was on marine hy-

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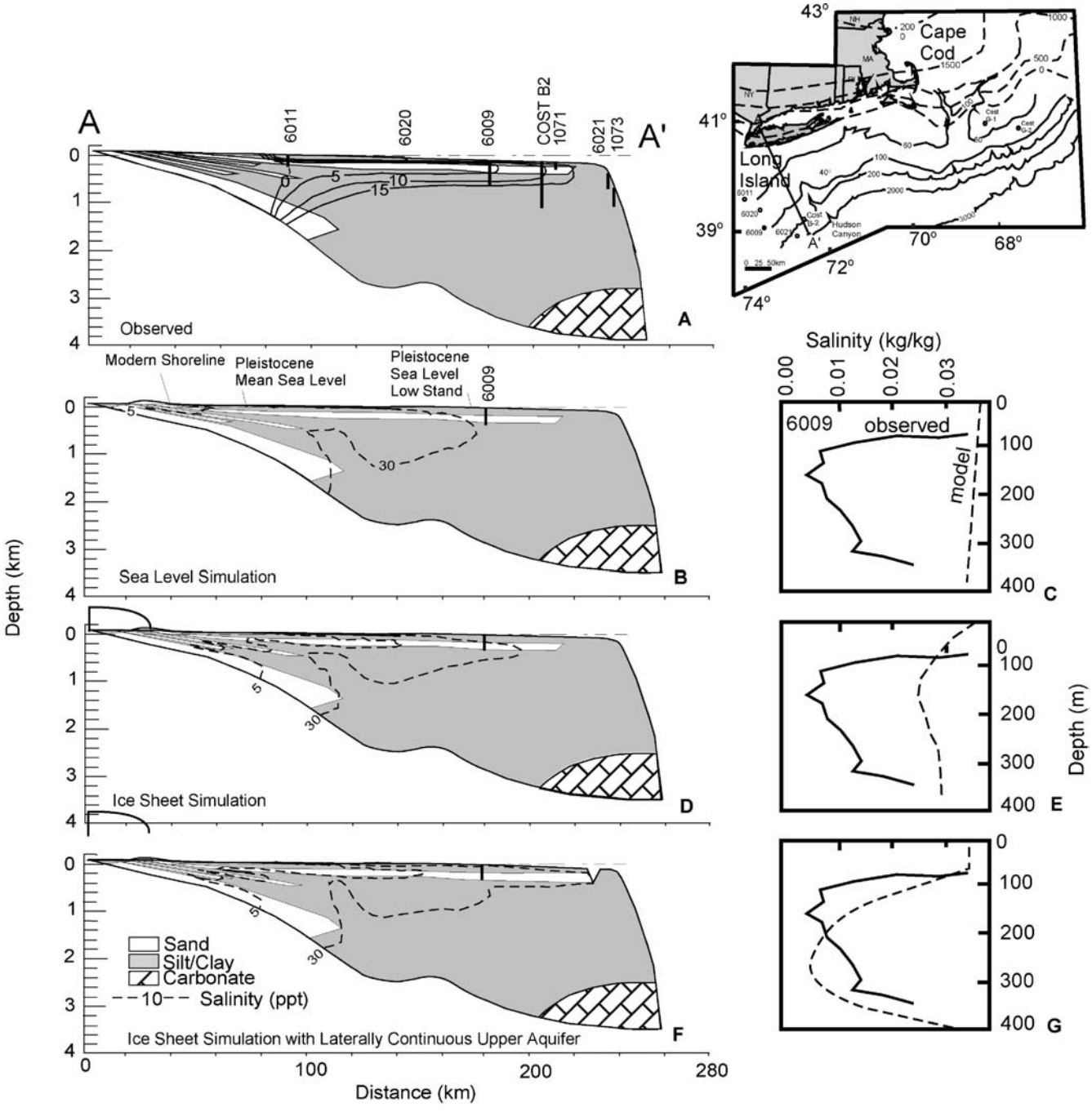

Fig. 12 Summary of observational constraints and modeling results from a study of terrestrial-marine groundwater flow within the continental shelf, NE United States (Person et al. 2003). **a** Geological setting and observed salinity profile (modified from Kohout et al. 1988). **b** Computed salinity contours (*dashed lines*, ppt) after 10 sea-level rise-fall cycles about the Pleistocene mean level (40 m below modern) using a period of 100,000 years with an amplitude of 120 m. **c** Comparison of observed and computed salinity profiles. **d** Computed salinity contours using ice-sheet recharge boundary condition. Salinity patterns from the Pleistocene sea-level simulation used as initial condition. **e** Comparison of observed and computed salinity profiles. **f** Computed salinity contours using ice-sheet recharge boundary condition and a continuous upper aquifer with a specified head boundary along the continental slope, assumed exposed by cutting of a submarine canyon. Computed salinity patterns from the Pleistocene sea-level simulation used as initial condition. **g** Comparison of observed and computed salinity profiles. This simulation best matches observational constraints

drogeologic systems (FUMAGES 1997). Major NSF initiatives, including RIDGE-2000 and MARGINS, and their global counterparts (InterRIDGE, InterMARGINS) include significant hydrogeologic components. Similarly, the scientific ocean drilling community has embraced marine hydrogeologic objectives with great enthusiasm.

In anticipation of the end of at-sea ODP operations, scientists from around the world held a multi-year series

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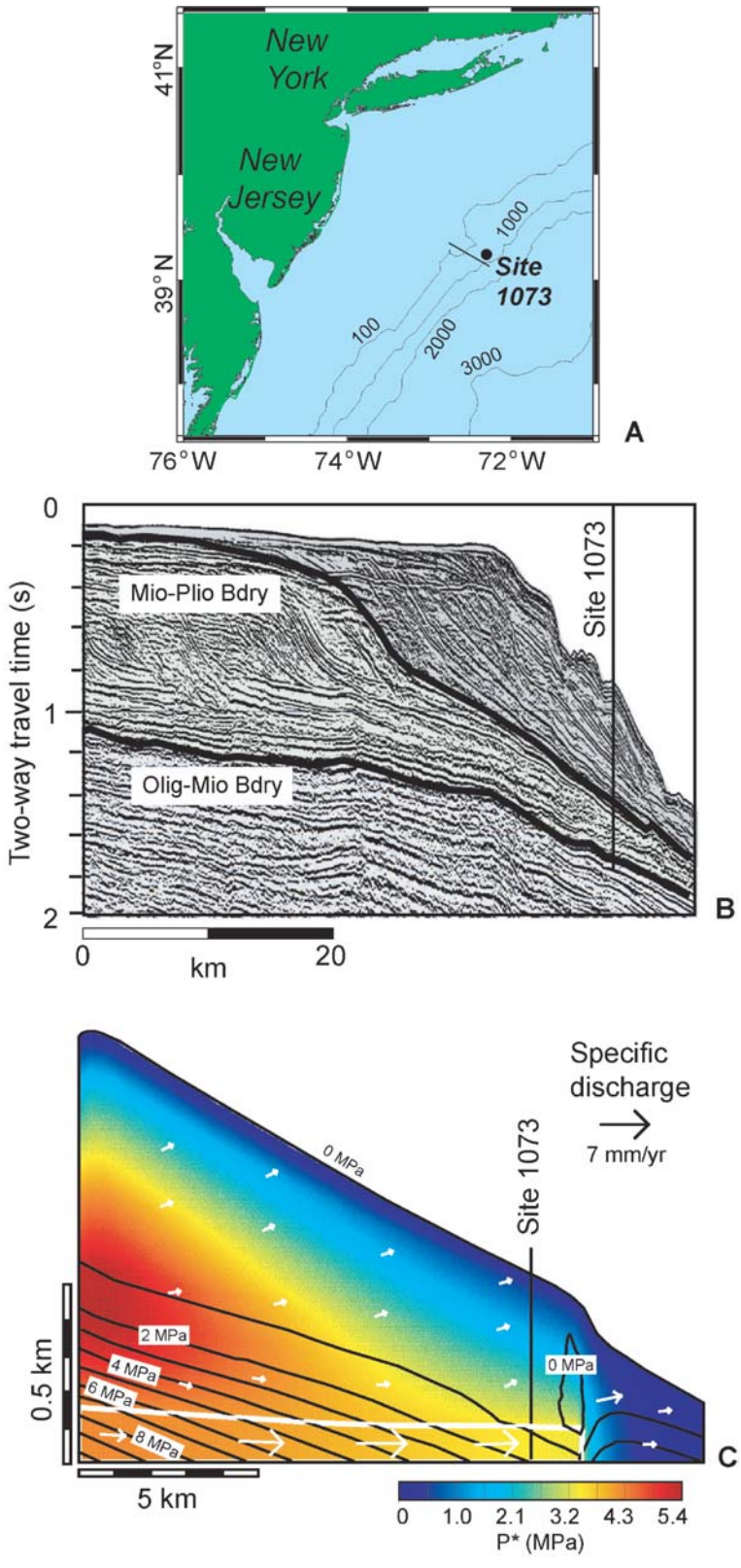

Fig. 13 Results from a study of coupled fluid flow and sediment deformation on the continental shelf and slope offshore of New Jersey (Dugan and Flemings 2000, 2002). **a** Site map showing location of seismic profile, drill hole, and modeled domain. **b** Interpreted seismic profile illustrating the age and distribution of sediment layers and the location of the drill hole that provided estimates of fluid overpressures in the form of arrested compaction. **c** Results of a coupled computer simulation illustrating how fluid pressures in excess of hydrostatic can develop, and how these fluid pressures lead to fluid flow under the continental shelf. Highly permeable materials at depth allow the excess fluid pressure to extend very close to the edge of the shelf and slope, potentially leading to catastrophic failure and underwater landslides

of workshops and conferences to design and create a new international research program. The initial science plan (ISP) for the Integrated Ocean Drilling program (IODP) (Integrated Ocean Drilling Program (IODP) Planning Sub-Committee (IPSC) 2001), which began marine operations in summer 2004, describes several themes and initiatives that include marine hydrogeologic components. IODP will operate several kinds of drilling platforms,

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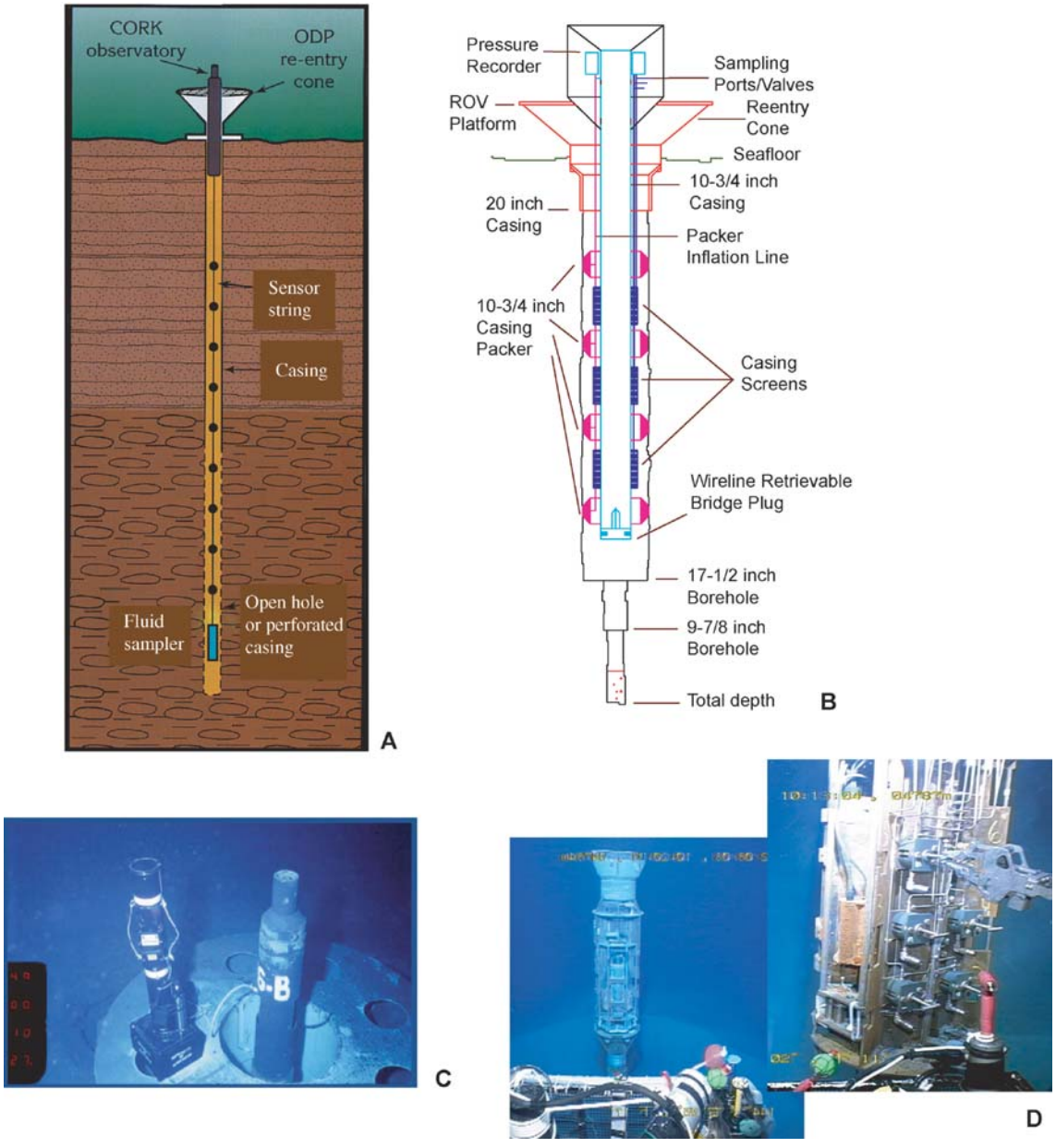

Fig. 14 ODP long-term, subseafloor observatories (CORKs). **a** Cartoon of original CORK concept, showing seafloor re-entry cone, landing platform for submersible or ROV, and sensor string to monitor pressure and temperature and collect fluid samples. A data logger is located in the CORK head at the top of the system. **b** Schematic of multi-level CORK system, with nested casing and casing packers set in open hole. Drawing courtesy T. Pettigrew. **c** Photo from submersible of top of CORK system installed at Hole 1026B, with adjacent "BioColumn" used for microbiological sampling (Cowen et al. 2003). **d** Photos from remotely operated vehicle, Kaiko, of top of advanced CORK system in Hole 1173B, Nankai Trough. Complex valve manifold being manipulated in right panel. Photos courtesy K. Becker

including a non-riser ship like the DR/V JOIDES *Resolution*, the DR/V *Chikyu* that will have riser capabilities, and a series of "mission-specific" platforms that will be leased for short-term operations in environments in which the other platforms cannot work, including shallow water and very high latitudes.

The ISP for IODP describes several important technical developments, including tools for establishment of long-term, subseafloor observatories. The first generation of ODP observatories were relatively simple, comprising mainly a seafloor seal, fluid pressure and temperature sensors and loggers, and a fluid sampler at depth (Fig. 14). The fluid samplers used in these observatories are innovative and elegant in their design, requiring no moving parts and collecting samples continuously for 2–3 years or more (Jannasch et al. 2003, 1994; Wheat et al. 2000, 2004a). The first generation of these observatory systems were intended to monitor a single formation depth or integrated conditions over a long interval of open or screened hole. New borehole observatories include the

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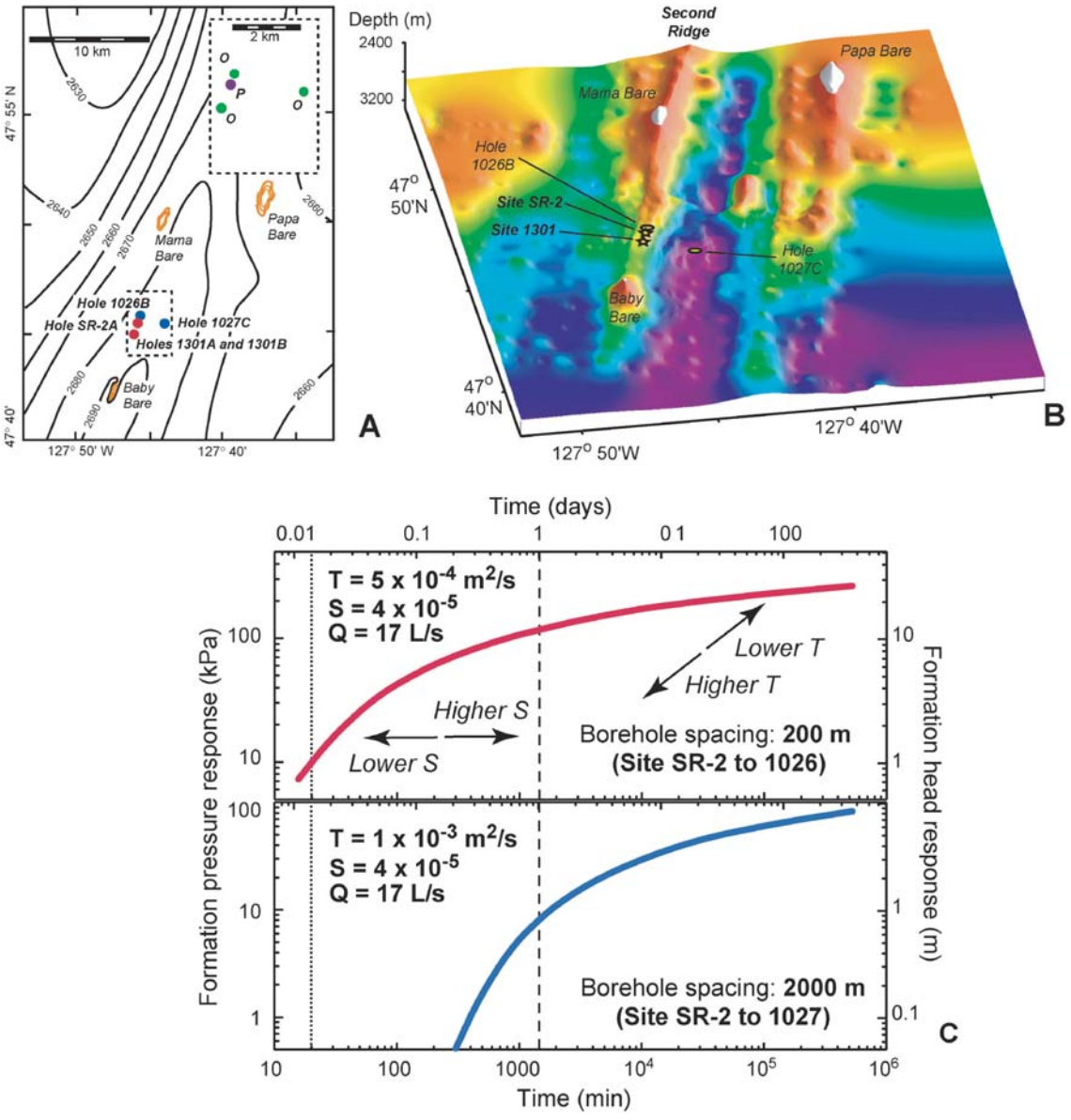

Fig. 15 Crustal-scale hydrogeologic testing on the eastern flank of the Juan de Fuca Ridge. **a** Map view indicating spatial relations between CORKed Holes 1026B, 1027C, 1301A, 1301B, planned Site SR-2, and nearby basement outcrops. *Inset* shows relative locations of pumping (*P*) and observation (*O*) wells for cross-hole experiments. Depth contours in meters. **b** Topography of top of basement around experimental sites based on dozens of seismic reflection lines, showing tops of nearby outcrops (in *white*), and existing and planned drill sites. Basement relief image courtesy L. Zühlsdorff and V. Spiess, University of Bremen. **c** Calculated cross-hole responses to pumping and free-flow borehole experiments. *Upper figure* shows response between wells at Sites SR-2 and 1026, separated by 200 m. *Lower figure* shows response between wells at Sites SR-2 and 1027. See Fig. 15a, b for site locations. Formation properties based on previously completed packer, free flow, and CORK experiments. Differences in formation-scale values of T and S relative to those used would shift the curves as indicated by the *arrows* in upper figure. Earlier pumping tests in DSDP and ODP were typically only 20 min long (*dotted vertical line*); new tests will begin with 24 h of pumping (*dashed vertical line*), and ultimately will last 1–2 years or more through venting of overpressured holes and pumping at the seafloor

ability to monitor and sample from distinct subseafloor levels; several of these systems have been deployed in the last few years (Davis and Becker 2002b, 2004).

New observatory systems will play important roles in future IODP experiments. This article was written while operations were underway on IODP Expedition 301, on the eastern flank of the Juan de Fuca Ridge (Fig. 15). Multi-level CORK observatories established during this expedition will facilitate the first controlled, cross-hole hydrologic experiments in oceanic basement. Expedition 301 operations included deployment of three new observatories, one in an existing hole (at Site 1026) and two in new holes (at Site 1301), 1 km south of Site 1026 along the same buried basement ridge (Fig. 15). The new holes were drilled, cored, logged, sampled, and subjected to hydrogeologic (packer) testing. A multilevel observatory

DOI 10.1007/s10040-004-0400-y

deployed in the deeper of the new holes will assist in isolation, measurement, and sampling of distinct basement levels. The new observatories contain downhole fluid samplers and microbiological incubators, and wellhead fluid samplers and pressure monitoring systems attached to tubing extending to depth.

Two additional holes will be drilled during a subsequent expedition at Site SR-2, between the other holes, and a multilevel observatory will be installed at Site 1027, two kilometers to the east. One hole at Site SR-2 will act as a perturbation well for long-term hydrogeologic experiments that are different from those conducted previously within DSDP or ODP in three critical ways: (1) test duration, (2) test scale, and (3) multidisciplinary nature. These experiments will begin with a 24-h injection test. The magnitude and timing of pressure responses detected at the observation wells, located at different distances and in different directions from the pumping well, will allow quantification of crustal properties, including the nature of permeability anisotropy, vertical and horizontal compartmentalization, and formation storativity. Although 24-h aquifer testing is standard practice on land (indeed, such a test often would be considered relatively short), it is orders of magnitude longer than controlled, active hydrogeologic experiments run during DSDP and ODP (Fig. 15). And although there have been measurements of uncontrolled cross-hole perturbations during ODP (e.g, Screaton et al. 2000), there has not previously been an opportunity for a controlled experiment of this kind. After completion of the 24-h pumping test, the new hole(s) at Site SR-2 will be sealed and left to equilibrate. Like the Site 1301 CORKs, the Site SR-2 CORKs will be instrumented with fluid and microbiological samplers, incubation substrate, and pressure and temperature monitoring instruments.

The fluids pumped into the seafloor at Site SR-2 will be spiked with inert tracers, allowing single-hole and cross-hole testing of solute transport properties. Other CORK systems, instrumented with long-term fluid samplers, will be observation wells for tracer experiments, collecting fluids for several years. Results from tracer experiments will be combined with analysis of cross-hole hydrologic and offset seismic experiments to elucidate the nature of permeable pathways in the crust. Seismic work will include single-hole and offset vertical seismic profile (VSP) experiments in the deeper of the new basement holes. VSPs are useful for determination of seismic stratigraphy within and below the depth of the holes, which will be helpful for regional correlation with reflection seismic data. In addition, the offset (directional) VSP will allow assessment of seismic anisotropy in the basement. Seismic anisotropy in oceanic basement has been interpreted previously to indicate preferential orientation of fractions and other pores, leading many to wonder about relations between seismic and hydrogeologic properties (Detrick et al. 1998; Dunn and Toomey 2001; McDonald et al. 1994; Stephen 1981, 1985). For the first time, researchers will be able to test all of these relations directly in a single region.

Conditions within the new holes will be overpressured relative to ambient hydrostatic, based on previous observations and theoretical considerations of buried basement highs (e.g., Davis and Becker 2002a; Davis et al. 1997; Fisher et al. 1990; Spinelli and Fisher 2004). Once conditions have equilibrated below the observatories, a CORK at Site SR-2 will be vented at the seafloor, initiating a longer-term "artesian well" test. This test can continue for 1–2 years or more, facilitating the collection of basement fluid chemical and microbiological samples. By running tests of different durations in the same network of holes, from short-term packer slug tests to longer-term injection and free flow tests, researchers can explore relations between apparent formation properties and the scale of the experiments (Fig. 5).

An even more challenging series of drilling projects is likely to occur over the next 5–8 years in the accretionary complex and seismogenic zone offshore of Japan, as part of the Nankai Trough Seismogenic Zone (NanTroSEIZE) experiment (Fig. 16). The primary goal of this ambitious program is to create a distributed observatory spanning the up-dip limit of seismogenic and tsunamigenic behavior within the subduction zone. This project will involve sampling and instrumenting an active plate-boundary fault system at several locations, where the plate interface and other active faults are accessible to drilling. The most challenging technical objective is to access and instrument the plate boundary within the seismogenic zone, to evaluate aspects of aseismic and seismic faulting, including relations between tectonic, chemical, thermal, and hydrogeologic processes. NanTroSEIZE will document the evolution of fault zone properties by trading time for space along the dipping plate boundary (Fig. 16). Three distinct drilling components are planned: (1) documenting inputs to the seismogenic zone system; (2) drilling of out-of-sequence-thrust faults to sample and instrument splays from the basal décollement, at depths of 1–3.5 km; and (3) sampling and instrumenting the tectonic plate décollement ~6 km below the seafloor. Long-term subseafloor monitoring will augment seismological and geodetic instrument arrays, geologic studies, and laboratory and modeling efforts.

Both the NanTroSEIZE and the Juan de Fuca Ridge flank drilling projects rely on observatory systems for long-term active experiments and passive monitoring. These efforts overlap with another multidisciplinary research effort having hydrogeologic components: the Ocean Research Interactive Observatory Networks (ORION) program. The development of ORION follows on recommendations from subcommittees of the U.S. National Research Council (Detrick et al. 2003; Ryan et al. 2000), and ultimately will involve technical development, scientific prioritization, education, and outreach. ORION is likely to have a planning and management structure similar to that of IODP, with advisory panels, implementing organizations, and a competitive proposal process. Although ORION is presently a US-based program, future internationalization seems likely.

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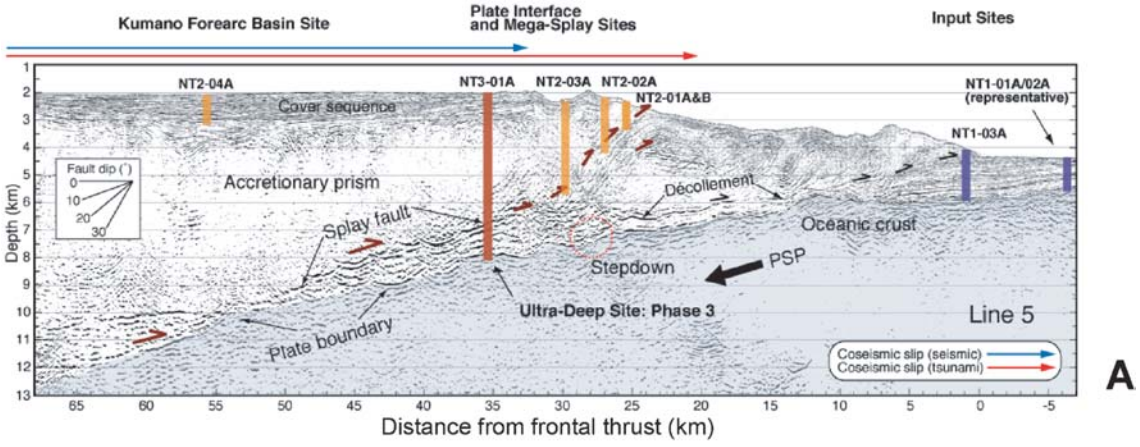

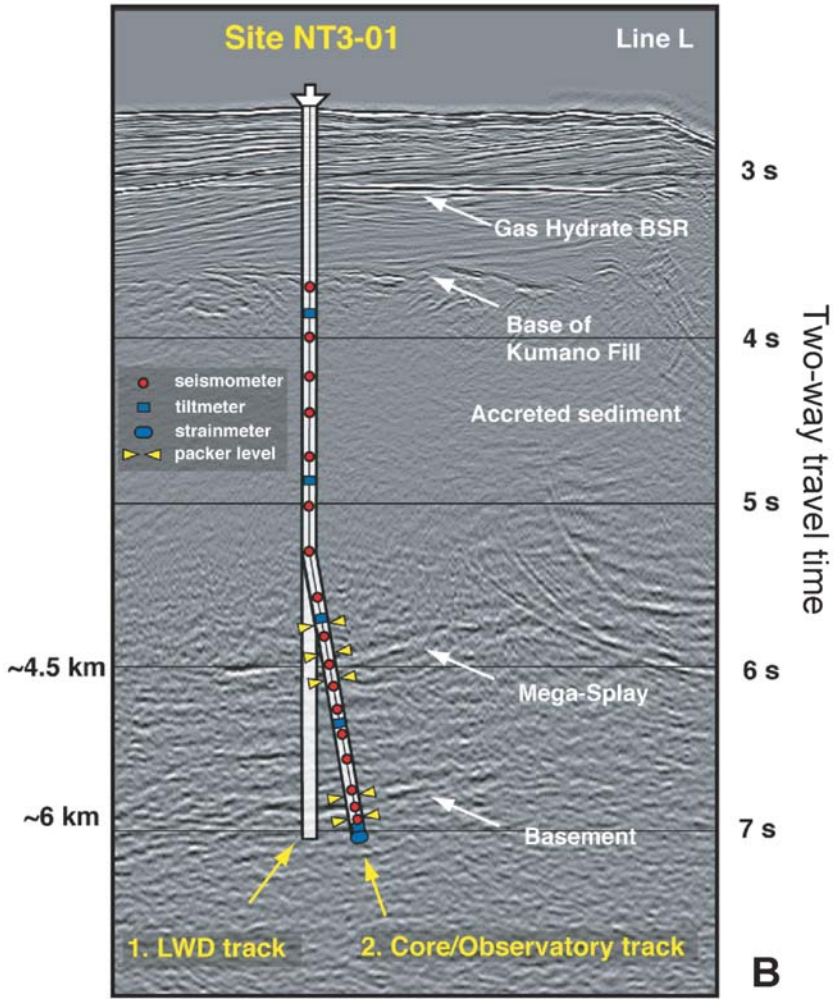

Fig. 16 **a** Planned sites and operational components comprising the NanTroSIEZE experiment. Poststack depth-migrated MCS profile showing the plate boundary, accretionary prism, Kumano basin, and prominent splay fault system (after Park et al. 2002). The seaward distribution of the 1944 Tonankai coseismic slip estimated from tsunami (*red line*) and seismic (*blue line*) inversions are projected over the profile. Location of the décollement stepdown to the top of the oceanic basement is marked with an *orange dotted circle*. Drill sites are in some cases projected onto this line. **b** Conceptual drilling and instrumentation plan for Phase 3 (ultra deep) drilling at NT3-01A. Drilling will proceed with a mix of logging-while-drilling and coring with casing to total depth, followed by sidetracking to core the prime fault targets and install monitoring instrumentation. Sensors shown are positioned schematically. A number of sensor elements are not shown for clarity, including fiber optic temperature and thermistor arrays, fluid pressure, and osmotic fluid sampling tubes. Packers isolate perforated zones for fluid communication to the formation above, below, and inside each of the two target fault zones. Borehole deviation is not to scale. Images courtesy of H. Tobin, New Mexico Institute of Mining and Technology

DOI 10.1007/s10040-004-0400-y

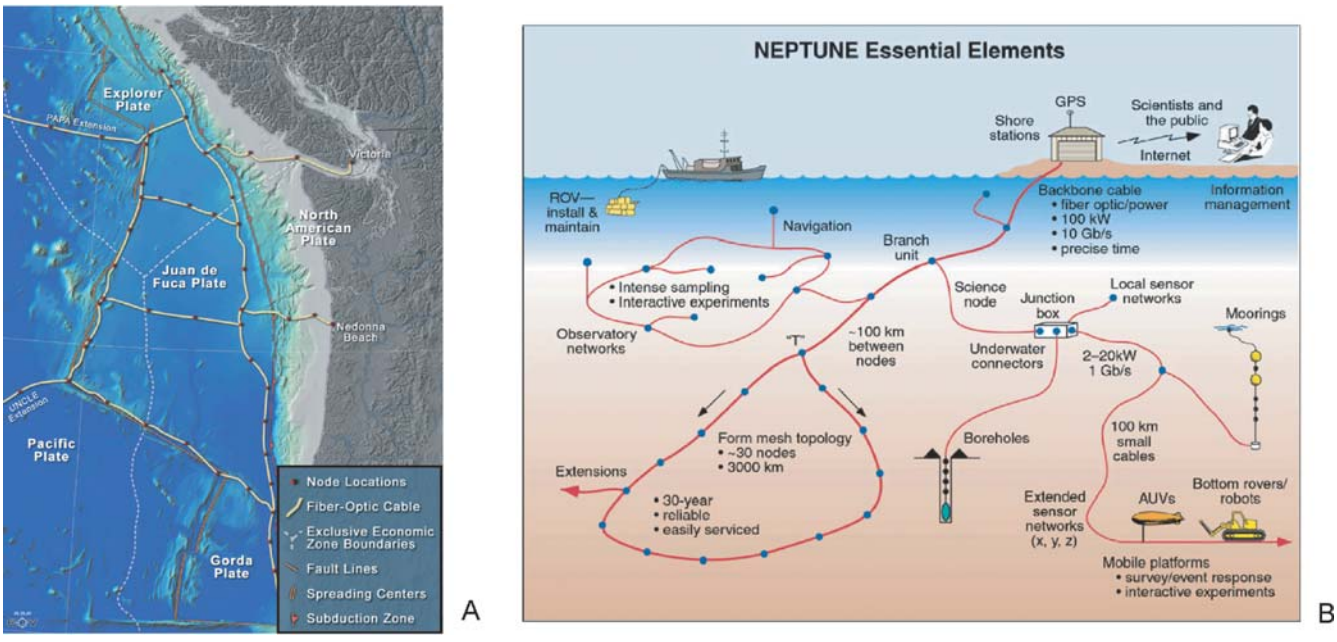

Fig. 17 Conceptual drawings of one part of the Ocean Research Interactive Observatory Networks (ORION) program. ORION is intended to comprise regional, global, and coastal components. **a** Schematic of layout for fiber-optic power and data transmission cable that may be used for a regional observatory in the northeast Pacific Ocean (NEPTUNE). **b** Schematic of various components of a fully functional NEPTUNE system, including borehole and other tools that could be used for hydrogeologic experiments at the scale of a tectonic plate. Images provided courtesy of the NEPTUNE Project (http://www.neptune.washington.edu), Paul Zibton, and the Center for Environmental Visualization, University of Washington

One component of ORION is a "plate-scale" cabled observatory, to be located in the northeast Pacific Ocean, as part of the NEPTUNE program (Fig. 17). Scientific and technical components for this system are currently being designed, including a >2,000-km-long network of fiber-optic/power cables that will encircle and cross the Juan de Fuca plate; experimental sites located at "nodes" along the cable network; instrumentation at the nodes that allows monitoring and interaction with physical, chemical, and biological phenomena; robotic vehicles that will reside at depth, recharge at nodes, and respond to events such as submarine volcanic eruptions; and Internet connections, allowing real-time access to information, command-and-control capabilities, and education-and-outreach activities.

Concluding remarks

This paper has summarized only a small fraction of the marine hydrogeologic work completed during the last few decades, and just a few of the opportunities that will be available to interested researchers during coming years. Future studies will be intensely interdisciplinary, and will help to link hydrogeologic, geologic, thermal, chemical, and biological properties and processes. Complete development of programs like IODP and ORION will require considerable determination, organization, cooperation, patience, and financial resources. Marine scientists learned long ago to think big, to be ambitious, and to let fundamental scientific goals drive exciting research programs. New programs bring new resources and new opportunities; this is not a zero-sum game. Astronomy, biology, and other scientific communities have not let tight budgets limit their goals, and there is no reason for marine hydrogeologists to fall into the trap of low expectations. The scientific problems and technical challenges described in this overview are fundamentally important for advancement of human knowledge and understanding our planet. Hydrogeologists work with water, one of the basic requirements for life. Now more than ever we need to be bold in asking difficult questions, and thinking creatively about how to answer them.

Acknowledgements Helpful suggestions were provided by reviewers S. Ge and H. Villinger and associate editor C. Voss. Funding in support of this synthesis came the U.S. National Science Foundation (OCE-0001892), the Institute for Geophysics and Planetary Physics/Los Alamos National Laboratory (Project 1317), and the U.S. Science Support Program for IODP (Award SJA-7).

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