Barbados Ridge hydrogeologic tests: Implications for fluid migration along an active decollement

Elizabeth J. Screaton
Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309
Andrew T. Fisher
Earth Sciences Department, University of California, Santa Cruz, California 95064
Bobb Carson
Department of Earth and Environmental Science, Lehigh University, Bethlehem, Pennsylvania 18015
Keir Becker
Division of Marine Geology and Geophysics, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida 33149

ABSTRACT

Hydrogeologic tests were conducted at a sealed borehole penetrating the decollement of the Barbados Ridge accretionary complex. At low excess pore pressures [$\lambda^* = (P_p - P_h)/(P_l - P_h)$ = 0.0 to 0.36, where P_p = pore pressure, P_h = hydrostatic pressure, and P_l = lithostatic pressure], estimated permeabilities were comparable to those of similar, unfractured sediment. These tests complement shipboard packer tests completed at higher fluid pressures (λ^* = 0.5 to 1.0) during Ocean Drilling Program (ODP) Leg 156. Together, the test results suggest a 4- to 5-order-of-magnitude permeability increase as fluid pressure varied from hydrostatic (λ^* = 0) to lithostatic (λ^* = 1). However, unlike the results of the shipboard packer tests, the test results presented here exhibit no evidence of a relationship between permeability and pore pressure. The combined findings from the two sets of hydrogeologic tests indicate that significant permeability increases can occur within the decollement at pore pressures below lithostatic pressure.

INTRODUCTION

Compaction of sediments accreted at convergent margins produces pore pressures that are higher than hydrostatic and results in fluid migration, expulsion, and sediment lithification. Researchers have speculated that fault zones play a major role in focusing fluid expulsion. Indirect evidence of long-distance migration of fluids along accretionary-prism fault zones is provided by geochemical and thermal anomalies (Fisher and Hounslow, 1990; Gieskes et al., 1990; Vrolijk et al., 1990). However, the mechanisms for creating fluid conduits within accretionary prism fault zones are poorly understood. Existing conceptual models of fluid flow in accretionary-prism thrust faults suggest that permeability is enhanced by the episodic opening of hydrofractures at above-lithostatic pore pressures (Behrmann, 1991; Moore and Vrolijk, 1992; Brown et al., 1994). Likewise, numerical modeling of chloride anomalies within the decollement of the Barbados accretionary complex yielded the most promising results when an instantaneous permeability increase within the decollement was assumed (Bekins et al., 1995).

Only recently have in situ tests provided data on fault-zone permeabilities and pore pressures. Shipboard packer tests and submersible-based tests were conducted at a sealed borehole that intersects a shallow thrust fault within the Oregon accretionary prism (Screaton et al., 1995). Test results suggested an instantaneous increase in permeability as fluid pressures reached a critical value (λ^* = 0.5). In contrast, shipboard packer testing of the Barbados accretionary-prism decollement (Fisher and Zwart, 1996; 1997) suggested a logarithmic increase in permeability with increasing pore pressure (above λ^* = 0.5).

In this paper we present the results of hydrogeologic tests conducted from the French submersible, *Nautile*, in a sealed borehole (Ocean Drilling Program [ODP] Hole 949C) that penetrates the decollement of the Barbados accretionary complex. These tests were conducted at pore pressure conditions from $\lambda^* = (P_p - P_h)/(P_l - P_h)$ = 0.0 to 0.36, where P_p = pore pressure, P_h = hydrostatic pressure, and P_l = lithostatic pressure. These pore pressures are lower than those of the earlier shipboard tests (λ^* = 0.5 to λ^* = 1) in the same borehole (Fisher and Zwart, 1997). Test data were of good quality because the submersible operations allowed much greater flow control and introduced less noise than operations from a surface vessel. In combination with earlier data, these results provide a more complete picture of the relationship between pore pressure and permeability within the decollement of the Barbados accretionary prism. Because the suggested relationship between pore pressure and permeability challenges the existing conceptual model of fluid migration in accretionary-prism fault zones, we begin to address mechanisms and implications of pressure-dependent permeability.

GEOLOGIC SETTING

The Barbados Ridge accretionary complex forms where the North American plate is subducted beneath the Caribbean plate (Fig. 1). The toe of the accretionary complex has been investigated by Deep Sea Drilling Project (DSDP) Leg 78A and ODP Legs 110 and 156 along a northern transect. At the location of this transect, deformation is dominated by closely spaced thrust

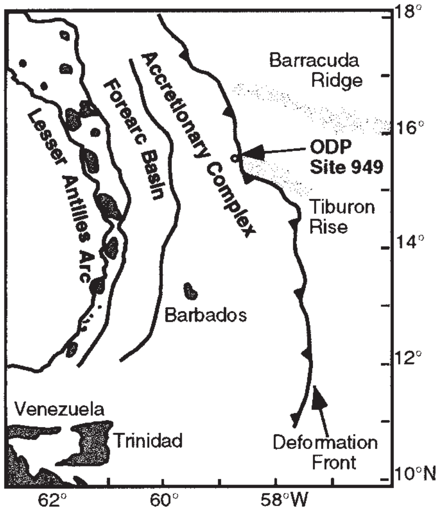

Figure 1. Location map of Barbados accretionary prism and ODP Site 949 (after Brown and Westbrook, 1987).

faults (Brown et al., 1990) and sediment cover is thinner and finer grained than to the south, where turbidite deposition is more common.

Previous investigation (Brown and Behrmann, 1990) of the decollement zone described intervals of scaly fabric (anastomosing, polished, and slickensided fracture surfaces) within Miocene claystone. Scaly fabric formed a crude planar foliation parallel to the fault zone, but foliation dips also occurred at 10° to 25° to the fault-zone orientation. Site 949 is located 1.8 km west of the thrust front and was intended to penetrate the decollement zone at a location where negative-polarity seismic reflections suggested high porosity and the possibility of elevated fluid pressures (Shipboard Scientific Party, 1995a). At this site, decollement sediments were described as relatively soft and plastic, with clear stratal disruption, scaly fabric, and fracture networks. A dissolved chloride minimum at ~425 m bsf (below sea floor) suggested focused fluid migration at this depth (Shipboard Scientific Party, 1995b).

METHODS

Following drilling, installation of casing, and packer testing of Hole 949C, a sea-floor borehole seal (CORK [circulation obviation retrofit kit]; Davis et al., 1992) was installed to isolate borehole fluids from seawater. Within Hole 949C, solid casing was installed from the seafloor to 398 m bsf, and the annulus was cemented. Perforated and screened casing extends from 398 to 451 m bsf to span the decollement zone. The isolated interval of the formation below the CORK seal extends from the top of the perforated casing (398 m bsf) to the total depth of the borehole (468 m bsf). Throughout this paper, calculation of λ^* is referenced to lithostatic pressure at the top of the isolated interval (398 m bsf). Lithostatic and hydrostatic pressures at 398 m bsf were calculated as 57.8 and 55 MPa, respectively, by Fisher and Zwart (1997). Two absolute-pressure transducers monitored fluid pressures within and outside of the sealed borehole. This configuration allowed accurate determination of borehole fluid pressure relative to hydrostatic pressure (taking into consideration that the exterior-pressure transducer is located 2.2 m above the interior-pressure transducer).

This study was conducted nearly 1.5 years after CORK installation, during a joint Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) and National Science Foundation (NSF) project (hereafter referred to as ODPNaut). Initial dives were dedicated to data downloading and visual inspection of the borehole seal. The background fluid pressure (P_b) within the borehole was determined to be 1.0 MPa above hydrostatic ($\lambda^* = 0.3$) . The long-term pressure record and data from downhole thermistors are discussed by Becker et al. (1997).

During two dives, three pressurized slug tests and one discharge test were conducted (Fig. 2). The pressurized slug tests (hereafter referred to simply as "slug tests") consisted of releasing pressure briefly by opening the valve at the seafloor, closing the valve, and monitoring the pressure recovery as fluid flowed from the formation into the borehole. The discharge test was conducted by releasing fluid from the overpressured borehole for 20 min. Allowing an instantaneous pressure drop to hydrostatic had yielded unsatisfactory results during ODP Leg 156 packer testing (Fisher and Zwart, 1997). Therefore, a metering valve that constricted flow was used to slow the pressure drop. The flow period was limited because of shipboard mechanical difficulties. At the end of the flow period, borehole pressure had begun to level off at 0.006 MPa above hydrostatic pressure. Following the flow period, the valve on the borehole was closed and recovery was monitored for 66 min.

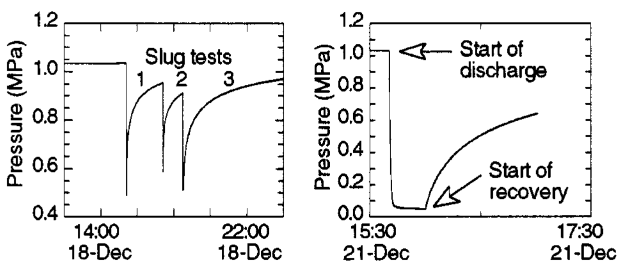

Figure 2. Pressures (above hydrostatic) during ODPNaut hydrogeologic tests. Slug-test pressures are shown on the left, and pressures during the 20-min discharge test and recovery are shown on the right.

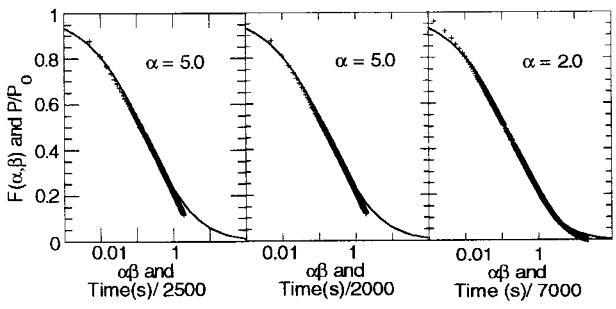

Figure 3. Plots of normalized pressures as function of time for slug tests and selected type curves for F(α, β) against $\alpha\beta$. $P/P_o = (P_m - P_b)/(P_{min} - P_b)$, where P_m is the measured pressure and P_{min} is the lowest pressure during the slug test. Time values have been shifted as noted on axis labels.

DATA ANALYSIS

Slug Tests

Transmissivities were estimated from the slug-test data by using the curve-matching procedure of Bredehoeft and Papadopulos (1980). Use of this method requires that the fault zone be represented as an equivalent porous medium. This assumption is consistent with the observations that the fault zone consists of a network of scaly fractures, each of which is thin relative to the thickness of the tested interval (Brown and Behrmann, 1990). The assumption of an equivalent porous medium and the potential effects of varying transmissivities during the course of the test will be considered further in the discussion section. The compressibility of the fluid within the isolated zone was assumed to be that of seawater (4×10^{-10} Pa^{-1}). This assumption was checked by monitoring fluid discharge during slug test 2 and calculating compressibility as suggested by Neuzil (1982). A slight discrepancy between the result (3×10^{-10} Pa^{-1}) and seawater compressibility is probably caused by flowmeter inaccuracy.

To analyze the test data, observed pressures were normalized and plotted as a function of the logarithm of time and matched with a family of type curves of a function F(α, β) against the product, $\alpha\beta$, for various α, where α is proportional to storativity, and β is proportional to transmissivity. For each of the three slug tests, data were sufficient to identify a type curve (Fig. 3) and allow calculation of transmissivity (Table 1). The matches to the type curves are generally good, although the data fall below the type curve at late times.

In calculating permeability values from estimated transmissivities (Table 1), we assumed equal contribution throughout the 70 m of screened formation to be consistent with Fisher and Zwart (1997). Because fluid flow is likely to be concentrated within parts of the isolated interval, permeabilities presented here will underestimate true permeabilities in those zones.

Discharge Test

Because the discharge test at Hole 949C was neither constant drawdown nor constant discharge, and because the flow rate fell below the resolution of the flow meter, numerical modeling using MODFLOW (McDonald and Harbaugh, 1984) was conducted to estimate hydrogeologic parameters. For the numerical simulations, two layers were used. One layer represented the fault zone, and a second layer represented lower-permeability overlying material. No vertical flow between the two layers was allowed except at the borehole cell, located at the center of the grid. At this cell, the vertical conductivity was assigned based on the flow resistance of the metering valve attached to the CORK. Because flow resistance of the metering valve increases with greater flow velocity, it was necessary to break the flow period into two time intervals and assign a different ver-

Table 1. Results of ODPNaut Tests

	Transmissivity (m^2/s)	Permeability (m^2)	λ^* initial	λ^* final	λ^* average
Slug test 1	2×10^{-9}	5×10^{-18}	0.15	0.33	0.24
Slug test 2	3×10^{-9}	7×10^{-18}	0.20	0.32	0.26
Slug test 3	2×10^{-9}	5×10^{-18}	0.14	0.36	0.25
Recovery from discharge test	9×10^{-9}	2×10^{-17}	0.00	0.31	0.11

tical conductivity to the borehole cell for each of the time intervals. The modeled pressure changes reasonably reproduced those determined by the Hole 949C pressure gauge during the flow period. The pressures during the flow period and the recovery were well simulated by using a transmissivity of 9×10^{-9} m^2/s (bulk permeability of 2×10^{-17} m^2) and a storativity of 0.005 (Fig. 4).

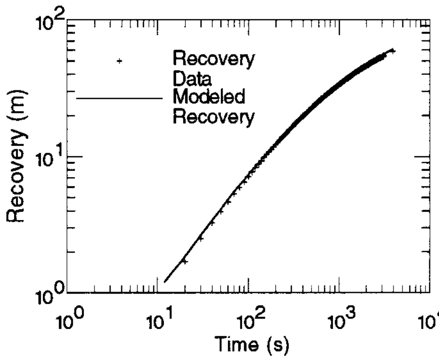

Figure 4. Recovery data and modeled recovery following the 20-min discharge test. The model result used a uniform transmissivity of 9×10^{-9} m^2/s and a uniform storativity value of 0.005. Model result suggests that drawdown extends approximately 0.6 m beyond the borehole.

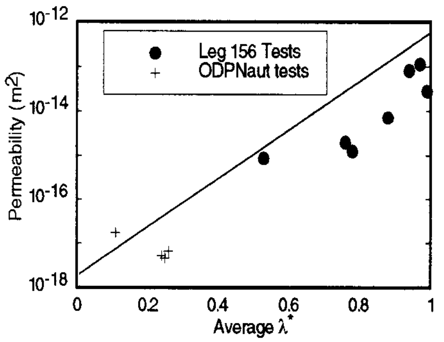

Figure 5. Permeability as function of average λ^* during ODPNaut and Leg 156 packer tests at Hole 949C. Line shows equation proposed by Fisher and Zwart (1997), based on combined packer test interpretations from Holes 948D and 949C.

RESULTS

Results of the ODPNaut tests, conducted at low pore pressures ($\lambda^* = 0$ to $\lambda^* = 0.36$), indicate permeabilities within the fault zone of 5×10^{-18} to 2×10^{-17} m^2 (Table 1). These results are similar to those from laboratory tests on samples of unfractured sediment from ODP Leg 110 (Taylor and Leonard, 1990), which yielded intergranular permeabilities ranging from 10^{-20} to 10^{-16} m^2. At near-hydrostatic pressure, the decollement permeability would be similar to the permeability of surrounding sediments, and, consequently, the decollement could not act as a preferential fluid conduit. The ODP Leg 156 packer-test results from Hole 949C provided bulk permeability values ranging from 9×10^{-16} to 1×10^{-13} m^2 (Fisher and Zwart, 1997). Taken together, the two sets of tests document a variation of four to five orders of magnitude in fault-zone permeability as pore pressure increases from hydrostatic to lithostatic (Fig. 5).

DISCUSSION

Based on packer-test results, Fisher and Zwart (1997) suggested a relationship between permeability and pore pressure ($\log k = -17.9 + 5.2\,\lambda^*$). The results from the ODPNaut tests are consistent with that trend (Fig. 5), but, because no data exist from $0.36 < \lambda^* < 0.5$, the exact nature of the relationship cannot yet be defined.

Several considerations suggest that the response of the decollement zone at Hole 949C may be more complex than indicated by the proposed equation. The four ODPNaut test results do not show an obvious relationship between permeability and pore pressure. The pressure decays from the slug tests were fit well by type curves for constant permeability porous media. We attempted to better match the slug test data by incorporation of the relationship between permeability and λ^* proposed by Fisher and Zwart (1997). The MODFLOW code (McDonald and Harbaugh, 1984) was modified such that, at each time step, transmissivity was recalculated as a function of pore pressure. This modification did not yield improved matches to the ODPNaut data. One possible explanation for the observed discrepancy is that storativity variations during pore pressure changes moderate the pressure response to the pulse decay.

The recovery data from the discharge test were also simulated well using a constant permeability numerical model. This agreement contrasts with interpretations made of the ODP Leg 156 packer tests, in which calculated permeabilities differed by an order of magnitude for two segments of recovery data following a constant-rate discharge test (Fisher and Zwart, 1997).

Although the relationship between permeability and pore pressure cannot be unequivocally defined, the combined results of the ODPNaut and packer test data do suggest a significant increase in permeability with increasing pressure in the decollement at pore pressures below lithostatic pressure. Previous investigators have suggested that permeability increases are the result of the opening of hydrofractures (Moore and Vrolijk, 1992; Brown et al., 1994), which, during thrust faulting, presumably requires pore pressures in excess of the lithostatic load (Sibson, 1981; Behrmann, 1991). In contrast, the ODPNaut and packer test results suggest that either hydrofractures are opening at below-lithostatic pressure (implying that the least principal stress in the decollement is not vertical) or that significant permeability increase occurs without opening of hydrofractures.

Permeability increases caused by increased fluid pressure have previously been observed in both fractured and unfractured rock at fluid pressures below that necessary for hydrofracturing (Witherspoon and Gale, 1977; Gangi, 1978; Rutqvist et al., 1992). The proposed mechanism for the permeability increase is an increase in fracture aperture resulting from reduced effective stress across the fracture (Witherspoon and Gale, 1977). As an example, Jung (1989) documented an increase of two orders of magnitude in transmissivity and one order of magnitude in storativity as pore pressures increased during constant-rate pumping into an artificial fracture in granite.

Permeability response behavior of the decollement to pore pressure changes at Hole 949C would be expected to have greater complexity than that of a single fracture in granite. Because the decollement contains a network of fractures at different orientations (Brown and Behrmann, 1990), its overall transmissivity probably reflects the combination of transmissivities of individual fractures, which will undergo varying reponses to a given pore pressure depending on orientation.

Material from the decollement of Site 949 was described as soft, plastic, and highly porous (55% to 62%; Shipboard Scientific Party, 1995b), implying high compressibility. Unusually high compressibility of the unfractured porous blocks in this part of the decollement may be responsible for the large variation in permeability with pore pressure documented at Hole 949C. As a result, the observed relationship between permeability and pore pressure may be unique to this location or might be characteristic of fault zones developed in fine-grained unlithified sediments.

IMPLICATIONS

The results of these hydrogeologic tests have important implications for the conceptual model of how fluids migrate from the prism. Increases of permeability with sub-lithostatic pore pressure at Site 949 would seem to preclude the existence of above-lithostatic pore pressures unless pressures are valved elsewhere in the decollement, possibly either as the decollement propagates seaward into unfractured material or deeper in the prism, where fault-zone properties may differ significantly from those observed at Hole 949C.

Further understanding of the relationship between permeability and pore pressure in the decollement may require a more detailed treatment than allowed by the assumption of an equivalent porous medium. Within fractured porous media, the pressure field within the fractures may be distinct from that within the unfractured matrix, and that difference requires modification of the effective-stress equation (Tuncay and Corapcioglu, 1995). Because transient pressure differences between the fractures and the matrix will alter effective stress conditions, permeability response to testing may be affected by the timing of pore-pressure changes (whether they occur rapidly or gradually) as well as the recent pressure history of the tested material.

SUMMARY

Results of the ODPNaut hydrogeologic tests at Site 949C indicate bulk permeabilities of 5×10^{-18} to 2×10^{-17} m^2 at fluid pressures from $\lambda^* = 0.0$ to 0.36. Combined with results of tests completed during ODP Leg 156 at higher pressures ($\lambda^* = 0.5$ to 1.0), permeability shows an increase of four to five orders of magnitude as fluid pressures increased from hydrostatic ($\lambda^* = 0$) to lithostatic ($\lambda^* = 1$). Because no data exist from $\lambda^* = 0.36$ to 0.5, the exact nature of the relationship cannot yet be defined.

Pressure-dependent permeability has been documented previously, but the magnitude of permeability change observed at Hole 949C is unusually large and may be the result of the high compressibility of the mudstone within this part of the decollement at the Barbados accretionary complex. Consequently, the observed relationship may be unique to this geologic environment. In addition, transient pressure differences between fractures and matrix will alter effective stress conditions and, as a result, permeability. Therefore, hydrogeologic test results may be very sensitive to test procedures and recent fault-zone pressure history.

ACKNOWLEDGMENTS

Supported by National Science Foundation grants OCE-9301995 and OCE-9415924. These measurements would not have been possible without the expertise and hard work of the crews of the *SEDCO BP 471*, the *Nautile*, the *Nadir*, and the ODPNaut scientific team. Reviews from Barbara Bekins and Ben Clennell improved this manuscript.

REFERENCES CITED

Becker, K., Fisher, A. T., and Davis, E. E., 1997, The CORK experiment in Hole 949C: Long-term observations of pressure and temperature in the Barbados accretionary prism, *in* Ogawa, Y., Shipley, T., Blum, P., Bahr, J. et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 156: College Station, Texas, Ocean Drilling Program (in press).

Behrmann, J. H., 1991, Conditions for hydrofracture and the fluid permeability of accretionary wedges: Earth and Planetary Science Letters, v. 107, p. 550–558.

Bekins, B. A., McCaffrey, A. M., and Dreiss, S. J., 1995, Episodic and constant flow models for the origin of low-chloride waters in a modern accretionary complex: Water Resources Research, v. 31, p. 3205–3215.

Bredehoeft, J. D., and Papadopulos, S. S., 1980, A method for determining the hydraulic properties of tight formations: Water Resources Research, v. 16, p. 233–238.

Brown, K. M., and Behrmann, J. H., 1990, Genesis and evolution of small scale structures in the toe of the Barbados Ridge accretionary wedge, *in* Moore, J. C., Mascle, A., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 110: College Station, Texas, Ocean Drilling Program, p. 229–241.

Brown, K. M., and Westbrook, G. K., 1987, The tectonic fabric of the Barbados Ridge accretionary complex: Marine Petroleum Geology, v. 4, p. 71–81.

Brown, K. M., Mascle, A., and Behrmann, J. H., 1990, Mechanisms of accretion and subsequent thickening in the Barbados Ridge accretionary complex; balanced cross sections across the wedge toe, *in* Moore, J. C., Mascle, A., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 110: College Station, Texas, Ocean Drilling Program, p. 209–227.

Brown, K. M., Bekins, B., Clennell, B., Dewhurst, D., and Westbrook, G., 1994, Heterogeneous hydrofracture development and accretionary fault dynamics: Geology, v. 22, p. 259–262.

Davis, E. E., Becker, K., Pettigrew, T., Carson, B., and MacDonald, R., 1992, CORK: A hydrologic seal and downhole observatory for deep-ocean boreholes, *in* Davis, E. E., Mottle, M. J., Fisher, A. T., et al., Proceedings of the Ocean Drilling Program, Initial results, Volume 139: College Station, Texas, Ocean Drilling Program, p. 43–53.

Fisher, A. T., and Hounslow, M. W., 1990, Transient fluid flow through the toe of the Barbados accretionary complex: Constraints from Ocean Drilling Program Leg 110 heat flow studies and simple models: Journal of Geophysical Research, v. 95, p. 8845–8858.

Fisher, A., and Zwart, G., 1996, Relation between permeability and effective stress along a plate-boundary fault, Barbados accretionary complex: Geology, v. 24, p. 307–310.

Fisher, A. T., and Zwart, G., 1997, Packer experiments along the decollement of the Barbados Accretionary Complex: Measurements of in situ permeability, *in* Ogawa, Y., Shipley, T., Blum, J., Bahr., J. et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 156: College Station, Texas, Ocean Drilling Program (in press).

Gangi, A. F., 1978, Variations of whole and fractured porous rock permeability with confining pressure: International Journal of Rock Mechanics, Mining Sciences, and Geomechanics Abstracts, v. 15, p. 249–257.

Gieskes, J. M., Vrolijk, P., and Blanc, G., 1990, Hydrogeochemistry of the northern Barbados accretionary complex transect: Ocean Drilling Program Leg 110: Journal of Geophysical Research, v. 95, p. 8809–8818.

Jung, R., 1989, Hydraulic in situ investigations of an artificial fracture in the Falkenberg Granite: International Journal of Rock Mechanics, Mining Sciences, and Geomechanical Abstracts, v. 26, p. 301–308.

McDonald, M., and Harbaugh, A., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geologic Survey Open-File Report 83-875, 528 p.

Moore, J. C., and Vrolijk, P., 1992, Fluids in accretionary prisms: Reviews of Geophysics, v. 30, p. 113–135.

Neuzil, C. E., 1982, On conducting the modified "slug" test in tight formations: Water Resources Research, v. 18, p. 439–441.

Rutqvist, J., Noorishad, J., Stephansson, O., and Tsang, C. F., 1992, Theoretical and field studies of coupled hydromechanical behavior of fractured rocks—2. Field experiment and modeling: International Journal of Rock Mechanics, Mining Sciences, and Geomechanical Abstracts, v. 29, p. 411–419.

Screaton, E. J., Carson, B., and Lennon, G. P., 1995, Hydrogeological properties of a thrust fault within the Oregon accretionary prism: Journal of Geophysical Research, v. 100, p. 20025–20035.

Shipboard Scientific Party, 1995a, Introduction, *in* Shipley, T. H., Ogawa, Y., Blum, P., et al., Proceedings of the Ocean Drilling Program, Initial results, Volume 156: College Station, Texas, Ocean Drilling Program, p. 3–13.

Shipboard Scientific Party, 1995b, Site 949, *in* Shipley, T. H., Ogawa, Y., Blum, P., et al., Proceedings of the Ocean Drilling Program, Initial results, Volume 156: College Station, Texas, Ocean Drilling Program, p. 193–257.

Sibson, R. H., 1981, Controls on low-stress hydrofracture dilatency in thrust, wrench and normal fault terrains: Nature, v. 289, p. 665–667.

Taylor, E., and Leonard, J., 1990, Sediment consolidation and permeability at the Barbados forearc, *in* Moore, J. C., Mascle, A., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 110: College Station, Texas, Ocean Drilling Program, p. 129–140.

Tuncay, K., and Corapcioglu, M. Y., 1995, Effective stress principle for saturated fractured porous media: Water Resources Research, v. 31, p. 3103–3106.

Vrolijk, P., Chambers, S., Gieskes, J., and O'Neil, J., 1990, Stable isotope ratios of interstitial fluids from the northern Barbados accretionary prism, *in* Moore, J. C., Mascle, A., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 110: College Station, Texas, Ocean Drilling Program, p. 189–205.

Witherspoon, P. A., and Gale, J. E., 1977, Mechanical and hydraulic properties of rocks related to induced seismicity: Engineering Geology, v. 11, p. 23–55.

Manuscript received August 16, 1996
Revised manuscript received November 14, 1996
Manuscript accepted November 22, 1996