Relation between permeability and effective stress along a plate-boundary fault, Barbados accretionary complex

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ABSTRACT

In situ bulk permeability was measured in a borehole that intersected the decollement zone (a low-angle detachment fault) between the North American and Caribbean plates. Permeability measurements were made at a variety of fluid-pressure conditions, defining a quantitative relation between bulk permeability and effective stress for this plate-boundary fault zone. The bulk permeability in this zone changed by several orders of magnitude as a consistent function of fluid pressure. This relation may help to explain the dynamics of fluid-fault interactions and the transient nature of hydrologic processes during deformation at convergent margins.

INTRODUCTION

The distribution of fault-zone permeability influences the spatial and temporal magnitude of fluid flow and fluid pressures. Variations in fluid pressure may influence permeability and deformational mechanics. For example, overpressured fluids may allow the weak, semilithified sediments of an accretionary complex to glide aseismically over an underthrust plate along a low-angle detachment surface at convergent margins (Hubbert and Rubey, 1959; von Huene and Lee, 1983). Overpressured fluids may also be responsible for the presence of long, mechanically "weak" faults along crustal transform boundaries (Byerlee, 1990; Kerr, 1992; Rice, 1992), and for increases in permeability associated with reductions in effective stress (Yeung et al., 1993). The existence of such overpressures within an active fluid-flow system requires lateral heterogeneity, a sealing mechanism (Deming, 1994), or transient formation properties (Fisher and Hounslow, 1990).

The plate-boundary fault (decollement) between the Caribbean and North American plates is accessible to drilling beneath the toe of the Barbados accretionary complex. Ocean Drilling Program (ODP) Leg 156 investigated the subsea-floor hydrogeology of this plate boundary, occupying sites along an east-west transect established during two previous drilling expeditions (Moore et al., 1982; Moore et al., 1988). Operations included drilling and casing through the decollement zone (the tectonic boundary between the North American and Caribbean plates), followed by active testing of hydrogeological properties with a drill-string packer system (Becker, 1990). We present analyses of one set of these tests, results that allow for the first time the delineation of a relation between in situ permeability and effective stress for a plate-boundary fault within an active accretionary complex. Although this quantitative relation applies only to the Barbados decollement, it has implications for fault zones in other settings.

GEOLOGIC SETTING AND OPERATIONS

Ocean Drilling Program (ODP) Site 948 was located 5 km arcward of the deformation front of the Barbados accretionary complex (Fig. 1). The decollement zone separates Miocene and younger accreted claystone and ash from relatively undeformed Oligocene claystone, siltstone, and chalk (Moore et al., 1988; Shipley et al., 1995). At Site 948 the decollement zone was found to extend from 498 m below the sea floor (bsf) to 529 m bsf on the basis of structural analysis of cores. Geochemical and geophysical measurements made on core samples and in the open borehole support this interpretation (Shipley et al., 1995).

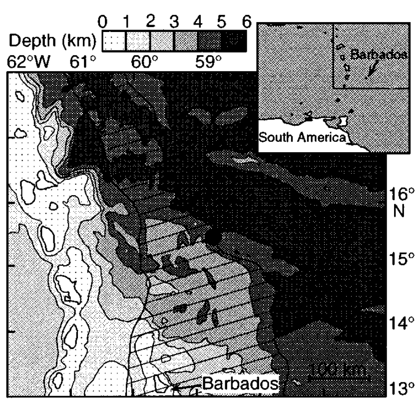

Figure 1. Location of Barbados accretionary complex (striped area). Large dot shows location of drilling transects (including ODP Site 948) and three-dimensional seismic survey (Moore et al., 1988; Shipley et al., 1994, 1995).

Experimental Methods

Hole 948D was stabilized with an assembly of casing, including 42 m of perforated and screened casing extending into and across the decollement zone. The casing was cemented to the formation above the decollement. A drill-string packer was used to isolate the bottom of Hole 948D so that hydrologic properties could be estimated through manipulation and monitoring of fluid pressures within the test interval. Pressure gauges located within the isolated interval recorded fluid pressures throughout testing. Two kinds of tests were employed during packer experiments: pulse tests, where the fluid in the isolated zone was exposed to a nearly instantaneous pressure change (Bredehoeft and Papadopulos, 1980; Cooper et al., 1967), and flow tests, where fluid was pumped into the formation at a constant rate (Horner, 1951; Matthews and Russell, 1967). After each flow test, the well was sealed and pressure recovery of the isolated zone was monitored, providing an additional estimate of hydrologic properties (Horner, 1951).

The packer was inflated in casing immediately above the screened section, isolating ~57 m of the formation, including all of the decollement zone. When the packer was set, pressure in the isolated zone immediately rose by more than 2 MPa above hydrostatic; four pulse and three flow tests were then conducted (Fig. 2). The pressure vs. time record from these tests is similar to records from other ODP packer experiments, with two important differences. First, the background pressure was initially much greater than hydrostatic and rose by an additional 1 MPa in a three-hour period. Second, the shapes of the pressure vs. time curves during individual tests indicate a quantitative increase in bulk permeability as background fluid pressure increases (effective stress decreases).

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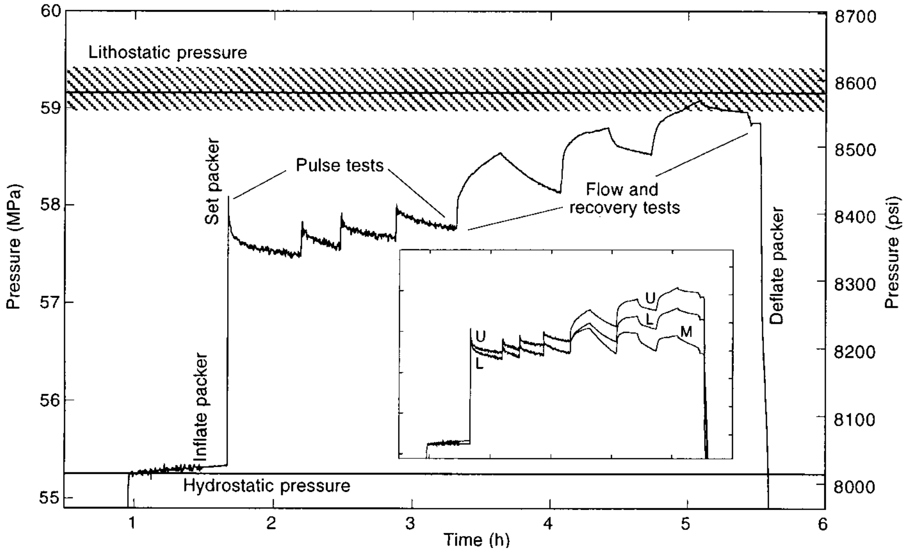

Figure 2. Pressure record for one set of hydrologic tests in Hole 948D. Lower horizontal line shows hydrostatic pressure recorded by downhole gauge at start of tests. Because hydrostatic and lithostatic gradients have different slopes, vertical effective stresses at any time during test are different at different depths within test interval. Shaded area shows range of gauge pressures that would exceed lithostatic over 57 m test interval. Upper horizontal line (within shaded area) indicates lithostatic pressure in center of test interval. All lithostatic pressure values have been adjusted to account for actual depth of electronic pressure gauge. Inset shows uncorrected pressure data (U), pressure data with initial linear correction (L; based on observed pressure rise between 1.0 and 1.6 h), and pressure data with maximum linear pressure correction (M; based on residual pressure remaining at 5.4 h, after correcting for decay of all pulse and flow tests). Record shows four pulse tests and three flow tests. Each flow test consists of pressure buildup (corresponding to steady pumping) followed by pressure decay and recovery (after pumping stops and test interval is isolated). This record thus shows total of 10 independent hydrologic tests (four pulse, three flow, and three recovery).

Analytical Methods

The standard hydrologic methods used to analyze these data are based on fitting measured pressure-time values to analytical solutions of a mass-conserving flow equation. These methods generally require (1) that formation hydrologic properties remain constant throughout individual tests, and (2) that the background fluid pressure during each test is fixed so that all pressure changes can be attributed to the tests themselves. In our analyses, we initially neglect an explicit pressure dependence of hydrologic properties, noting that differences in properties between tests are greater than the changes that occur during the segments of the individual tests used to estimate formation properties. We applied corrections for changes in background pressure during the tests, but we found that these corrections had only a small influence on calculated hydrologic properties. Additional assumptions in these analyses include radial, Darcian flow to and from the borehole, constant fluid viscosity during the tests (based on measurements of fluid temperature), and an idealized isotropic and homogeneous representation of the formation around the borehole. The calculations thus provide equivalent porous-medium (bulk) permeabilities, allowing comparison with other marine and terrestrial data.

For pulse tests, system compressibilities were calculated directly from observations (Neuzil, 1982), as $(\Delta V/V)/\Delta P$, where P is pressure and V is volume. Pulse tests examine only the area immediately adjacent to the borehole and are not considered to be as reliable as flow tests. The log-linear method used in interpretation of flow and recovery test data is a standard of ODP permeability testing (Becker, 1990). This simplified method (Cooper and Jacob, 1946) is valid for measurements in a pumping well only for relatively long times, when $u = r^2S/(4Tt) < 0.05$, where r is borehole radius, S is storage coefficient, T is transmissivity, and t is time. This condition was met for each test. Hydrologic properties were also calculated using the full Theis (1935) solution, with essentially identical results. During one of the flow tests and two of the pressure recovery tests, there was a change in the slope of the best-fitting pressure-log time curve. This difference in pressure response during a single test could reflect formation damage near the borehole (related to drilling and casing emplacement), transient or natural lateral variations in formation properties, or some combination of these effects. Because it is impossible to resolve with certainty the cause of these changes in pressure-time response, data were selected from two sections of these records, resulting in two estimated values for bulk permeability and vertical effective stress.

Other solutions are possible, including the presence of vertical leakage, partial penetration, dual porosity, fracture-based flow, and skin effects (Hantush, 1960; Moench, 1984), but there are insufficient data to constrain the extra parameters associated with these more complex approaches. Additional numerical analyses now underway may elucidate the role of some of these conditions. However, experience has shown that the application of more complicated models to data collected in pumped wells generally produces results that are no more than 20%–30% different from results derived with the log-linear approximation (Cooper and Jacob, 1946) using late-time data (i.e., Moench, 1984; Johns et al., 1992).

RESULTS

The initial hydrostatic pressure was determined with the pressure gauge when it landed in the packer (Fig. 2), and was consistent with the depth of the gauge. All subsequent pressure readings were analyzed and adjusted relative to this reference as follows. Background pressure rose at the start of the experiment before the tests began, probably due to partial sealing of the inflation element against the casing wall (Fig. 2). The linear shift required to keep this background pressure constant was applied to the full record (curve L in Fig. 2 inset); we believe this correction to be a conservative lower bound on the overall trend of the background pressure rise during the tests. This single correction was sufficient to remove any residual excess pressure from the individual pulse tests (i.e., after accounting for excess pressure due to the pulse tests, the background pressure at the end of all pulse tests was equal to the initial value at t of 1.6 h). An additional linear correction was applied to the pressure record following the pulse tests (curve M in Fig. 2 inset), in order to remove the excess pressure remaining at the end of the flow tests (i.e., after accounting for the residual pressure decay from the flow tests). We believe this to be the maximum justifiable linear correction. Because the results of the tests are remarkably consistent over the range of linear corrections, however, only results from curve L are shown (Fig. 3).

Analyses from this set of tests reveal an increase in bulk permeability (1×10^{-15} m^2 to 6×10^{-13} m^2) as background pressure rose in the isolated zone. This increase in fluid pressure corresponds to a decrease in the vertical effective stress (from 1.6 MPa to 0.1 MPa) within the isolated formation (Fig. 3). The maximum principal stress at depth within this active accretionary com-

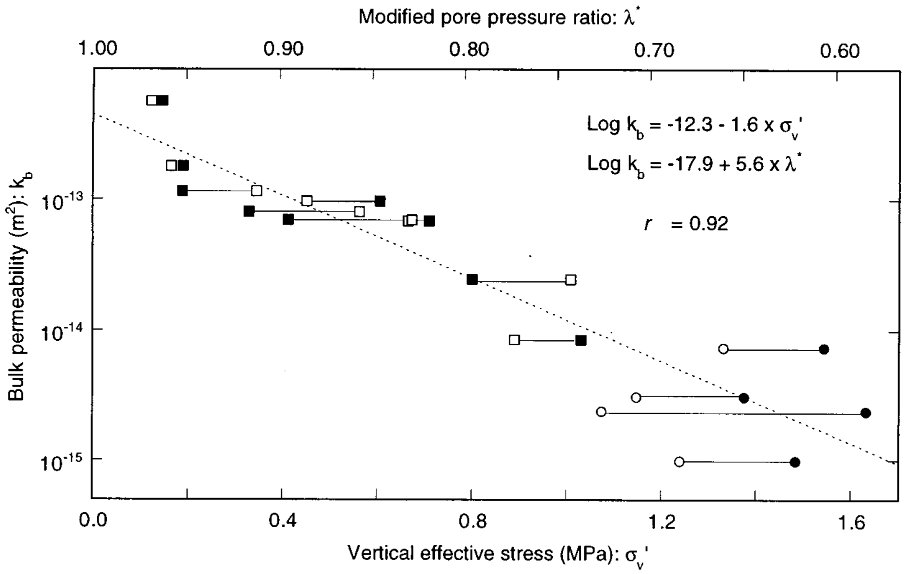

Figure 3. Bulk permeability (k_b) vs. vertical effective stress (σ_v') and vs. modified pore pressure ratio (λ^*) for center of test interval, based on simple linear correction to raw data (curve L in Fig. 2). Open symbols indicate effective stresses at start of test periods; solid symbols indicate effective stresses at end of test periods. Circles are results for individual pulse tests. Squares are results for individual flow and recovery tests. Horizontal lines connect initial and final effective stress values for individual tests. Vertical effective stress was calculated as $\sigma_v' = P_l - P_m$, and modified pore pressure ratio was calculated as $\lambda^* = (P_m - P_h)/(P_l - P_h)$. P_l is lithostatic pressure at center of test interval (calculated from weight of overlying sediments based on laboratory and borehole measurements; Moore et al., 1995; Shipley et al., 1995), and P_h is hydrostatic pressure at center of test interval. P_m is pressure measured at gauge and adjusted to center of test interval. Dotted diagonal line and equations are least-squares best fits of log-permeability to vertical effective stress (MPa) and modified pore pressure ratio; all data are weighted equally in regression.

plex probably exceeds than this vertical value, particularly if there is significant horizontal compression (Moore et al., 1988; Brown et al., 1994). The maximum test pressure was too low to exceed lithostatic pressure within most of the test interval, but fluid pressure apparently was sufficient to exceed lithostatic near the top of the tested interval during the final flow test (Fig. 2). Increases in fluid pressure above this value would have exceeded lithostatic at successively greater depths within the test interval.

DISCUSSION

The relation between bulk permeability and vertical effective stress defined through these in situ tests is consistent with a variety of indirect estimates. At the upper extreme, bulk permeability approaches 10^{-12} m^2 when fluid pressure approaches lithostatic. This is approximately the same value predicted with an independent model of transient fluid flow at lithostatic pore pressure based on simple thermal considerations (Fisher and Hounslow, 1990). If most of the bulk permeability in Hole 948D is concentrated within a narrow part of the tested zone, as suggested by borehole logs of bulk density (Shipley et al., 1995), the permeability within this thin zone could be significantly greater. At the lower extreme (projected beyond the range of this data set; Fig. 3), a bulk permeability of about 10^{-18} m^2 is predicted when fluid pressure is hydrostatic. This lower extreme is consistent with laboratory tests of fine-grained material from the same area (Taylor and Leonard, 1990).

The natural state of fluid pressures in the formation is not fully constrained. Moore et al. (1995) concluded that the fluid in the formation surrounding the test interval in Hole 948D was initially at a pressure close to lithostatic. We believe that drilling the hole allowed partial drainage of the formation, the greatest reduction in pressure being in the zone closest to the borehole. Setting the packer allowed a partial recovery toward natural, in situ pressure conditions.

Although we have found that bulk permeability in the formation surrounding the borehole changed rapidly with fluid pressure, the changes (in both pressure and permeability) that occurred during the parts of each test used to construct Figure 3 are much smaller than the differences in properties measured throughout all the tests. In addition, by plotting bulk permeability against a range of pressure values observed during the tests, the effect of property changes during each test was averaged. These data are from a single borehole within a transient, multidimensional system. The overall trend and magnitude of the result is more significant than the exact values, particularly because there are no other in situ data available for this setting.

The consistency of the in situ test results with other studies suggests that permeability along the decollement may vary with pore pressure along a continuum, from intergranular flow when fluid pressure is low, to "fracture" flow when pressure approaches lithostatic. The use of the term "fracture" in this context may actually be misleading, because it suggests the presence of competent rock. The sediments recovered from within the decollement zone during ODP Leg 156 were soft, weak, and highly porous (Shipley et al., 1995).

Several conceptual models of accretionary systems have emerged in recent years to explain (1) the distribution of deformation (Brown and Behrmann, 1990; Moore et al., 1988); (2) the preservation and implications of near-sea-floor porosities at great depth (Shi and Wang, 1985; Shipley et al., 1994); (3) the association of geochemical anomalies and faults (Gieskes et al., 1990); and (4) the ability of a thin, wide wedge of semilithified sediments to glide aseismically over an underthrust plate (Dahlen, 1990). Prior to the collection in situ permeability data, this property was estimated using indirect inferences drawn from laboratory measurements (Taylor and Leonard, 1990), numerical modeling (Screaton et al., 1990; Shi and Wang, 1988), and the apparent association of faults with flow conduits (Fisher and Hounslow, 1990; Gieskes et al., 1990).

Laboratory tests of samples from the Oregon accretionary prism have defined quantitative trends of permeability vs. effective stress (Brown, 1994), but matrix-scale permeability increases due to decreases in effective stress tend to be several orders of magnitude lower than those indicated by the new in situ tests. These differences probably reflect the corresponding experimental scales or the disruption of fragile sediment structures during handling and testing. Steady-state numerical models (Screaton et al., 1990) also predict permeabilities significantly lower than those measured in situ at low effective stresses, as expected if natural prism dewatering is transient and dynamic. Transient models suggest somewhat higher permeabilities than steady-state models (Bekins et al., 1994; Henry and Wang, 1991).

The increase in bulk permeability with reduced effective stress, at sublithostatic fluid pressures, may help to explain the discontinuous distribution of zones having a negative seismic polarity (a possible indication of elevated porosity) in this region (Shipley et al., 1994). Development of overpressures requires balancing fluid production and fluid flow. If fluid production is slow, or if permeability changes greatly with small changes in fluid pressure, little fluid will be retained within the fault zone to generate overpressures. If fluid production is rapid relative to changes in permeability with decreasing effective stress, fluid pressure can build until sufficient lateral permeability is generated to release the overpressured fluid.

CONCLUSIONS

The first in situ measurements along the decollement of an active accretionary complex reveal relatively high bulk permeabilities and a consistent relation between bulk permeability and vertical effective stress. This relation agrees with results of laboratory experiments and inferences drawn from models and indirect calculations. The in situ measurements also suggest that natural fluid pressures within the decollement of the Barbados accretionary complex at Site 948 are close to lithostatic, although additional analyses are required to quantitatively determine the extent of the drilling-induced component of excess fluid pressure, and the reason for the apparently linear rise in background pressure with time. Long-term monitoring of fluid pressures in the Barbados accretionary complex and additional active testing by submersible, undertaken in late 1995, should provide additional insight.

Whether the observed increase in fluid pressure during packer tests reflects a return to a pre-drilling natural state of fluid pressure close to lithostatic (Shi and Wang, 1988; Screaton et al., 1990; Moore et al., 1995) or was partially induced by borehole operations, active testing defines a valid permeability-effective stress relation. Understanding the causes of this relation is critical to the development of realistic, transient models of coupled deformation and fluid flow in tectonically active environments.

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