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19. *IN-SITU* BULK PERMEABILITY OF OCEANIC GABBROS IN HOLE 735B, ODP LEG 118[1]

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ABSTRACT

An inflatable drill-string packer was used at the end of Leg 118 to measure the bulk *in-situ* permeability of four intervals within the 500 m of 12-m.y.-old gabbros of oceanic layer 3 cored in Hole 735B. The packer was inflated six times successively, at depths of 49, 47, 389, 299, 223, and again 223 mbsf, to determine the average permeabilities of the respective intervals between the respective inflation depths and the bottom of the hole. Two of these inflations were essentially repeated tests to verify the packer seal and apparent indications of relatively high permeability below 49 and 223 mbsf.

The inflation depths of the packer were chosen on the basis of the dual laterolog resistivity log, which clearly distinguished the six major lithologic Units observed in the recovered core. Thus, the inflation at 389 mbsf essentially isolated the olivine-rich gabbros and troctolites of Unit VI; the inflation at 299 mbsf isolated Unit VI plus most of the olivine gabbros of Unit V; the inflations at 223 mbsf isolated Units V and VI plus the iron-titanium oxide-rich gabbros of Unit IV; and the inflations at 49/47 mbsf isolated Units IV, V, and VI plus the olivine gabbros of Units II and III.

At each inflation, several standard slug tests and/or constant-rate injection tests were conducted, with good, repeatable results. Measured interval permeabilities decrease by two orders of magnitude with depth, ranging from about 24 to 0.2 × 10^{-15} m^2, similar to the range in permeabilities measured in the basaltic sections of Holes 395A and 504B. The permeabilities of the intervals between packer inflation depths were estimated from the differences in measured transmissivities, showing that Unit IV is the most permeable section, averaging about 80 × 10^{-15} m^2.

The log analysis of Goldberg et al. (this volume) shows that most of the permeability found above 299 mbsf, in Units II, III, and IV, can be attributed to a few zones of isolated fractures; the hydraulic conductivities of these fractures are probably much greater than the average permeabilities reported here. These fractures probably resulted from tectonic processes associated with the uplift of the fracture-zone transverse ridge in which the hole is located; thus, the relatively low permeability measured deeper in Hole 735B may be more representative of oceanic layer 3 gabbros *in situ.*

INTRODUCTION

The bulk porosity and permeability of the oceanic crust probably depend on irregular and relatively large-scale fractures and voids, which cannot be represented by dredged or cored samples. Given present technology, the crustal porosity and permeability are best measured *in situ* from deep boreholes, preferably at averaging scales large enough to fully include the effects of irregular fracture porosity. Here, I report the methods, data, and results of such *in-situ* packer experiments, which were conducted during Leg 118 of the Ocean Drilling Program (ODP) to assess the bulk permeability of the 500 m of gabbros penetrated in Hole 735B. The hole was cored at a shallow point within the transverse ridge east of the Atlantis II Fracture Zone (Fig. 1), and the cored gabbros represent uplifted oceanic layer 3 materials about 12 m.y. old (Robinson, Von Herzen, et al., 1989). In a companion paper, Goldberg et al. (this volume) discuss the relationship of the fractures detected with downhole logs to the interval permeability measurements described here.

METHODS—PACKER EXPERIMENTS

Equipment and Procedures

During Leg 118, the average permeabilities of four intervals of Hole 735B were measured using a reseatable drill-string packer manufactured by TAM International and described by Becker (1986, 1988). This packer incorporates inflatable rubber elements to isolate a section of the hole and can be configured as a single or a straddle packer. For the measurements in Hole 735B, it was configured with one element and used as a single-seal packer to isolate the zone between the bottom of the hole and the seal (Fig. 2A). This packer was inflated six times at four depths to determine the bulk permeabilities of the respective intervals between these depths and the bottom of the hole.

The packer is actuated using a "go-devil" that is dropped down the drill string into the packer inflation subassembly, where a rubber seal on the go-devil directs seawater pumped from the ship into the inflatable packer elements. Once the packer elements are fully inflated and gripping the borehole, the packer locks the bottom-hole assembly in the hole, and the drill-string heave compensator is adjusted to transfer and maintain a weight of 10,000 to 20,000 lb (in the form of drill collars just above the packer) onto the inflated packer. This weight shifts a sleeve in the inflation subassembly downward, closing the inflation–deflation port to the packer elements and opening the interval isolated by the packer to fluid pressure or flow applied by shipboard pumps. As this occurs, some of the inflation pressure is applied to the isolated formation in a poorly controlled slug test; thus, the first slug test at each inflation depth results from the inflation procedure and may be less reliable than subsequent slug tests at the same inflation depth.

The go-devil also carries pressure recorders (in this case, two carefully calibrated mechanical Kuster K-3 recorders) to monitor downhole fluid pressures in the isolated, pressurized zone during the experiment. While it would have been possible to include a one-way check valve in the go-devil to restrict the pressurized zone to the section isolated by the packer (that

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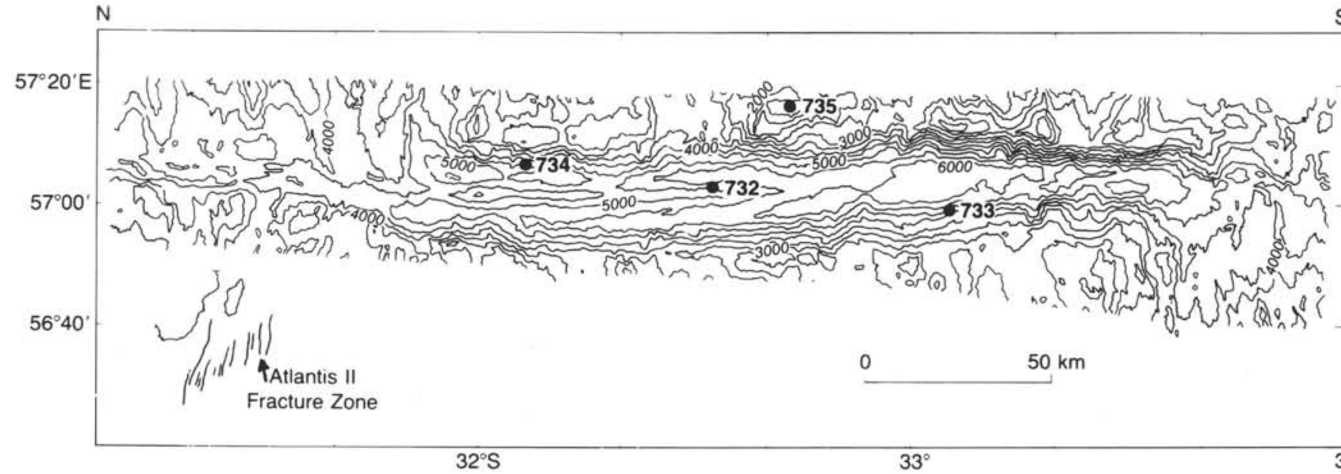

Figure 1. Location of Hole 735B and other Leg 118 drill sites on a bathymetric map of the Atlantis II Fracture Zone. Contour interval is 500 m. Data from *Conrad* cruise 27-09, 1986 (H. Dick, chief scientist, with D. Gallo and R. Tyce).

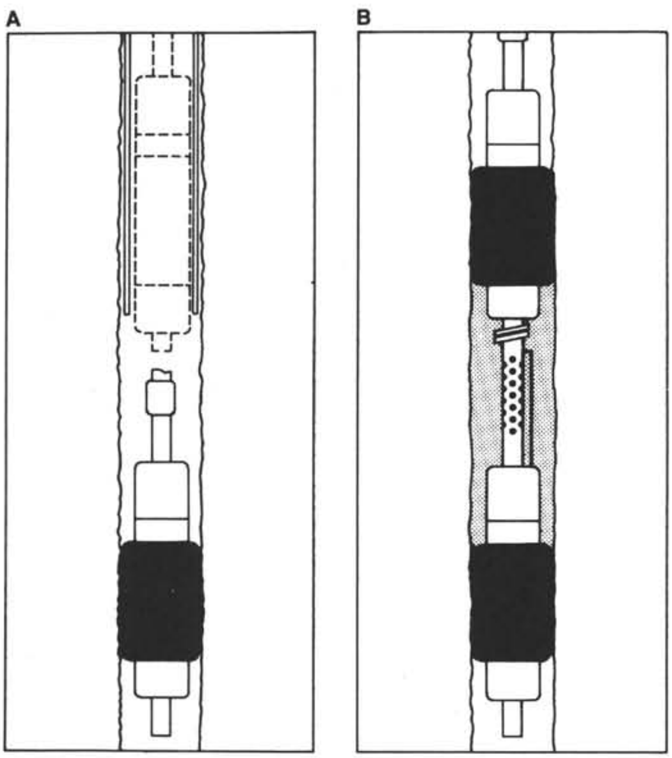

Figure 2. Sketches of inflatable drill-string packers. A. Single-element packer, which isolates the formation between the inflation element and the bottom of the hole, as used for the measurements reported here. B. Straddle packer, which isolates the zone between the elements.

is, excluding the volume within the drill string), no such check valve was used during Leg 118. Therefore, the fluid in the entire drill string as well as the isolated zone was pressurized during testing, and a pressure transducer at the rig floor was also used to provide a real-time indication of downhole events. Volumes and rates of fluids pumped into the isolated zone were monitored by timing changes in the volume of the pump reservoir.

Summary of Operations

The last day of scientific operations at Hole 735B was devoted to running the drill-string packer. During this period, the go-devil was deployed three times, and the packer was inflated six times at four depths to assess the variation of formation permeability (Table 1). During the packer measurements, fluid pressure, flow rate, and total volume pumped were measured at the rig floor, and fluid pressure was measured in the borehole within the intervals isolated by the packer.

Special care was taken to verify the hydraulic integrity of the testing system, which consisted of the rig pumps and lines, the drill string, and seals within the go-devil and the inflated packer. Before deploying the first go-devil, the hydraulic integrity of the rig-floor circulation system was satisfactorily tested to 10 to 15 MPa, more than twice the pressures used to inflate the packer or test the formation. At each packer inflation, the integrity of the drill string and go-devil seals was

Table 1. Summary of Leg 118 packer measurements in Hole 735B.

Go-devil run	Packer inflation depth (mbsf)	Test sequence[a]
1	49	4 slug tests with fast decays. Deflate packer with 20,000-lb pull and fifth slug test.
	47	Reset to verify previous results. 2 slug tests with fast decays. 3 injection tests: 100 strokes/min, with mud slug to verify packer seal, 50 strokes/min, 30 strokes/min.
2	389	2 slug tests with slow decays.
	299	4 slug tests with moderate decays.
	223	3 slug tests with fast decays. 1 injection test—50 strokes/min.
3	223	Re-set to verify previous results. 1 slug test with fast decay. 2 injection tests: 30 strokes/min, 50 strokes/min, with mud slug to verify packer seal

[a] One pump stroke equals 19.6 L.

satisfactorily tested by holding inflation pressure for 5 to 10 min before locking the packers in the inflated position. The effectiveness of the packer seal against the borehole was demonstrated by the excellent quality of the slowly decaying slug test records in relatively impermeable sections, and was directly tested in permeable zones by the method described in the following paragraphs.

The depths at which the packer was set were chosen primarily on the basis of logging results. It was decided to set the packer first at a shallow depth because there were a number of indications (e.g., superb recovery of massive core, very high electrical resistivity values and low porosity values from the logs) that much of the cored formation might be impermeable. Setting the packer first as shallow as possible in the hole allowed the permeability of the entire cored section to be assessed; if the entire section had been impermeable, the remaining time on site would have been used for other purposes. However, the results at the first inflation depth showed that there was significant permeability in the hole, and subsequent inflations were run from deep in the hole back up the hole to determine the variation of permeability with lithology and to locate the permeable section(s).

Once the packer was set as described above, two kinds of experiments were used to determine the permeability of the isolated interval, pressure pulse or "slug" tests and constant-rate injection tests. The methods used were similar to those described by Anderson and Zoback (1982), Hickman et al. (1984a), Anderson et al. (1985), and Becker (1989, 1990) when conducting packer experiments in Holes 395A and 504B for the Deep Sea Drilling Project (DSDP) and ODP. Injection tests generally disturb the pressure field in the formation around the hole much more than slug tests and thus were conducted after the slug tests at appropriate inflation depths.

The complete sequence of operations is summarized in Table 1. All operations proceeded smoothly, except for the first packer setting at 49 mbsf, as follows: When the pulse test results at this setting indicated unexpectedly high permeability, we decided to verify that the packer element was properly sealing, by resetting the packer at the same depth and repeating the measurements. However, the packer could not be deflated smoothly, and it required much more pull (20,000 lb) than normal to release the pressurized fluid inside the inflation element. For a short time, the packer was actually stuck in the hole, and it was not clear whether it was working properly. Nevertheless, when the packer was moved 2 m shallower in the hole and pressured up, it reset smoothly and gave similar indications of high permeability somewhere in the isolated interval.

Such indications could also have been produced by a "leaky" packer seal if the element had been damaged when it was pulled free. Therefore, the seal was then tested by utilizing the video reentry system, which was hanging immediately above the reentry cone, as follows: A small slug of mud was pumped into the isolated interval, immediately followed by a constant-rate injection test that involved pumping seawater into the isolated interval at nearly 2000 L/min for more than 20 min. This amount of seawater was more than twice that required to pump the mud back out of the hole if the packer had not been sealing properly. No mud or other fluid was seen exiting the cone on the video during this or two subsequent injection tests during this inflation. Although this particular injection test was flawed as a permeability measurement because of procedures required for the mud slug, fluid pressures during the subsequent injection tests closely followed the prescribed behavior, indicating that the packer was functioning properly.

Thus, we concluded that the packer was operating correctly, and there was indeed highly permeable formation in the hole. The go-devil was retrieved and redressed, and the packer was moved deep in the hole and set at successively shallower depths to locate the permeable zone(s). The packer and go-devil operated smoothly until the drill string had to be pulled to depart the site. At the end of the last packer setting at 223 mbsf, the mud-slug and injection test described above was repeated; no mud was seen exiting the cone, again verifying that the packer was sealing properly. When the packer was brought back on deck, the inflation element was in nearly perfect condition, in contrast to several previous examples of shredded, melted, or otherwise frazzled elements from basaltic Holes 395A and 504B.

Slug Test Procedures

The slug tests were conducted following the methods for the "modified" slug test of Bredehoeft and Papadopulos (1980), which is an adaptation of the slug test method of Cooper et al. (1967) and Papadopulos et al. (1973) for formations having relatively low permeabilities. The modified slug test involves applying a short pressure pulse to the fluid in the zone isolated by the packer, and monitoring the decay of this pulse as fluid flows from the borehole into the isolated formation.

The decay of such a pressure pulse is analogous to the decay of the frictional heating pulse on penetration of an oceanographic heat flow probe into sediments (Bullard, 1954; Carslaw and Jaeger, 1959) and is described by virtually the same equation (Cooper et al., 1967; Bredehoeft and Papadopulos, 1980):

$$P(t)/P_0 = F(\alpha,\beta).$$

Here, P is pressure in excess of the initial undisturbed value, P_0 is the initial pressure increase, α is a dimensionless parameter that depends on the storage coefficient (S) and porosity (ϕ) of the isolated formation, β is a dimensionless parameter that depends on the transmissivity (T) and permeability (k) of the formation, and F is a complicated infinite integral. More specifically,

$$\alpha = \pi a^2 S/V_w C_w \rho_w g,$$

$$\beta = \pi T t/V_w C_w \rho_w g,$$

$$S = b\phi C_i \rho_i g, \text{ and}$$

$$T = bk\rho_i g/\mu,$$

where t is time, g is gravitational acceleration, a is the radius of the hole in the isolated zone, b is the height of the isolated zone, C_i, ρ_i, and μ are the compressibility, density, and dynamic viscosity of the fluid in the isolated zone, respectively, and C_w and ρ_w are the compressibility and density of the fluid in the total pressurized volume, V_w. The function $F(\alpha,\beta)$ is given by

$$F(\alpha,\beta) = (8\alpha/\pi^2)\int_0^\infty du \exp(-\beta u^2/\alpha)/uf(u,\alpha),$$

where $f(u,\alpha) = [uJ_0(u)-2\alpha J_1(u)]^2 + [uY_0(u)-2\alpha Y_1(u)]^2$, u is the variable of integration, and J_0, J_1, Y_0, and Y_1 are Bessel functions of the first and second kind.

To process the pressure data measured during slug tests, we followed the standard curve-fitting method described by Cooper et al. (1967) and Papadopulos et al. (1973), as follows: A plot of the decay of measured pressures vs. log time was superposed on a family of type-curves of $F(\alpha,\beta)$ vs. log β calculated for various values of α spanning several orders of magnitude. The data plot was then shifted along the abscissa of the type-curve plot to visually determine the value of α for which the data best fit the type curve. Then, the transmissivity and average permeability of the tested interval could be calculated from the correspondence between the values of time and β for the best-fit curve, using the definitions for β and transmissivity listed above.

As noted by Cooper et al. (1967), Papadopulos et al. (1973), Bredehoeft and Papadopulos (1980), and Hickman et al. (1984), the calculated type-curves are similar over a wide range in values of α, and significant errors in the choice of α are likely in the curve-matching procedure. Fortunately, the large errors possible when determining α result in relatively small corresponding errors in the determination of transmissivity and permeability. Thus, this procedure yields relatively poor estimates of the storage coefficient and porosity, but reasonable determinations of transmissivity and average permeability.

To justify the application of this theory for an instantaneous pressure pulse to real slug test data, the rise time of the slug test should be short compared to the decay time. For each slug test conducted during Leg 118, the ship's "cement pump" or "mud pump" was used to inject a small volume or "slug" of seawater into the drill string (which was already full of seawater at hydrostatic pressure), and the decay of the resultant pressure pulse was monitored with the downhole and rig floor recorders. Typically, 500 to 1000 L were pumped into the drill string in 0.5 to 1 min, to produce a pulse having an initial pressure increase on the order of 0.5 to 2.5 MPa in the isolated zone. The decays of all of the pressure pulses took sufficiently long (>10 min) to justify the application of the theory for an instantaneous pressure pulse.

Constant-Rate Injection Tests

In a relatively permeable formation, a slug test will decay rapidly, and a better determination of permeability can be obtained by conducting a constant-rate injection test. In such an experiment, borehole pressure within the isolated zone is monitored as fluids are pumped into the formation at a constant rate. The increase in pressure as injection proceeds is analogous to the rise in temperature of a heated needle probe used to measure thermal conductivity of sediments (Jaeger, 1958; Von Herzen and Maxwell, 1959) and is described by the same type of equation (Horner, 1951; Matthews and Russell, 1967):

$$P(a,t) = (q\mu/4\text{-}kb)ln(\gamma\phi\mu C_i a^2/4kt),$$

where q is the flux of injected fluids, γ is Euler's constant, and the remaining parameters are as defined previously. Thus, the transmissivity and average permeability of the isolated zone can be determined directly from the slope of a plot of pressure vs. log time, given the measured constant injection rate.

For the six injection tests attempted in Hole 735B during Leg 118, seawater was pumped into the zones isolated by the packer for 0.4 to 0.7 hr at fixed rates of about 8 to 30 L/s. During each of these tests, the rate of injection was kept constant within 5% to 10%. The actual rates were determined by counting the strokes of the mud pump; each stroke pumps a volume of 5 gal at 98% efficiency, with a stroke per minute equivalent to 0.3 L/s. As noted previously, the first and last injection tests were complicated by the procedures required to first inject a mud slug for video verification of the packer seal; these two injection tests therefore are probably not reliable determinations of formation permeability.

ASSUMPTIONS, APPROXIMATIONS, AND SOURCES OF ERROR AND UNCERTAINTY

In-Situ Permeability vs. Calculated Bulk Permeability

Both slug and injection tests involve an important assumption—that the permeability of the rock in the zone isolated by the packer is uniform and isotropic. This assumption is not strictly valid for the gabbros penetrated in Hole 735B, where permeability may be dominated by isolated fractures (Goldberg et al., this volume). Nevertheless, it probably "becomes more valid as the scale of the permeability tests [i.e., the length of the zone isolated by the packer] increases with respect to the spacing of the fractures" (Hickman, 1984; Parsons, 1966). The permeabilities computed here are average Darcian or equivalent porous-media permeabilities, denoted as bulk permeabilities, obtained by applying the theory for uniformly permeable media. If the *in-situ* permeability is indeed dominated by isolated fractures, the actual hydraulic conductivities of such fractures may be orders of magnitude greater than the transmissivities reported here.

Integrity of the Packer Seal

The validity of results obtained with a packer obviously depends on the hydraulic integrity of the seal made with the inflatable elements. Given that the annulus of an ODP hole is open to an infinite reservoir of seawater at hydrostatic pressure, it is generally difficult in an ODP hole to sense any possible leakage of fluids upward past the inflation element(s). However, as described previously, the integrity of the packer seal was directly confirmed twice in Hole 735B by using the reentry video system. Moreover, major leakage would have resulted in slug and injection test data noticeably different from predicted form, which was closely followed. Nevertheless, slight, undetectable leakage past the packer might have been possible during the measurements in Hole 735B. If so, this would have resulted in calculated transmissivities and permeabilities greater than the real values; thus, the values calculated here must be considered upper bounds on the transmissivities and bulk permeabilities of the zones isolated in Hole 735B.

Model-Fitting Procedures

For both slug and injection tests, the bulk permeability is derived from parameters determined from the best fit of measured pressures to those predicted by models valid for isotropically permeable formations. For injection tests, the bulk permeability is calculated from the slope of a plot of pressure vs. log time; this slope is calculated using standard least-squares techniques, which then allow for objective error estimates. However, as noted previously, the analysis for slug tests involves fitting measured pressures to type-curves subjectively, with no rigorous assessment of possible errors. When interpreting past slug test results in the upper oceanic crust, Anderson and Zoback (1982), Hickman et al. (1984a), and Anderson et al. (1985) estimated the uncertainties in calculated transmissivities and bulk permeability values by deliberately misfitting the type-curves by plus or minus an order of magnitude in α. For bulk permeabilities typical of oceanic crust, this range in α results in uncertainties of about ±30% in permeabilities determined from slug tests.

Properties of the Fluids in the Pressurized System

The equations discussed previously demonstrate that the transient pressures measured during both slug and injection tests depend on the properties of the pressurized fluids, particularly viscosity and compressibility, which vary with both temperature and pressure. For the temperature-dependent viscosity of seawater, I followed Anderson et al. (1985) in using Gartling's (1977) equation, $\mu(10^{-3}$ Pa-s$) = 16.68T^{-0.8987}$, with T in °C. For *in-situ* temperatures of about 10°C in the zones tested during Leg 118, this yields a viscosity of about 2×10^{-3} Pa-s, which was used for all calculations reported here.

As noted by Neuzil (1982), the effective compressibility of the fluid in a shut-in hole is sometimes greater than that of the pure fluid (seawater in this case), because of (1) compliance of the drill string and test equipment and (2) air possibly trapped in the system. While every effort was made during Leg 118 to purge all air from the drill string, pump, and connecting plumbing, small amounts of air may have remained in the system. Such trapped air would affect the system compressibility, and the transmissivity and bulk permeability calculated in a slug test, which are directly proportional to the compressibility.

Therefore, we carefully recorded the volumes pumped downhole during slug tests, to determine the effective compressibility of the pressurized system using the definition of compressibility: $C = dV/VdP$. Our results (Table 2), like Neuzil's, showed actual compressibilities greater than the value for pure seawater, which is about 4.4×10^{-10} Pa^{-1} at 10°C. Also, our measured compressibilities are consistent during a given packer inflation, but vary among inflations, probably because of small changes in the air content within the pressurized fluids that may have occurred when adding or removing pipe as the packer was moved between inflation depths. These results reinforce Neuzil's recommendation that a proper slug test should include a determination of effective compressibility, and indicate that assuming the value of pure seawater in interpreting DSDP or ODP slug tests may result in calculated permeabilities that are erroneously low—by as much as an order of magnitude. Transmissivities and bulk permeabilities reported here were calculated using the average measured values of compressibility shown in Table 2 and were confirmed by the results of injection tests, which are less dependent on compressibility.

Table 2. System compressibilities determined from pressure increases measured in isolated zones during slug tests conducted in Hole 735B.[a]

Packer depth (mbsf)	Pressurized volume[b] (m^3)	Slug test	Volume pumped (m^3)	Pressure increase (MPa)	Calculated compressibility (10^{-9} Pa^{-1})
49	29.66	2	0.54	1.20	15.17
		3	0.56	1.38	13.61
		4	0.54	1.27	14.35
	Average value				14.38
47	29.74	7	0.38	0.86	14.94
389	15.28	9	0.06	2.43	1.58
299	19.08	11	0.23	2.81	4.37
		12	0.18	3.18	2.90
		13	0.20	3.49	2.93
	Average value				3.40
223	22.30	15	0.51	1.23	18.50
		16	0.57	1.36	18.65
	Average value				18.58

[a] Note the consistency of results obtained during the slug tests from each inflation and the difference in the average values among the different inflations.
[b] The total pressurized volumes include the isolated zones, the drill-string, and the rig-floor plumbing.

RESULTS

Downhole Pressure Records

Figures 3A through 3C show annotated pressures recorded with a Kuster K-3 pressure sensor in the isolated zones during all six packer inflations. These plots and subsequent analyses are based on about 500 points read from each original 5- × 10-cm analog record, using a microscopic caliper with a resolution of one part in 10,000, or about 4 kPa on the pressure axis. These records are exceptionally clean because of the shallow water depths and the superior drill-string heave compensation of the *JOIDES Resolution*. The wide variation in responses to similar experiments at different depths clearly indicates that there is a wide range of interval permeabilities in the formations cored in Hole 735B.

Testing with the Packer Inflated at 49 and 47 mbsf

As Figure 3A shows, while the packer was inflated at 49 mbsf, five slug tests (labeled 1–5) were applied to the zone isolated between 49 mbsf and the bottom of Hole 735B. As described above, these slug tests indicated unexpectedly high permeability; thus, the packer was deflated and reset at 47 mbsf to verify these indications with two slug tests (6 and 7) and three constant-rate injection tests (1–3). Slug test 5 was not deliberate, but instead occurred in a mysterious fashion during the attempts to unseat the packer at 49 mbsf.

The decay curves for slug tests 1 through 5 fit the type curves reasonably well (Figs. 4A through 4E), with $\alpha = 0.001$ for the better-controlled slug tests 2 through 4 and $\alpha = 0.0001$ for the poorly controlled slug tests 1 (on inflation) and 5 (on deflating the packer). Similarly, the decay curve from the poorly controlled slug test 6 on inflation at 47 mbsf fits the type curve for $\alpha = 0.0001$ (Fig. 4F), and the decay curve for the better-controlled slug test 7 fits the type curve for $\alpha = 0.001$ (Fig. 4G). Using the compressibilities determined directly from the slug tests (Table 2), all of these decay curves indicate bulk permeability on the order of 20×10^{-15} m^2 (20 md) and transmissivity of about 50×10^{-6} m^2/s for the section of Hole 735B between 49/47 and 500 mbsf (Table 3).

These values were confirmed by the results of the constant-rate injection tests, during which pressures closely approached the predicted linear relationship with the logarithm of time after about 5 min of injection (Figs. 5A through 5C and 6). As noted above, injection test 1 was probably invalid as a measurement of permeability, but the slopes of these lines for injection tests 2 and 3 yield bulk permeability of $20–40 \times 10^{-15}$ m^2 and a transmissivity of $50–80 \times 10^{-6}$ m^2/s for the section between 47 and 500 mbsf. As the calculation of permeability and transmissivity from injection tests does not depend on compressibility as directly as from a slug test, the results from the injection tests provide some confirmation that the value for the system compressibility measured during the slug tests is more realistic than the value for pure seawater (Neuzil, 1982).

Testing with the Packer Set at 389 and 299 mbsf

As Figure 3B shows, while the packer was inflated at 389 and 299 mbsf, only slug tests were conducted because the fairly long decay times indicated that the formation was impermeable. As occurred at 49 and 47 mbsf, the first slug test at 399 mbsf (8) fit the type curve for $\alpha = 0.0001$ (Fig. 4H), while the better-controlled slug test 9 fit the type curve for $\alpha = 0.001$ (Fig. 4I). Using the compressibility measured during slug test 9, these slug tests indicate transmissivity of about 0.1×10^{-6} m^2/s and bulk permeability on the order of 0.2×10^{-15}

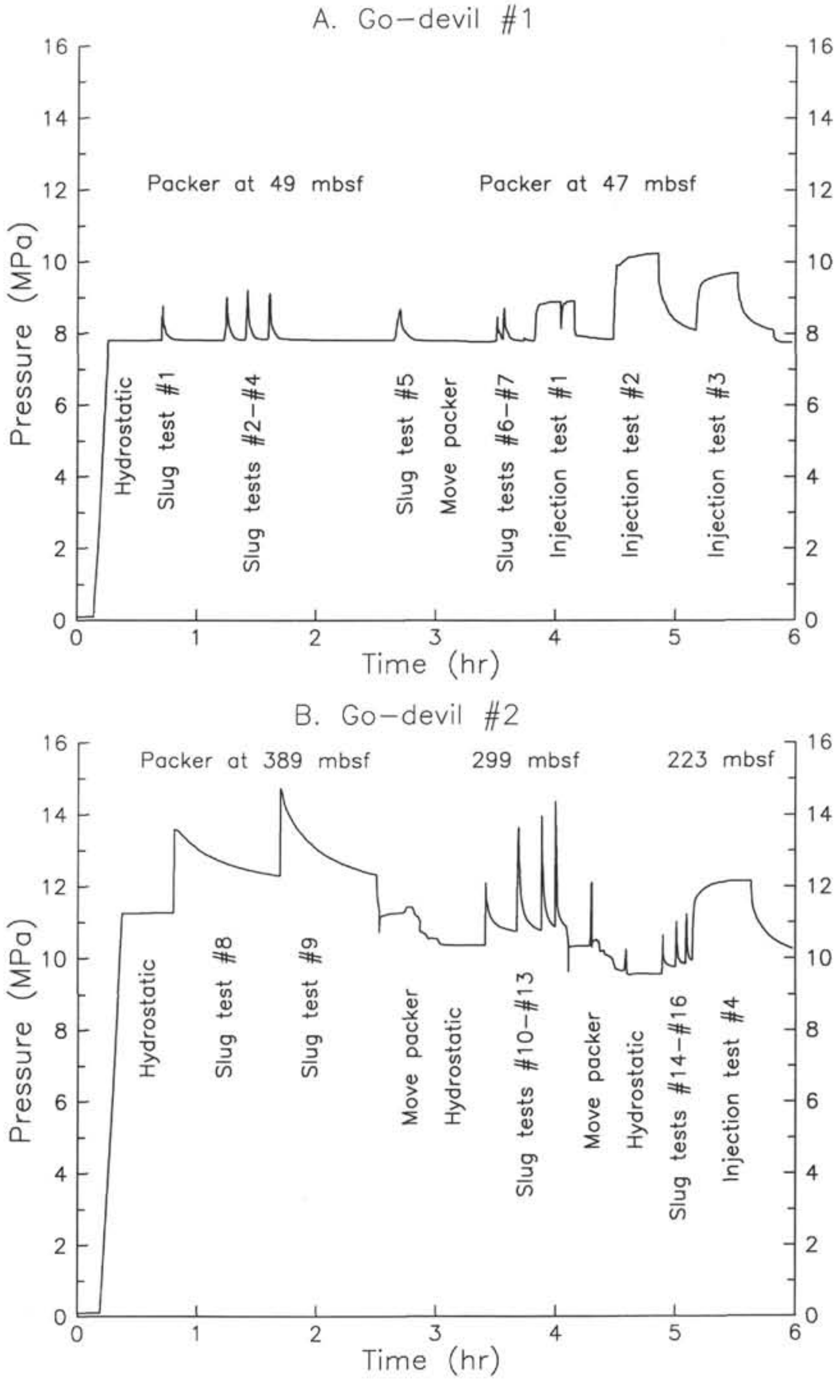

Figure 3. Pressures vs. time recorded in the zones isolated during the three go-devil deployments (A–C) and six packer inflations (A–C) in Hole 735B.

m^2 for the section from 389 to 500 mbsf, or two orders of magnitude less than the interval from 47 to 500 mbsf (Table 3).

The interval below 389 mbsf encompasses Unit VI, which was then eliminated as the source of the permeability measured below 47 mbsf. To assess the contribution of Unit V, the packer was then moved to 299 mbsf, where slug tests 10 through 13 fit the type curves for $\alpha = 0.1$ to 0.01 (Figs. 4J through 4M). Using the measured compressibilities, these slug tests indicate a transmissivity of about 2×10^{-6} m^2 and a bulk permeability of about 2×10^{-15} m^2 for the interval from 289 to 500 mbsf (Table 3). Like Unit VI, Unit V is much less permeable and transmissive than the interval from 47 to 500 mbsf.

Testing with the Packer Set at 223 mbsf

The packer was then moved to 223 mbsf, including in the tested interval Units III and IV, which are separated by a tectonic shear zone (Robinson, Von Herzen, et al., 1989). During the first inflation at 223 mbsf, three rapidly decaying slug tests were conducted followed by an injection test (Fig. 3B) all of which indicated high permeability. The packer was then deflated and reset at the same level to verify these

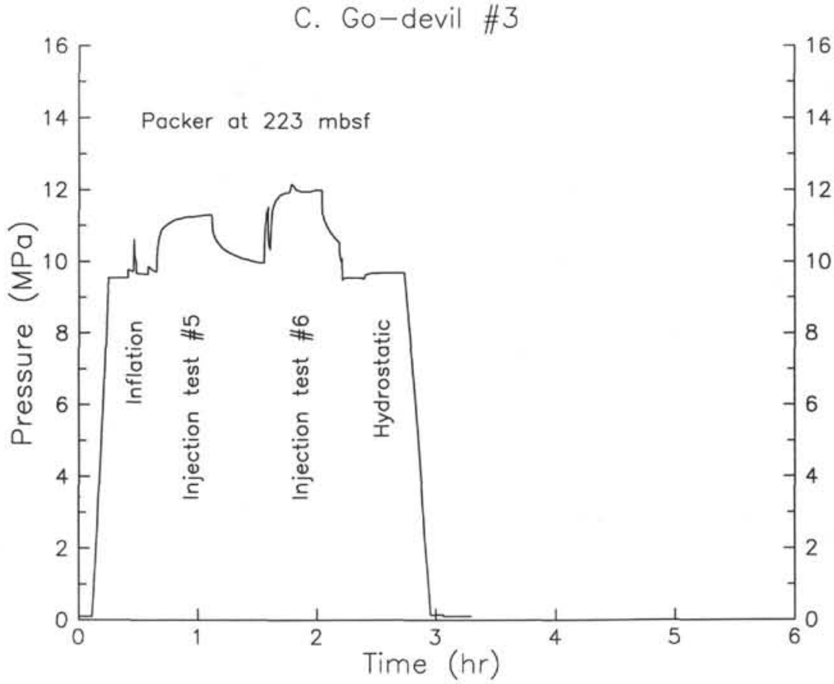

Figure 3 (continued).

indications with a slug test (on inflation) and two more injection tests (Fig. 3C); the last injection test is probably an invalid measure of permeability because a mud slug was injected for video verification of the packer seal.

The decay curves for slug tests 14 through 16 fit the type curves for $\alpha = 0.1$ (Figs. 4N through 4P), and the more reliable tests 15 and 16 yield a transmissivity of about 32×10^{-6} m^2/s and bulk permeability of about 24×10^{-15} m^2 (Table 3). These results were confirmed by the two valid injection tests (4 and 5; Figs. 5D through 5F and 6), which yield transmissivity of $32–52 \times 10^{-6}$ m^2/s and bulk permeability of $24–38 \times 10^{-15}$ m^2 (Table 3). These values are similar to the high transmissivity and permeability measured in the interval from 47 to 500 mbsf, suggesting that Units III and IV are the source of a significant proportion of the transmissivity below 47 mbsf.

SUMMARY OF PERMEABILITY DATA IN HOLE 735B

A total of 16 slug tests and six constant-rate injection tests were conducted during six separate packer inflations that isolated four different zones of Hole 735B. The results indicate that the shallowest 299 m of the hole is on average quite permeable, while the deepest 111 m of the hole is on average nearly two orders of magnitude less permeable. The most reliable experiments (which are marked with asterisks in Table 3)—slug tests for which compressibility could be directly measured and injection tests at low pumping rates—yield consistent determinations of transmissivity and permeability, which are summarized in Table 4 and Figure 7.

Given the consistency and reproducibility of the most reliable results from intervals directly isolated by the packer, the permeabilities of the smaller intervals between packer inflation depths (e.g., 49–223, 223–299, and 299–389 mbsf) could be estimated by taking the differences in measured transmissivities. The estimated interval permeabilities are given in Table 4 and also shown in Figure 7. The results indicate that the most permeable section intersected by Hole 735B is the sheared gabbros of Units III and IV.

Figure 8 shows that the range of permeabilities observed in Hole 735B is similar to the range of permeabilities observed in basaltic crust intersected by Holes 395A and 504B, both of which also show decreases of orders of magnitude in bulk permeabilities with depth (Anderson and Zoback, 1982; Hickman et al., 1984; Anderson et al., 1985; Becker, 1989, 1990). The log analysis of Goldberg et al. (this volume) shows that most of the permeability found in Hole 735B above 299 mbsf, in Units II, III, and IV, can be attributed to a few zones of isolated fractures; the hydraulic conductivities of these fractures are probably much greater than the average permeabilities reported here. These fractures appear to have resulted from the fracture-zone tectonic processes associated with the uplift of the transverse ridge in which the hole is located. Therefore, the relatively low permeability measured deep in Hole 735B—which is similar to the low values measured in sealed pillow lavas, basaltic flows, and sheeted dikes deep in Holes 395A and 504B—may be more representative of oceanic layer 3 gabbros *in situ*.

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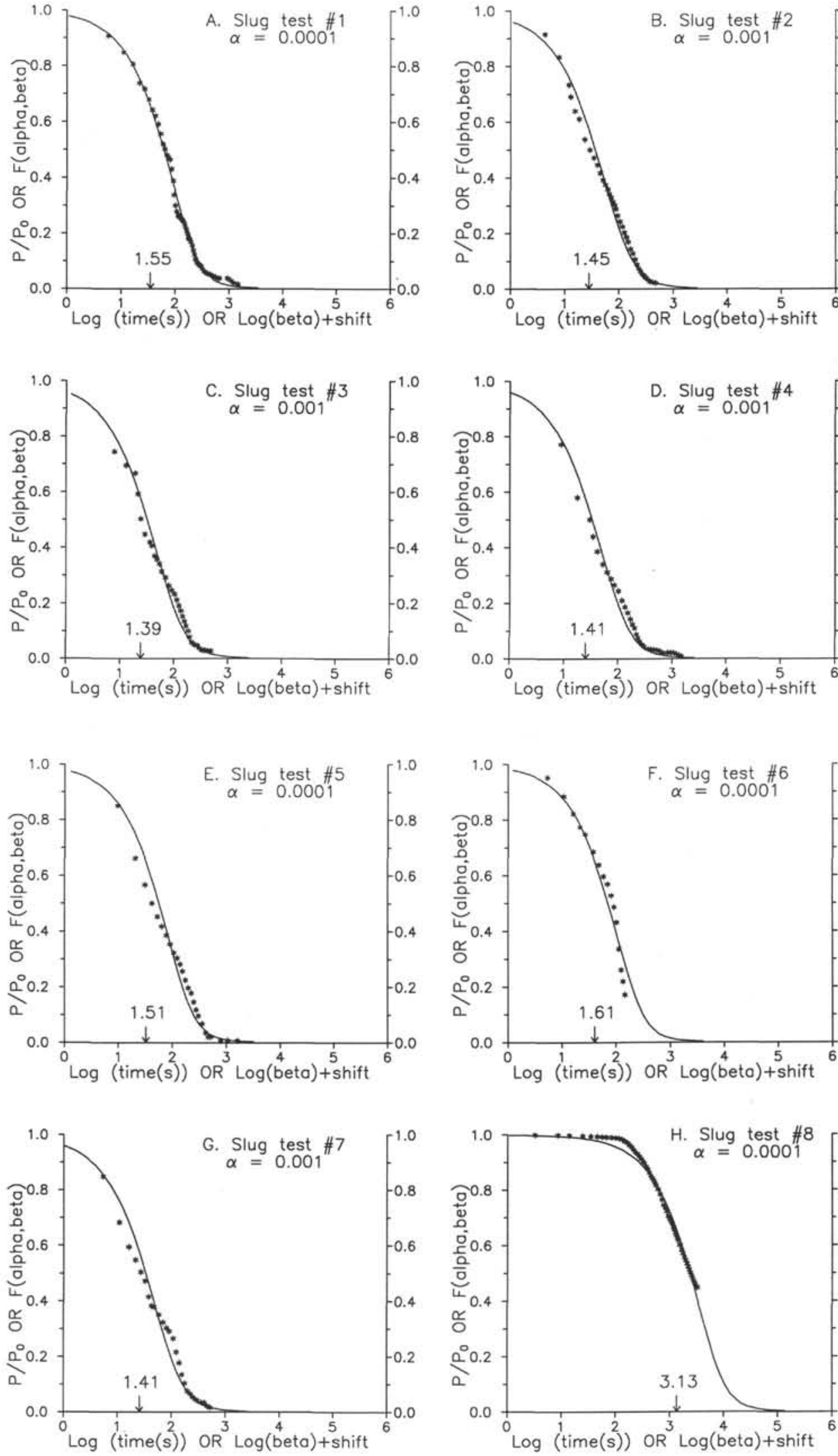

Figure 4. Best fits of the pressures recorded during the 16 slug tests (A–P) conducted with the packer inflated in Hole 735B to the type curves of Cooper et al. (1967). The arrow and number pointing to the abscissa indicate the amount (given as log time, with time in seconds) that the type curve was shifted to obtain the best fit. The quantity t_1 used for calculating permeability and transmissivity (Table 3) is given by 10 raised to this exponent.

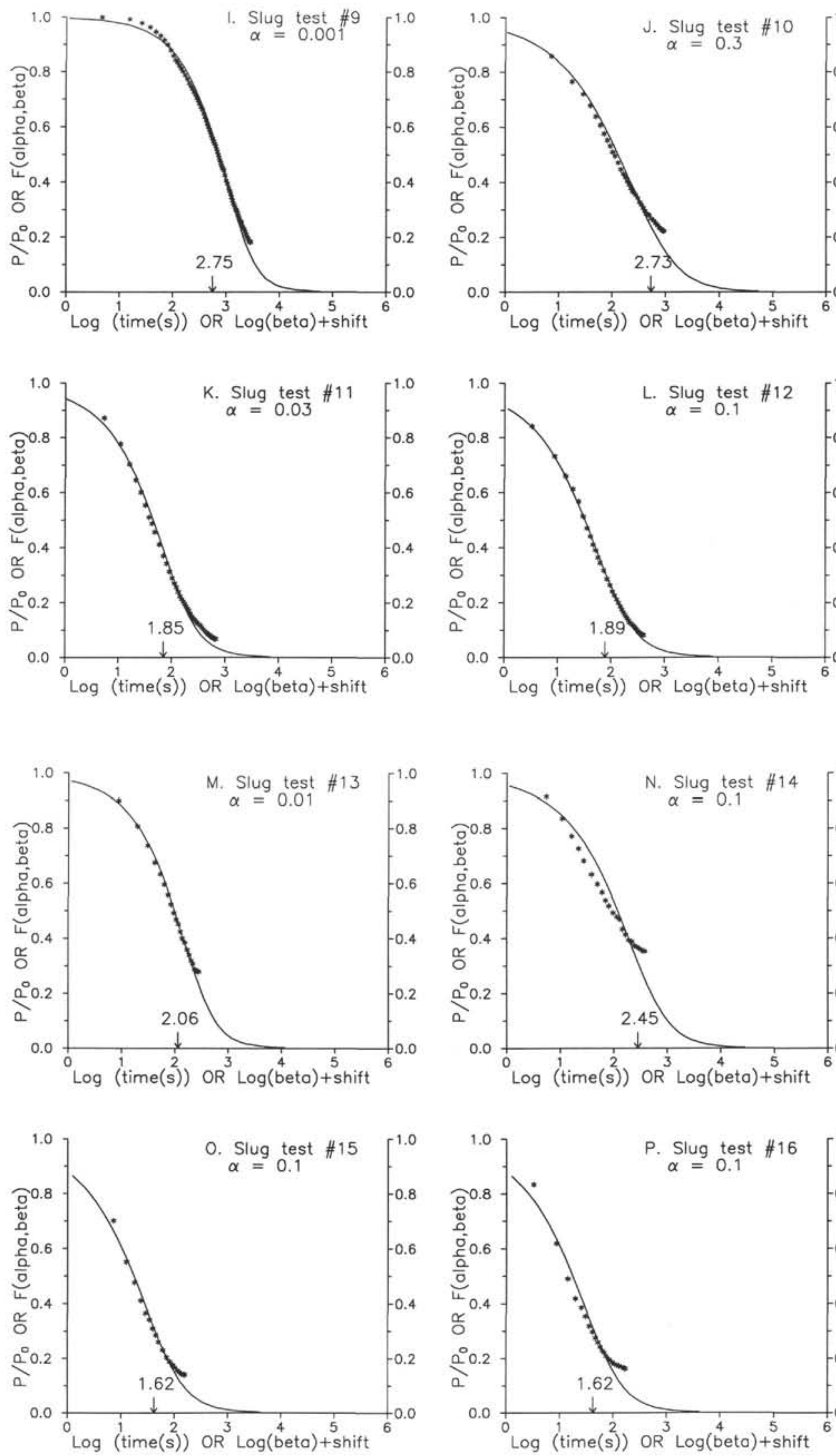

Figure 4 (continued).

Table 3. Summary of calculations of permeability (k) and transmissivity (T) from results of slug and injection tests conducted in Hole 735B.

Interval (mbsf)	Test[a]	α	t_1[b] (s)	Rate[c] (L/s)	k (10^{-15} m^2)	T (10^{-6} m^2/s)
49–500	S 1	0.0001	35	—	17.9[d]	39.2[d]
	S 2	0.001	28	—	23.7*	52.1*
	S 3	0.001	25	—	24.4*	53.7*
	S 4	0.001	26	—	24.6*	54.0*
	S 5	0.0001	32	—	19.6[d]	43.0[d]
47–500	S 6	0.0001	41	—	16.1[d]	35.6[d]
	S 7	0.001	26	—	25.6*	56.4*
	I 1	—	—	31.1	(221.8	489.0)[e]
	I 2	—	—	17.2	38.8	85.7
	I 3	—	—	11.7	24.4*	53.7*
389–500	S 8	0.0001	1349	—	0.11[d]	0.058[d]
	S 9	0.001	562	—	0.26*	0.140*
299–500	S 10	0.1	537	—	0.40[d]	0.38[d]
	S 11	0.03	71	—	3.93*	3.84*
	S 12	0.1	78	—	2.38*	2.33*
	S 13	0.01	115	—	1.62*	1.59*
223–500	S 14	0.1	281	—	(3.56[d]	4.8[d])[f]
	S 15	0.1	42	—	24.0*	32.3*
	S 16	0.1	42	—	24.2*	32.6*
	I 4	—	—	16.0	38.4	51.7
223–500	I 5	—	—	8.9	24.1*	32.4*
	I 6	—	—	16.7	(55.1	74.3)[e]

* Asterisks denote the most reliable values at each inflation, i.e., those from slug tests for which compressibility was directly measured and those from injection tests with low injection rates.

[a] S = slug test; I = injection test.

[b] For a slug test, the parameter t_1 corresponds to the amount that the type curve was shifted to produce the best fit; permeability (k) and transmissivity (T) are calculated from t_1 by the equations $k = \mu C_w V_w / \pi b t_1$ and $T = V_w C_w \rho_w g / \pi t_1$.

[c] For an injection test, rate denotes the constant rate at which seawater was pumped into the isolated zone.

[d] Compressibility could not be directly measured; average value for other slug tests at this depth assumed.

[e] Parentheses indicate dubious results from injection tests that were disrupted by pumping mud slug for visual verification of integrity of packer seal.

[f] Parentheses indicate dubious results from a slug test that was disturbed during the inflation procedure.

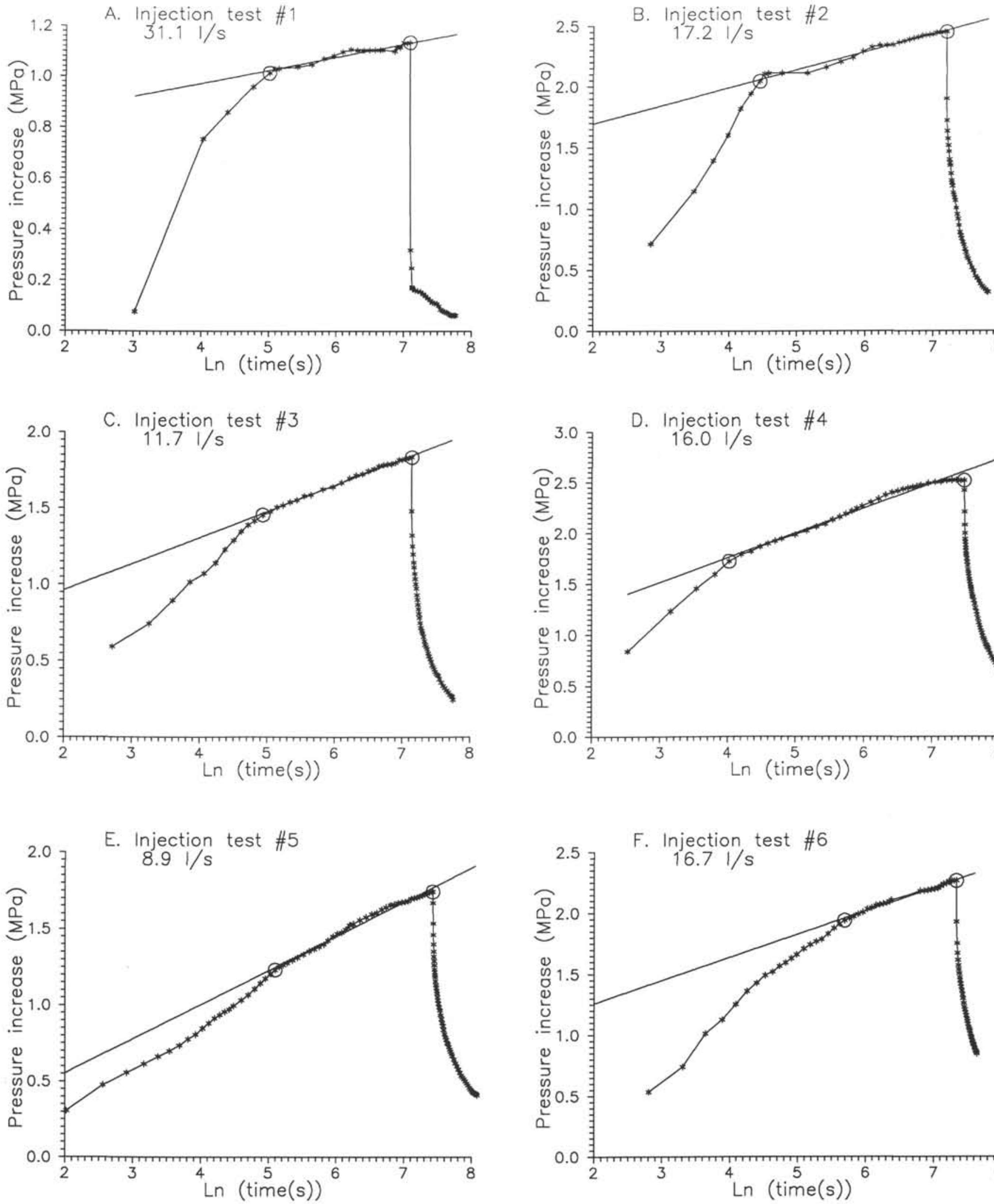

Figure 5. Pressures recorded during the six constant-rate injection tests (A–F) conducted with the packer inflated in Hole 735B plotted vs. natural log of time. For each injection test, bulk permeability is calculated from the slope of the linear segment that is reached after about 3 to 5 min of injection. On each plot, the line shown was obtained by linear regression through the data points encompassed by the two circled end-points.

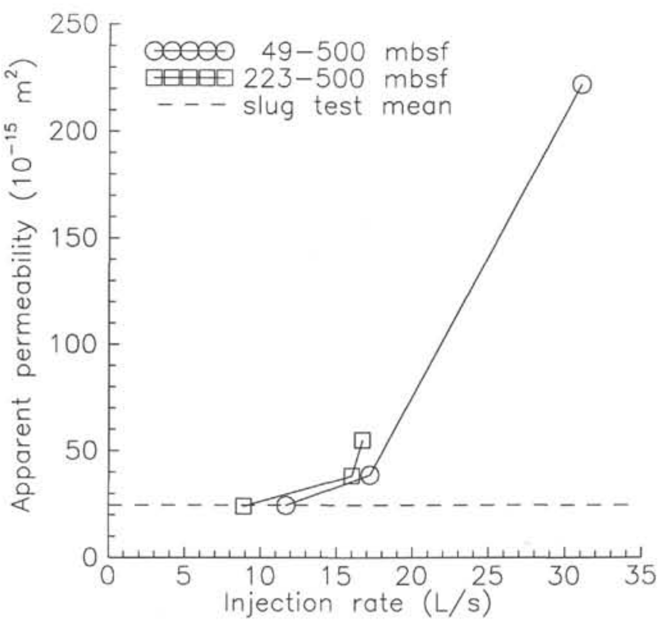

Figure 6. Comparison of bulk permeabilities determined from slug tests with those from injection tests in the intervals from 47 to 500 mbsf and from 223 to 500 mbsf. At each depth, the injection test with the highest rate was complicated by the interjection of a mud slug to test the packer seal, and is therefore the least reliable determination of permeability. In general, a lower injection rate disturbs the formation least and yields a more reliable determination of permeability; indeed, at each depth the injection test with the lowest injection rate yields a permeability very consistent with the value determined with the most reliable slug tests.

Table 4. Summary of interval transmissivities and permeabilities in Hole 735B.

Interval (mbsf)	Lithologic units	Transmissivity (10^{-6} m^2/s)	Permeability (10^{-15} m^2)
Actually measured:[a]			
49–500	II–VI	54	24
223–500	III–VI	32	24
299–500	V–VI	2.0	2.1
389–500	VI	0.1	0.2
Calculated from differences in transmissivities:[b]			
49–223	II	22	24
223–299	III–IV	30	81
299–389	V	1.9	4.4

[a] Average transmissivities and permeabilities for the most reliable results (those marked with asterisks in Table 3).
[b] Transmissivities can be directly subtracted; permeabilities (k) calculated from resultant transmissivities (T) by $k = T\mu/b\rho_w g$.

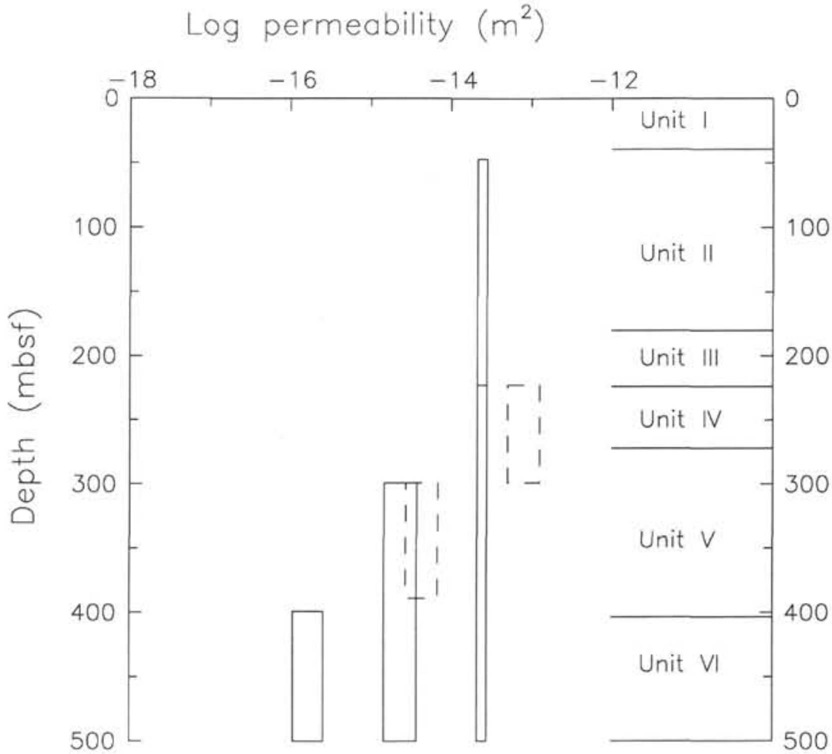

Figure 7. Bulk permeabilities (rectangles) in Hole 735B plotted vs. depth, with a generalized lithology from Robinson, Von Herzen, et al. (1989). The vertical extent of each rectangle indicates the interval over which average permeability was determined; the horizontal extent indicates the estimated uncertainty in the calculated average permeability. The rectangles drawn with solid lines represent results directly measured over intervals isolated by the packer; rectangles drawn with dashed lines represent results from smaller intervals obtained by subtracting measured transmissivities (Table 4).

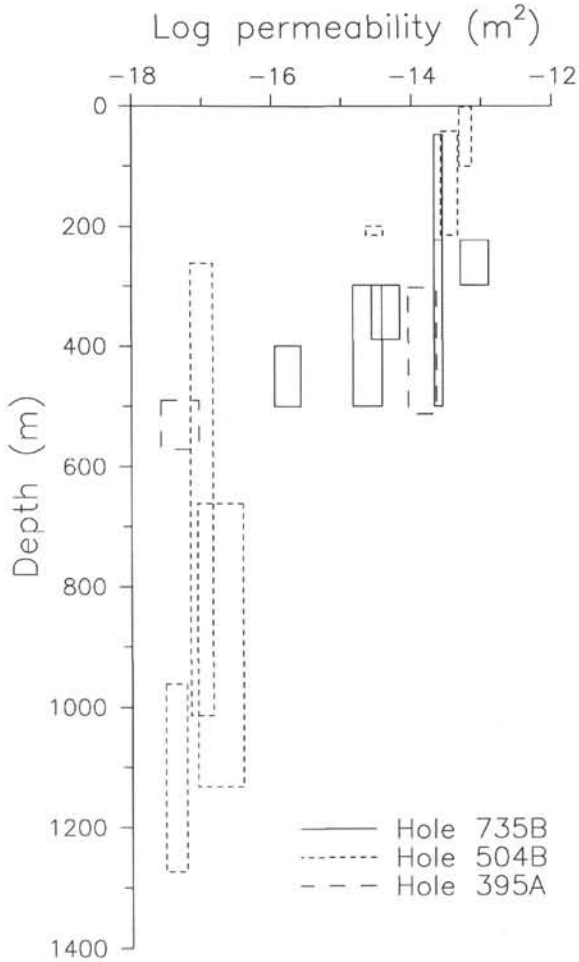

Figure 8. Comparison of bulk permeabilities measured in the basement sections of Holes 735B, 504B, and 395A. For Hole 735B, depth is given in mbsf; for Holes 504B and 395A, depth is given in m into basement (under 274.5 m and 93 m of sediment, respectively). As in Figure 7, the vertical extent of each rectangle indicates the measurement interval and the horizontal extent indicates the estimated uncertainty in the calculated permeability. Data from Hole 504B are from Anderson and Zoback (1982), Becker et al. (1983), Anderson et al. (1985), and Becker (1989); data from Hole 395A are from Hickman et al. (1984) and Becker (1990).