33. DIRECT MEASUREMENT OF PORE FLUID PRESSURE, LEG 84, GUATEMALA AND COSTA RICA[1]

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ABSTRACT

Evidence of considerable overpressuring of pore fluids in the sediment drilled during Leg 84 was obtained from direct measurement of pressure by two methods. The first involved measurement of back pressure when the annulus of the drill hole became constricted with unremoved drill cuttings or constriction was caused by plastic inflow of the drill hole walls. The second involved measurement of pressure ahead of the bit in conjunction with *in situ* water samples and heat flow. All measurements indicated abnormally high pore pressure even in slope deposits of the Middle America Trench off Guatemala.

INTRODUCTION

The possible role of pore fluid pressure in reducing friction along thrust fault zones was clearly described in the classic paper of Hubbert and Rubey (1959). Hubbert and Rubey considered inactive thrusts where the fluid pressure had probably returned to normal hydrostatic values, so a direct test of the proposed anomalous pressure was not possible. However, an opportunity to measure pressure in an active zone of thrust faulting arises when drilling is done in the vicinity of modern subduction zones. High pore fluid pressures in subduction-zone environments were encountered during industry drilling off British Columbia and in the Gulf of Alaska. These holes were drilled on the continental shelf and well above the area of thrust faulting, yet pressures above hydrostatic levels were measured indirectly by the greater-than-normal weight of drilling mud needed to counteract formation pressures (Shouldice, 1971; Hottman et al., 1979). Areas of elevated pore pressure near subduction zones off Indonesia, the Philippine Islands, Taiwan, and South America were listed by Fertl (1976). *Glomar Challenger* drilling, without a closed circulation system, does not provide this type of indirect indication of pore pressure through mud weight, and many DSDP holes on the convergent margins were not logged. However, in a logged hole located near the Japan Trench, a curious decrease in the density log with depth combined with fractured mudstones was thought to have resulted from overpressured fluids in a fracture porosity (Carson et al., 1982).

On Leg 78A, near the front of the Lesser Antilles subduction zone, pore fluid pressure at lithostatic levels was measured when the casing and drill collars inadvertently became stuck because the space between the collars and the hole was packed tightly by drill chips (Biju-Duval, Moore, et al., in press). This packing effectively sealed the bottom of the hole so that all pressure was vented through the jets in the bit and up the drill stem to the rig floor. The pore fluid measurement indicated that drill sticking, which frequently happens during *Glomar Challenger* drilling on modern convergent margins, could result in some scientific benefit.

During Leg 84 the drill became sufficiently stuck while drilling at four sites to measure elevated pore pressure. Additionally, I had proposed to DSDP that a relatively inexpensive pressure-measuring device be installed on the *in situ* water sampling–heat flow probe. The pressure-sensing unit had been designed and some materials purchased by the time Leg 84 began, but the unit had not yet been built; the fact that there were sufficient parts on board at the time of the cruise, combined with the cleverness of the shipboard technical staff who were able to use the parts available, resulted in assembly of the instrument and a series of successful measurements. In this chapter I summarize the information related to indications and direct measurements of elevated pore fluid pressure.

PRESSURE MEASURED AT THE RIG FLOOR

General Considerations

On *Glomar Challenger*, seawater is pumped down the drill stem to the bit where it circulates back up the drill hole to flush drill chips through the annulus of the hole (space between drill stem and side of hole). The lower 90 m of the drill string is composed of drill collars that have an 8-1/4-in. (20.95-cm) diameter; the drill bit has a 9-7/8-in. (25.08 cm) diameter. Thus the 13/16-in.-wide (2.06-cm) annulus around the collars can become packed with drill chips should circulation stop or become insufficient to carry them up the hole (Fig. 1). A driller tries to prevent packing of the annulus so that the drill collars do not become so firmly lodged in the hole as to exceed the pulling capacity of the drill rig and force abandonment of the bottom-hole assembly.

Loss of drill fluid circulation is commonly caused by leakage of drilling fluids into porous zones being drilled.

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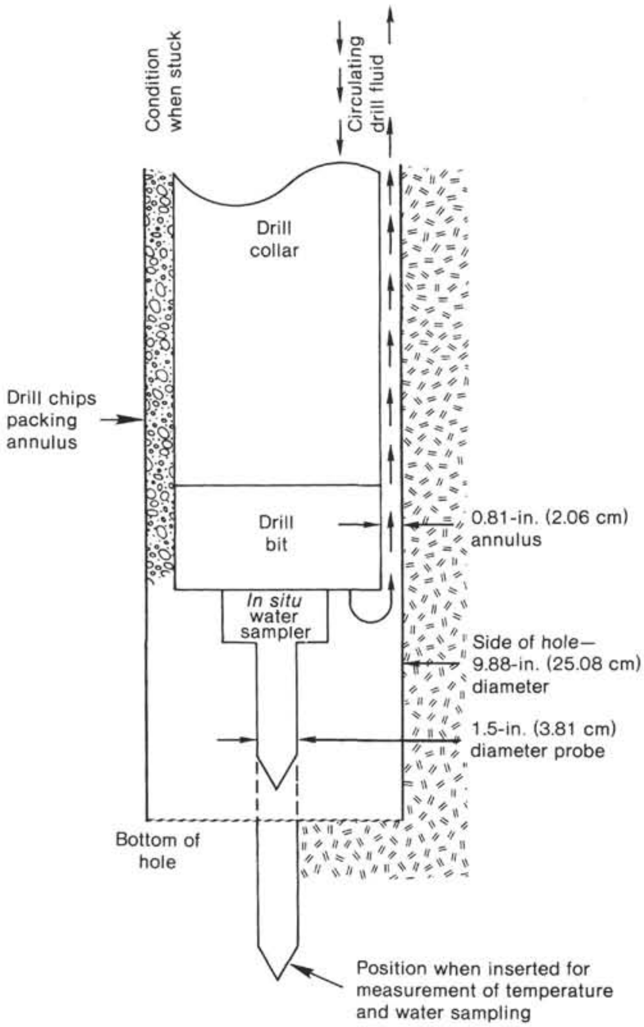

Figure 1. Diagram of bottom-hole assembly with *in situ* water sampling/temperature/pressure probe. One side shows condition during packing of the annulus with drill chips, the other during normal circulation.

Overpressured zones are commonly porous and will absorb drill fluids introduced at greater than formation pressure, thereby causing a loss of flushing in the hole. Thus chips will collect and pack into the annulus around the drill collars. Back pressure in the circulation system can be read on the circulation system pressure gauge to ±10 to 15 psi (7030–10,545 kg/m^2) at the rig floor about 10 m above the water line. Pressure is also recorded on the drill logging system. One sign of back pressure is water flowing out of the drill stem at the rig floor when the drill pipe has been unscrewed and stands open. This reverse flowage above a 10-m head can be caused not only by a zone of pressured pore fluid but also by a back flow from settling of the drill-chip-laden fluid within the drill hole; however, the column of drill fluid generally settles out in a few minutes, and this effect can be so identified. It must be remembered that contrary to most drilling for petroleum, *Glomar Challenger* drill holes are without a closed circulation system, and any signs of back pressure are in excess of those being vented directly up the hole to the ocean floor.

Site 565

The last 30 m at Site 565 off Costa Rica were difficult to drill because the bottom-hole assembly began to stick at about a depth of 300 m (Site 565 report, this volume). This was accompanied by back pressures measured at the drill rig of 250 to 350 psi (175 to 246 × 10^3 kg/m^2) and during 5- to 10-min. periods when water flowed out of the drill stem at the rig floor, 10 m above sea level. This reverse flowage could have been caused by a normal back flow from settling of the weighted column of fluids carrying chips up the annulus of the drill. After about 10 min. of flow, more than 20 gallons (75.7 L) per minute of returning fluid were measured coming out of the drill stem, and the rate of back flow had slowed only a little. The total volume of fluid in the drill hole was about 100 gallons (378.5 L), and I estimate that at least this volume had been vented. Thus any back flow from settling drill chips had ended, and after 10 min. the back flow was probably from the drainage of pore fluid. The zone of drilling difficulty corresponds to the change in lithology at the bottom of the hole and the zone of recovered gas hydrate.

Nonetheless, elevated pore fluid pressure is likely along the Costa Rican subduction zone because the 300 m of rapidly deposited massive mudstone with very low permeability (see Taylor and Bryant, this volume) will impede the flow of any fluids migrating from below. The zone of difficult drilling was the first zone with significant fracture porosity where gas hydrate could accumulate. Thus water forced from subducted sediment only 600 m below the bottom of the hole could probably migrate upward through fractures and be trapped by the more plastic upper 300 m of impermeable mud.

Site 567

Evidence of greater than hydrostatic formation pressure was observed at the bottom of Hole 567A (501 m below the seafloor) when the drill string became stuck. Just prior to sticking, the pressure at the surface when circulating 244 gal/min. (924 L/min.) read 300 to 350 psi (211–246 × 10^3 kg/m^2). When first stuck, the pressure when circulating at 230 gal/min. (871 L/min.) was 1000 psi (703 × 10^3 kg/m^2) read at the rig floor. With the pump turned off, the pressure decreased to 550 psi (387 × 10^3 kg/m^2) but did not go to zero pressure, and when the system was bled to zero, closed, but with no pump, the pressure built up again to 500 psi (351 × 10^3 kg/m^2). Because pumping had no effect on the stuck pipe, it was discontinued for nearly 2 hr. while the stuck pipe was worked to freedom. The pressure remained at 500 psi (351 × 10^3 kg/m^2). But once the pipe moved a short distance the pressure dropped to 250 psi (175 × 10^3 kg/m^2), and when the pipe came free it dropped to essentially zero.

These observations are explained as follows. The pipe stuck because cuttings collected around the bottom-hole assembly and sealed off the bottom of the hole. The hole may also have constricted because of mobile serpentinite. This caused the pressure to rise to 1000 psi (703×10^3 kg/m²) over hydrostatic pressure as measured at the rig floor, and the pressurized water being pumped down the drill stem escaped into the fractured rock. The steady 500 psi (351×10^3 kg/m²) for 2 hr. could not have been caused by normal back flow of water and cuttings from up the annulus because the pressure should diminish as the drill cuttings settle out. The drop in pressure to zero after the pipe was freed supports this conclusion. The conditions monitored at the rig floor are similar to those at Site 565.

Site 569

At Hole 569, sudden failure of the hole at 250.7 m depth was attributed to elevated pore pressure from the response of pump volume and circulation pressures at the rig floor. When the drill stem became stuck the pressure was vented twice to zero and it built up again to 250 lb. (176×10^3 kg/m²) without pumping. After about 2 hr., when the drill stem broke free, pressures returned to normal, indicating no back-flow condition from settling drill chips. The similarity of this experience with that in previous holes is considered to indicate overpressured pore fluid.

IN SITU MEASUREMENTS OF PRESSURE

Prior to Leg 84, the possibility of measuring pure fluid pressure with the *in situ* water sampling–heat flow probe was discussed with DSDP, and the necessary transducers were purchased prior to the cruise. Final design and assembly of the pressure-measuring instrumentation was done on board by the electronics and lab technicians. The instrument was ready for testing when we reached Site 568. The output of the pressure transducer was fed to a second heat flow unit recorder with timer and set for direct reading of pressure in pounds per square inch (psi). The successful operation of the instrument on its first lowering is a tribute to the skill and persistence of the technicians.

The combined measurements required changes in procedure. First, a reading of hydrostatic pressure at a set distance above the bottom of the hole was made with the instrument locked into the drill bit, and with no pumping of drilling fluids. Then the probe was inserted into the bottom ahead of the hole and left for 10 min. prior to water sampling. During extraction of pore water the pressure dropped from 2500 psi (1758×10^3 kg/m²) or more to 200 to 300 psi (141–211 $\times 10^3$ kg/m²), and when the extraction was completed the pressure rose quickly. The probe was left in place for about 10 min. after sampling and then raised to the mudline, where it was again left for 10 min. to record bottom water temperature. The length of time for a run was limited by the 1.5-hr. capacity of the recording units.

The plots of pressure versus time (Fig. 2) show (1) the rapid increase of pressure during lowering of the probe, (2) probable shutdown of the pump (time not recorded) and return to hydrostatic pressure as the probe sat in the bit, (3) a sharp pressure increase during lowering and insertion of the probe into the bottom sediment, (4) slowly decreasing pressure as insertion pressure bled off, (5) a sharp drop of pressure during extraction of the water sample, and a sharp increase of pressure to *in situ* values after closure of the valve, (6) a slow partial recovery of original pressure, (7) decreasing pressure as the probe was raised to the mudline, and (8) rapidly decreasing pressure during return of the probe to the rig floor. These recordings are diagrammed for all runs in Figure 3.

The pressure measured by the probe was compared to the depth measured from the length of drill pipe to the bit. This gave a hydrostatic pressure gradient of 1.50 psi/m (1.06×10^3 kg/m²), which is a bit less than the 1.53 psi/m (1.08×10^3 kg/m²) for salt water in wells of the Gulf of Mexico (Fertl, 1976). Generally the probe measurement showed minor pressure fluctuation; on runs 3 to 5 it showed a constant value (Fig. 3).

Lowering and insertion of the probe commonly showed a small sharp pressure increase followed by a sharp decrease and then a slowly decreasing pressure until the water sampling valve opened. These measurements never seemed to return completely to the pre-water-sample value, and some runs showed a slow constant decreasing pressure.

The sharp decrease in pressure to 200 to 300 psi (141–211 $\times 10^3$ kg/m²) during water extraction indicates a strong seal between the intake part of the probe and the overlying water. This seal was able to withstand up to 3600 psi (2531×10^3 kg/m²) pressure differential. This large drawdown in pressure to fill the evacuated water sampler appears to have affected the system's stability, perhaps by clogging the intake system with mud. The subsequent sequence of measurements often fluctuates, particularly the measurements at the mudline.

Several causes other than transducer stability, such as banging of the tool within the pipe, ship motion, or wire stretch, could have been responsible for the fluctuation.

The results of five measurements with the pressure probe are listed in Table 1. The measurements show that a good seal was established in the type of sediment drilled on Leg 84, providing an effective isolation of the probe from bottom-hole waters. It also showed that the method can provide *in situ* pressure measurements. This first attempt resulted in less than desired precision because of three main factors: (1) instability of the pressure transducer, (2) insufficient time in the disturbed sediment to return to normal pressure, (3) interference from the water sampling. The first two are easily solved electronic problems, whereas the third is solved by a separate small-diameter pressure port projecting about 8 cm in front of the probe, which creates less disturbance of sediment and some isolation from extraction of the water sample.

Another uncertainty may be introduced by the weight of the bit in the bottom of the hole. However, the effect of bit weight probably did not exceed the pressure observed during withdrawal of the pore fluid sample, or 200 to 300 psi (141–211 $\times 10^3$ kg/m²). The uncertainties introduced by instrument drift and inadequate time *in situ* exceeded any departure from hydrostatic pressure on the first three runs, but on the fifth run the depth was sufficient to provide a departure of pressure in ex-

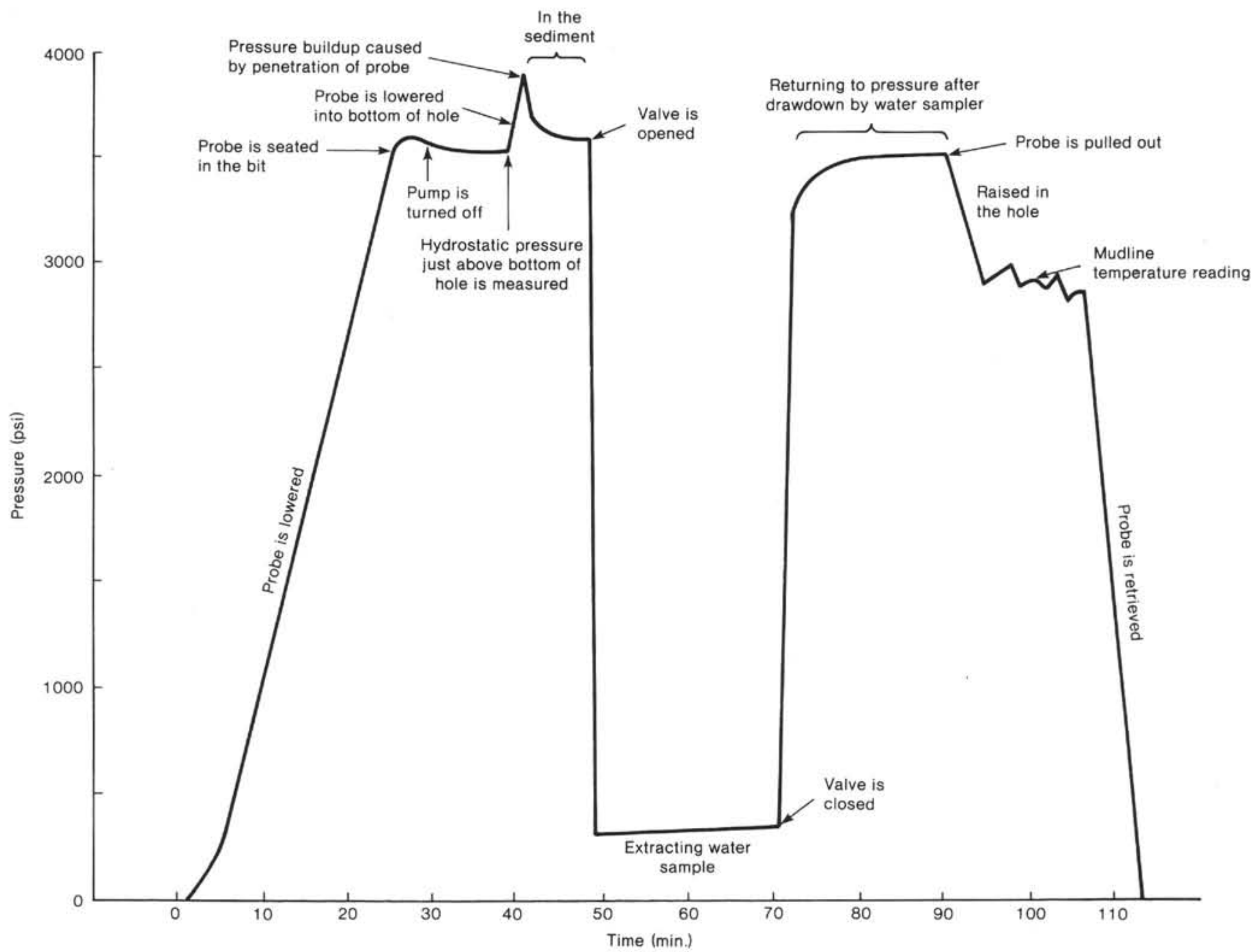

Figure 2. A generalized record of pressure annotated to show functioning of probe during a set of measurements.

cess of hydrostatic pressure. This last measurement was the only one made where cores recovered mudstone with dewatering veins, suggesting an association of the veins with overpressure.

SUMMARY

Table 2 summarizes the pressure information from measurements on Leg 84. Only the measurement at Site 567 was made in or near the subduction zone. The rest were made at the base of the slope sediment or from within it. Thus it appears that much of the Guatemalan margin is overpressured, because these measurements cover the lower and midslope areas. However, no high pore pressure was encountered in the Esso Petrel Well at the edge of the shelf, as deduced from the maximum mud weight of 10.4 ppg (pounds per gallon) needed below 5500 ft. (1676 m) to control the hole (Moore and von Huene, 1981).

The measurements of fluid back pressure at the rig floor are most likely minimum pressures, because the seal around the drill collars was probably not impermeable. The measurement made with the transducer is most likely an average between the limiting values in Table 2, for the probe was not inserted long enough to come to equilibrium from a higher pressure prior to water sampling or from a lower pressure after water extraction.

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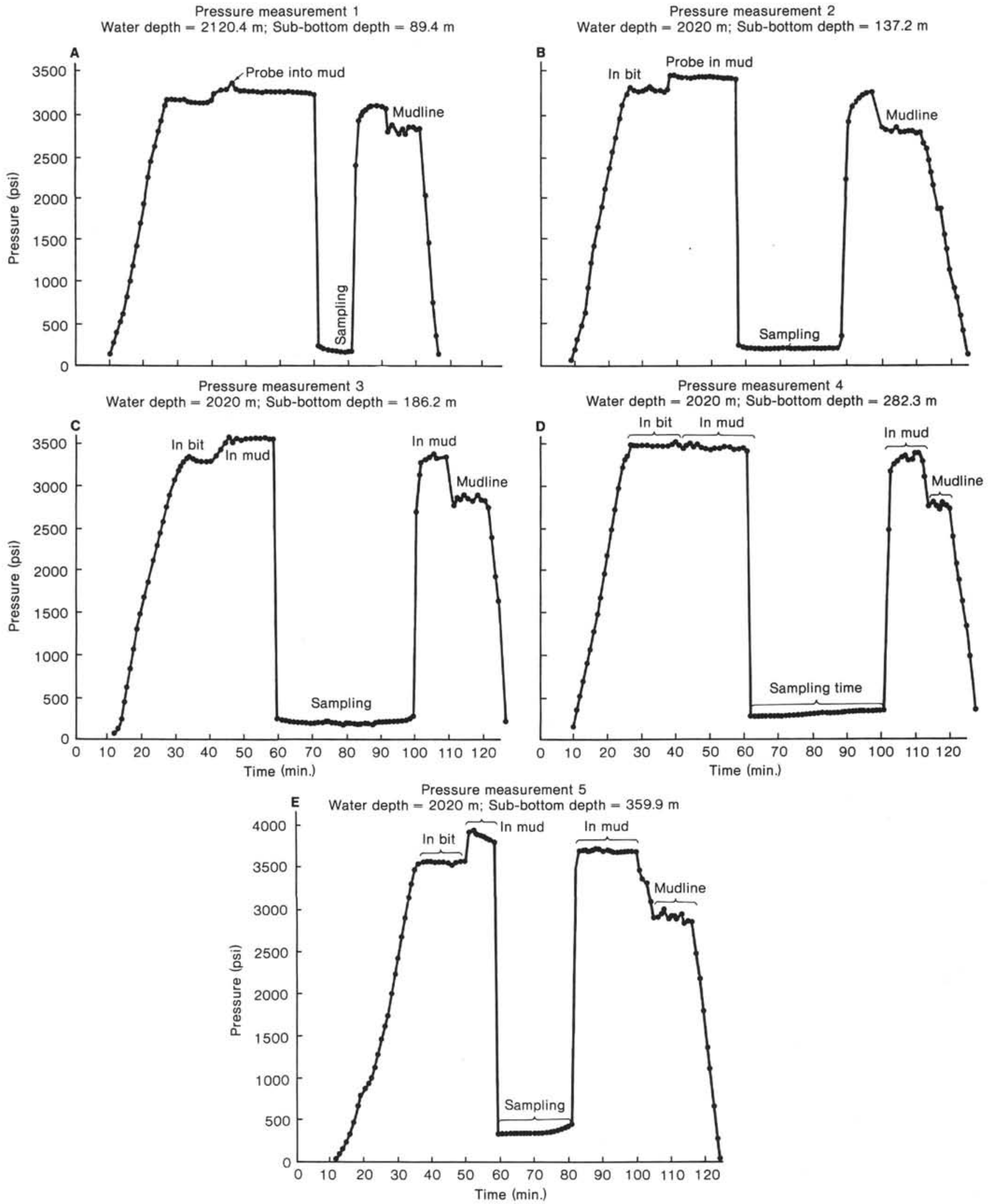

Figure 3. Graphs of pressure versus time during runs of the pressure/temperature/water sample probe.

Table 1. Pressure measurements at Site 568 with a transducer.

Run	Total depth (m)	Sub-bottom depth (m)	Calibration difference (psi)	Hydrostatic pressure (psi)	Minimum pressure before sample (psi)	Maximum pressure after sample (psi)	Remarks
1	2109.4	89.4	34	3171	3258	3135	
2	2157.2	137.2	0	3237	3394	3238	At hydrostatic pressure
3	2206.2	186.2	?	3309	3555	3394	Slightly overpressured
4	2302.3	282.3	28	3488	Less than hydrostatic pressure		Water sample contaminated—probe did not seat
5	2379	359.9	19	3537	3795	3701	

Note: Total depth = sub-bottom + water depth; calibration difference = difference, beginning and end of run at 5000 psi proportionate to hydrostatic pressure (1 psi = kPa); hydrostatic pressure = pressure at bottom of hole from reading in bit + 1.5 psi × height (in meters) above bottom of hole; minimum pressure before sample = last or lowest measurement prior to opening of water sampler valve; maximum pressure after sample = highest value before pullout and return of probe to ship.

Table 2. Summary of pore fluid pressure data, Leg 84.

Site	Water depth (m)	Sub-bottom depth (m)/ pressure differential (psi)	Average density to pressure measurement (g/cm^3)	Hydrostatic pressure (psi)	Lithostatic load (psi)	Percentage above hydrostatic presure	Remarks
565	3101	328/250–350	1.55	5144	727	34–48	Associated with fractured rock and hydrate
567	5519	501/500	1.87	9030	1340	37	125 m serpentinite of questionable density
568	2020	360/164–258	1.44	3537	737	25–30	From pressure transducer
569	2804	250.7/250	1.55	4582	556	45	

Note: pressure differential = pressure read at rig floor; average density = weighted density average to depth of pressure measurement from measured core densities; hydrostatic pressure = pressure gradient of 1.5 psi/m × depth to pressure measurement; lithostatic load = average density × depth conversion from kg/m^2 to psi (1.43); percentage above hydrostatic pressure = lithostatic load divided by measured pressure minus hydrostatic pressure.