OCEAN DRILLING PROGRAM

LEG 111 SCIENTIFIC PROSPECTUS

DSDP HOLE 504B REVISITED

Keir Becker
Rosenstiel School of Marine
& Atmospheric Science
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149

Hitoshi Sakai
Ocean Research Institute
University of Tokyo
1-15-1, Minamidai
Nakano-ku, Tokyo 164
Japan

Russell B. Merrill
Staff Scientist, Leg 111
Ocean Drilling Program
Texas A&M University
College Station, TX 77843-3469

Philip D. Rabinowitz
Director
ODP/TAMU

Robert B. Kidd
Manager of Science Operations
ODP/TAMU

Louis E. Garrison
Deputy Director
ODP/TAMU

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INTRODUCTION

During Leg 111 of the Ocean Drilling Program, D/V JOIDES Resolution will return to Site 504 in the eastern equatorial Pacific (Figure 1; Table 1). The primary purpose of Leg 111 is to deepen and log Hole 504B, which now extends nearly twice as deep into oceanic basement as any other DSDP/ODP hole. Hole 504B already penetrates through the pillow lavas of oceanic Layers 2A and 2B, and Leg 111 will focus on the sheeted dike complex forming Layer 2C. About 44 days are to be spent at Hole 504B, roughly 30 for coring another 300-500 m, and 14 for downhole measurements and logging. In addition, up to 5 days will be spent sampling the sediments near Site 504 with the Advanced Piston Corer (APC) for biostratigraphic, paleoceanographic, and hydrologic studies of the 275-m-thick layer of siliceous nannofossil ooze and chalk.

The deep sampling of the oceanic crust has long been a goal of the JOIDES Ocean Crust and Lithosphere Panels, in order to document the in situ lithostratigraphy, alteration history, and geophysical properties of the crust, and to test the analogy drawn between ophiolites and oceanic crust. This goal went largely unfulfilled during DSDP, partly because of the technical problems of achieving deep penetration, except for the breakthrough success in Hole 504B. DSDP Legs 69, 70, and 83 cored roughly 775 m of pillow lavas of Layers 2A and 2B and nearly 300 m of sheeted dikes from the upper part of Layer 2C. Layer 2C may extend as much as one kilometer deeper at Site 504, so the nature of the sheeted dike complex remains poorly understood. The critical effects of hydrothermal circulation at temperatures higher than 300°C have never been sampled in situ. Studies of ophiolites indicate that hydrothermal alteration in the dike complex grades with depth from greenschist to amphibolite facies. Sampling these high temperature assemblages is critical to understanding the mass budget and history of the chemical evolution of the oceanic crust.

The time spent in Hole 504B during Leg 111 will consist of three separate phases: (1) immediately after re-entry, measurements of equilibrium borehole temperatures and sampling of borehole fluids in partial equilibrium with formation fluids, followed by limited permeability and logging measurements crucial to existing section (4-5 days); (2) coring 300-500 m in the sheeted dikes (30 days); and (3) logging and geophysical measurements in the newly-cored section (9-10 days).

The five days to be spent in coring the sediments near Site 504 will probably be left until the end of Leg 111. However, some of this work might be attempted earlier, should unforeseen interruptions occur in the program at Hole 504B. The separate purposes of the sediment coring - studies of hydrogeology and biostratigraphy/paleoceanography - will require two separate sites and may be difficult to complete in the allotted five days. PCOM has directed that we attempt the biostratigraphic work first, at a site with locally low heat flow near Site 504. The site for hydrogeologic studies will be located where the results of a May, 1986 survey indicate that the problem of lateral advection in the sediments and shallow basement will be addressed best.

If operations in Hole 504B must be terminated prematurely, the primary contingency plan for Leg 111 will involve an expanded version of the study of such shallow advective processes.

SUMMARY OF DSDP RESULTS FROM HOLE 504B[1]

Located in 5.9-m.y.-old crust about 200 km south of the Costa Rica Rift (Figure 1), Hole 504B presently extends through 274.5 m of sediment and 1075.5 m of basement, for a total penetration of 1350 m. The basement penetration is nearly twice that of the second-best 583 m in Hole 332B in the Atlantic. Hole 504B is the only basement hole to have clearly penetrated through the extrusive pillow lavas and into the underlying sheeted dikes predicted from studies of ophiolites. The 1075.5 m of basement cored in Hole 504B consisted of 571.5 m of pillow lavas and minor flows, underlain by a 209 m zone of transition into 295 m of sheeted dikes and massive units (Figure 2). The lithostratigraphy was determined from a core recovery averaging only about 20% (25% in the pillows, 15% in the dikes); it was generally corroborated by an extensive suite of geophysical logs, except that the logs suggested a sharper transition between the pillows and dikes. To date, the lithostratigraphy sampled in Hole 504B is the best direct verification of the ophiolite model of the oceanic crust. However, this verification is only partial, as the lowermost 3-4 km of oceanic crust has never been sampled in situ.

Site survey seismics and heat flow measurements (Figure 3) and downhole temperature, porosity, and permeability data (Figures 4 and 5) indicate that the crust at Site 504 is at a particularly interesting stage in its evolution: At a relatively young crustal age, the thick, even sediment cover has mostly sealed the basement against pervasive hydrothermal circulation, and crustal temperatures vary closely about values consistent with predicted, conductive plate heat transfer. Judging from the present-day pattern of low heat flow closer to the spreading axis, the crust at Site 504 may have recently rebounded to a conductive geothermal state, after undergoing hydrothermal cooling in the past few million years. Recent detailed heat flow work and numerical simulations indicate that convection still occurs in the permeable, uppermost 500 m of basement beneath the impermeable sediment cover, partly controlled by the presence of isolated basement faults and topographic highs. (The grid of APC and single-bit holes planned as primary Leg 111 backup is designed to investigate the extent and nature of this presently-active convection.) Site 504 is nicely situated for studies of the sealing effect of sediment cover on a ridge-flank hydrothermal system, yet the crust is young enough that alteration record of the ridge-axis circulation remains clear.

The basement rocks recovered from Hole 504B are fine- to medium-grained, plagioclase-olivine +/- clinopyroxene +/- chrome spinel, phyric basalts, with aphyric types more abundant with depth. All of the recovered basalts are mineralogically and chemically altered to some

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[1] This section summarizes without proper references work reported in literature listed in an appended bibliography.

extent. Detailed studies of the downhole variation of secondary minerals and mineral assemblages document the existence of three major alteration zones (Figure 6):

(1) An upper alteration zone in the pillows (274.5 to 584.5 m BSF) displaying typical effects of mostly oxidative "seafloor weathering" commonly observed in DSDP holes.
(2) A lower alteration zone in the pillows (584.5-836 m BSF) that was presumably produced by reactions with low-temperature suboxic to anoxic solutions at low water/rock ratios.
(3) A high-temperature alteration zone (898 to 1350 m BSF) that produced the first *in situ* samples of ocean floor basalt containing greenschist-facies alteration minerals.

The pronounced changes in alteration mineralogy observed from 836 to 898 m BSF is interpreted to have resulted from a steep temperature gradient between low-temperature (<100°C) alteration solutions circulating in the pillow lavas and very high-temperature fluids (>300°C) which affected the lower portion of basement at the site. The transition between pillow lavas and underlying dikes corresponds closely to the transition from low- to high-temperature alteration, because the bulk permeability and porosity of the dikes are orders of magnitude lower than in the pillows.

Despite the effects of alteration, the primary composition and variation of the recovered basalts can be reliably established. The lavas and dikes recovered from Hole 504B are remarkably uniform in composition. Their high MgO contents (up to 10.5 wt.%) and very low abundances of K (<300 ppm) classify these basalts as olivine tholeiites. Judging from their high Mg-values (0.60 to 0.75), the basalts appear to have undergone only limited high-level crystal fractionation. Glass analyses from Hole 504B and nearby Holes 501 and 504A provide strong evidence for the existence of a compositionally nearly steady state magma chamber along this portion of the Costa Rica Rift.

Hole 504B has been surveyed with the most extensive suite of *in situ* geochemical and geophysical experiments in any submarine borehole (Table 2). The geophysical data indicate that the *in situ* physical properties of the crust change dramatically across the transition from pillow lavas to sheeted dikes: *in situ* sonic and seismic velocities and electrical resistivity increase sharply, while bulk porosity and permeability drop by orders of magnitude. These measurements demonstrate that the velocity structure of Layer 2 at the site is controlled by variations in porosity with depth. The sonic and seismic data are generally consistent with a sharp Layer 2B/2C boundary at the top of the sheeted dikes. The sonic data, but not the much longer-wavelength seismic data, indicate a thin Layer 2A, consisting of the uppermost 100-200 m of highly porous pillow lavas. This layer corresponds to a highly permeable, under-pressured zone into which ocean bottom water has been drawn since the hole was drilled. Layer 2B comprises the lowermost 500 m of pillows, in which the original porosity has been partially sealed by alteration products.

WHAT LIES DEEPER IN HOLE 504B?

Leg 83 cored through the major lithologic transition between pillow lavas and sheeted dikes in Hole 504B, which closely corresponds to both the Layer 2B/2C boundary and the transition between zeolite- and greenschist-facies alteration. The next major structural boundary is that between Layers 2 and 3, corresponding to the transition between dikes and underlying gabbros. Based on studies of ophiolites, the transition between greenschist- and amphibolite-facies alteration should occur within the dike complex, and probably will not correspond to a major seismic or structural boundary. Seismic data from sonobuoys and the oblique seismic experiment suggest that the Layer 2C/3 transition is 2 to 2.5 km into basement at Site 504, or about 1 km deeper than Hole 504B now extends. Based on past drilling experience, Leg 111 can be expected to core a few hundred meters, which should be predominantly within the dike complex.

As drilling through the dikes proceeds, the basalts can be expected to remain uniform in composition, although there may be highly evolved intrusions near the top of the cumulate section which never reached the surface. The dimensions, orientations, and compositions of dikes and other intrusions near the principal mass of cumulates will provide the next critical body of information regarding the functioning of magma chambers, their shape, and the stresses that controlled intrusion and eruption at the Costa Rica Rift.

LEG 111 DRILLING PROGRAM AT SITE 504

As noted above, Leg 111 will comprise four separate phases, of which the first three will be devoted to Hole 504B in a manner similar to the successful Leg 83 program (Table 3):

(1) Measurements before drilling (Hole 504B, 4-5 days)
(2) Coring the sheeted dikes (Hole 504B, 30 days)
(3) Logging the sheeted dikes (Hole 504B, 9-10 days)
(4) Sediment coring with limited logging (Site ?, 5 days)

These phases are described in detail below, along with pertinent operational considerations.

(1) Measurements before drilling (4-5 days)

Immediately after re-entry of Hole 504B, and before any disturbance by the drill pipe to the water column in the hole, a program of borehole temperature measurements and water sampling will be run to the bottom of the hole. Temperatures in the cooler upper part of the hole will provide an estimate of the rate of flow of ocean bottom water down the hole into the uppermost basement. This flow started at about 7000 liters/hour during Leg 69, and is predicted to have decayed by Leg 111 to less than 1% of this original rate. Temperatures in the deeper, hot (100-160^{o}C) section of the hole have never been accurately measured, and will require the use of the French or USGS high-temperature probes which will be on board Leg 111.

Samples of borehole fluids are of course extremely valuable if the fluids have even partially equilibrated with formation pore waters. Past water samples from Hole 504B have produced equivocal results, largely due to contamination by bentonite drilling muds, and possibly because of mixing by slow convection within the borehole induced by the thermal gradient. At the end of the last occupation of the hole during Leg 92, an attempt was made to flush the hole clean of the drilling mud by circulating 6.8 hole-volumes of seawater over several hours from the pipe at the bottom of the hole. It is not clear whether the dense mud slurry was completely flushed from the hole. Nevertheless, 3.5 years will have passed since Leg 92, and there should be a recoverable signal of formation fluid composition in the borehole waters.

Fluid samples will be drawn from the formation or borehole at four depths in Hole 504B, where the equilibrium temperatures are about 80°C, 120°C, 140°C, and 160°C, respectively. The primary sampling tool will be the Schlumberger RFT, which is run on the logging cable and is capable of drawing a 3-l sample of formation fluid through a seal against the borehole wall. This tool will be backed up by 1-l Kuster borehole fluid samplers run on the coring line.

The borehole fluid taken by these in-situ samplers will be analyzed for conventional major and minor element contents, as well as for (1) dissolved volatile components such as CO_2, H_2S, rare gases, and methane, (2) isotopic compositions of H_2O, CO_2, H_2S and rare gases, and (3) ^3H if possible. Some of these analyses will be conducted on board *JOIDES Resolution*, but many will be left for shore-based laboratories.

The major purposes of these measurements are to clarify the chemical and isotopic compositions of fluid in equilibrium with basalts and their vertical compositional gradients, which are important to estimates of transport rates and budget of these components in the crust - sea water system at 504B. The complete analyses will require that the dissolved gases be withdrawn from the fluid samplers without contamination from or loss to air; therefore, special sample transfer apparatus will be required. Sample storage tubes, which prevent exchange with atmospheric helium, will also be needed for rare gases. These precautions will be equally necessary for pore water samples as for borehole fluid samples.

Interval permeability measurements using a drillstring straddle packer will be attempted before drilling any deeper into Hole 504B, because (1) the permeability of the lowermost pillows and upper dikes has not yet been measured in sufficient detail, and (2) the bottom of the hole is utilized as the bottom of the tested interval. Packer measurements can be accomplished during the same pipe trip as the temperature and water sampling, with special rubber packer elements designed to withstand present temperatures up to 160°C.

Before Leg 111 drills Hole 504B, we will run three logs that have not yet been run in the existing section: Schlumberger NGT/GST/ACT (neutron activation/spectral gamma tool), L-DGO multi-channel sonic tool, and Japanese magnetometer. (The latter two tools can be run together in a single lowering.) This will complete the logging of layers 2A and 2B, so that the drill pipe can be run to 900 m BSF when we log the dikes after Leg 111 drilling.

(2) Coring the sheeted dikes in Hole 504B (30 days)

Reasonable recovery in the sheeted dikes of Hole 504B is essential, considering that the dikes probably contain the crucial geochemical and alteration signals of high-temperature, axial hydrothermal circulation. Leg 83 penetrated 514 m of transition zone and dikes during a drilling program of about one month duration, including coring, pipe trips, bit changes, and contingency time (Table 3). However, the recovery and penetration rates in the dikes were marginal using standard steel rotary bits: The deepest 184 m of the hole required five bits that lasted an average of 20 hours rotating time each, with an overall recovery of 15.3%.

Leg 111 can expect better performance using steel bits, simply because the superior heave compensation on JOIDES Resolution will allow the proper weight to be maintained on the bit during drilling. In addition, Leg 111 will have some steel bits with diamond cutting inserts, which should also improve recovery and penetration rates. Nevertheless, based on their own experience and the advice of bit manufacturers, ODP engineers consider a penetration rate of one m/hr to be quite good in dense crystalline rocks like the sheeted dikes. Therefore, a proposed minimum penetration rate of one m/hr may be unrealistic, and Leg 111 will not sacrifice recovery for greater penetration rates.

(3) Logging and Experiments (9-11 days)

The uppermost km of basement in Hole 504B was successfully logged with an extensive suite of Schlumberger logs and special experiments during Legs 83 and 92 (Table 2). Most of these logs and experiments showed sharp changes in the in situ physical properties across the transition into the dikes (e.g., Figure 5). After Leg 111 drills deeper into the hole, the full dike section will be logged with the standard suite of tools, and several special experiments will be run: vertical seismic profile, packer permeability tests, and large-scale electrical resistivity. (See Table 4.) Although a very successful oblique seismic experiment was run during Leg 92, the geophone was never clamped in the dike section; a VSP in the dikes would provide valuable data regarding the depth to the Layer 2/3 transition that is a long-term objective of drilling in Hole 504B.

In-situ sampling of formation fluids may be attempted in the newly-cored section using the Schlumberger RFT, in order to observe the mixing curve between formation and sea waters. Analyses of CH_4 and ^3He provide very sensitive tracers of mixing relationships, and are not affected by bentonite mud. The gas sampling apparatus will be critical to these experiments.

The major operational constraint on these logs and experiments is temperature: The present equilibrium temperature in the bottom of Hole 504B is 160°C, and the gradient is about 8°C/100m in the dikes. Given

300-500 m of additional Leg 111 coring, equilibrium bottomhole temperatures will approach 200°C. This temperature is well above the 150°-rating of the standard logging cable, and is near the upper operational limits of many of the logging tools. Even if the hole is cooled by circulation during Leg 111 drilling and before logging, temperatures deep in the hole will rebound very quickly, probably exceeding 150°C within a few hours of cooling. Thus Leg 111 will require the use of a section of high-temperature logging cable attached to the end of the present logging cable; two 1-km-long high-temperature extensions for the logging cable will be available during Leg 111. Given these cable extensions, we will be able to minimize circulation and the thermal disturbance to the formation, and log the dikes at conditions as close as possible to equilibrium. The order in which tools are to be deployed after drilling will be determined partly by their requirements for cooling the hole before logging.

(4) Sediment coring (5 days)

PCOM approved no more than 5 days during Leg 111 to core the sediments near Site 504 using the Advanced Piston Corer (APC), with two separate purposes: (1) biostratigraphic and paleoceanographic studies of double-APC cores from a location with locally low heat flow, and (2) geochemical and thermal studies of hydrologic processes in the sediments, particularly at locations with locally low and high heat flow. The latter objectives are discussed in detail in a drilling proposal written by M. Mottl, which is included here as an appendix, because it also describes the primary contingency plan for Leg 111.

As the sediments near Site 504 accumulated at a moderately high rate (40-50 m/m.y.) that has not varied much with glacial-interglacial fluctuations, double-APC cores should provide an especially good high-resolution Plio-Pleistocene record. It should be possible to determine an accurate biostratigraphy of both calcareous and siliceous microfossils. With detailed analyses of isotopes, the area around Site 504 will provide an excellent opportunity to determine a complete, astronomically-tuned biostratigraphic timescale back to the Gauss-Matuyama boundary at 2.5 Ma.

The locations for both the biostratigraphic site and the hydrogeologic site will be determined based on the results of a survey in May, 1986, to complete the fine-scale mapping of short-wavelength heat flow variations in the vicinity of Site 504. The biostratigraphic/paleoceanographic site (MM-1, Table 1) will be located in a low heat flow zone about 3 km south of Hole 504B, where we will double-APC to refusal and XCB to basement to investigate the hydrogeologic causes of the low heat flow. Then we will move to one of two local heat flow maxima mapped within 5 km of Site 504 (MM-2 or MM-3), for APC/XCB/RCB coring through the sediments and possibly into the uppermost basement. This coring will be accompanied by measurements of heat flow and pore pressure, water sampling, and possible limited logging.

CONTINGENCY PLANS

If unforeseen circumstances should require us to abandon work at Hole 504B, Leg 111 will pursue a program of regional drilling around Sites 501/504, as outlined in the appended drilling proposal by M. Mottl, and as modified to reflect the results of a detailed heat flow study (piston coring survey by Mottl and Langseth in May, 1986). This work involves several APC holes and single-bit basement holes, with measurements of temperature, pore-water chemistry, pore pressures, and flow rates, to define the nature and patterns of hydrothermal circulation probably confined to the shallow basement and sediments. As each of these holes will require roughly 1-2 weeks, nearly any amount of available Leg 111 time can be profitably applied to this contingency plan.

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TABLE 1
LEG 111 OCEAN DRILLING PROGRAM
DSDP SITE 504 REVISITED

Location of proposed sites

SITE NO.	LATITUDE	LONGITUDE	WATER DEPTH (m)	MAXIMUM PENETRATION	OPERATIONS	PRIMARY OBJECTIVES
504	1°13.62'N (DSDP Hole 504B)	83°43.81'W	3474	As far as possible in 30 days of drilling	RCB/re-entry, logging, VSP, special experiments	Deepen penetration of layer 2B; log deep section of oceanic crust; hydrology
MM-1	1°13'N (in downwelling limb near DSDP Hole 504B)	83°43'W	3500	275 m	APC to refusal; APC/XCB to basement, water sampling	Biostratigraphy Hydrology Heat flow
MM-2	1°13'N (high heat flow zone near DSDP Hole 504B)	83°43'W	3500	325 m	APC/XCB/RCB; logging; water samples	Hydrology; Sediment chem.; Physical prop.; Lateral P gradients in basement
MM-3	1°13'N (second high heat flow zone near DSDP Hole 504B)	83°43'W	3500	325 m	APC/XCB/RCB; logging; water samples	Hydrology; Sediment chem.; Physical prop.; Lateral P gradients in basement

*MM-2 and MM-3 are alternate sites.

TABLE 2
LEG 111 OCEAN DRILLING PROGRAM
DSDP SITE 504 REVISITED

Logs and experiments already run in Hole 504B

Log/Experiment	Interval successfully logged (m BSF)	
Caliper log	274.5-1287.5	
Neutron log	274.5-1287.5	
Density log	274.5-1287.5	
Sonic logs		
P.S. full wave-form	274.5-1287.5	
Multi-channel sonic	274.5-426	
Borehole televiewer (analog)	274.5-1287.5	
Oblique seismic experiment	316.5, 546.5, 726.5, 941.5 (geophone depths)	
Resistivity		
Spherically focused laterolog	274.5-1287.5	
Large-scale experiments	274.5-836	(45, 91, 182 m spacing)
	274.5-1287.5	(10,20,40,80 m spacing)
Temperature (11 data sets)	0.0-1287.5	
Borehole fluid samplings	numerous	
Packer - permeability intervals	316.5-489	
	473.5-489	
	536.5-1287.5	
Magnetometer (Russian)	274.5-489	

TABLE 3
LEG 111 OCEAN DRILLING PROGRAM
DSDP SITE 504 REVISITED

DSDP Leg 83 time budget at Hole 504B

	Days	%
Total time on site	41.0	100.0
Coring (8 bits, 514 m)	13.9	34.0
Pipe trips	10.2	25.0
Re-entries (16)	3.8	9.4
Experiments and logging	7.2	17.5
Circulation	1.4	3.3
Lost time (2 broken pipes, etc.)	4.4	10.8

TABLE 4
LEG 111 OCEAN DRILLING PROGRAM
DSDP SITE 504 REVISITED

Logs and experiments to be run in Hole 504B during Leg 111

MEASUREMENT	TOOL AND/OR OPERATOR	DEPTH INTERVAL (m BSF)	TIME ESTIMATE
(A) Before drilling - listed in order of deployment			
Temperature	France/USGS	0-1350	2 days
Water Sampling	Schlumberger RFT/Kuster	400-1350	
Permeability	Straddle packer	500-1350	1 day
Neutron activation	NGT/ACT/GST	275-1350	
Multi-channel sonic	L-DGO	275-1350	1.5-2 days
Magnetometer	Japan	275-1350	
(B) After drilling - not listed in order of deployment			
Temperature (2)	France or USGS	900-bottom	18 hours
Sonic/Electrical	LSS/DIL/SFL Schlumberger	900-bottom	
Density/Porosity	LDT/NGT/CNT "	900-bottom	
Spectral gamma	GST or ACT "	900-bottom	3 days
	ACT or ERT "	900-bottom	
Electrical resistivity	DLL	900-bottom	
Borehole televiewer	USGS	900-bottom	18 hours
Multi-channel sonic	L-DGO	900-bottom	12 hours
Magnetometer	Japan	900-bottom	
Large-scale resistivity	UMiami/L-DGO	900-bottom	18 hours
Permeability	Straddle packer	900-bottom	1-2 days
VSP/walkaway VSP	UTexas	900-bottom	2 days

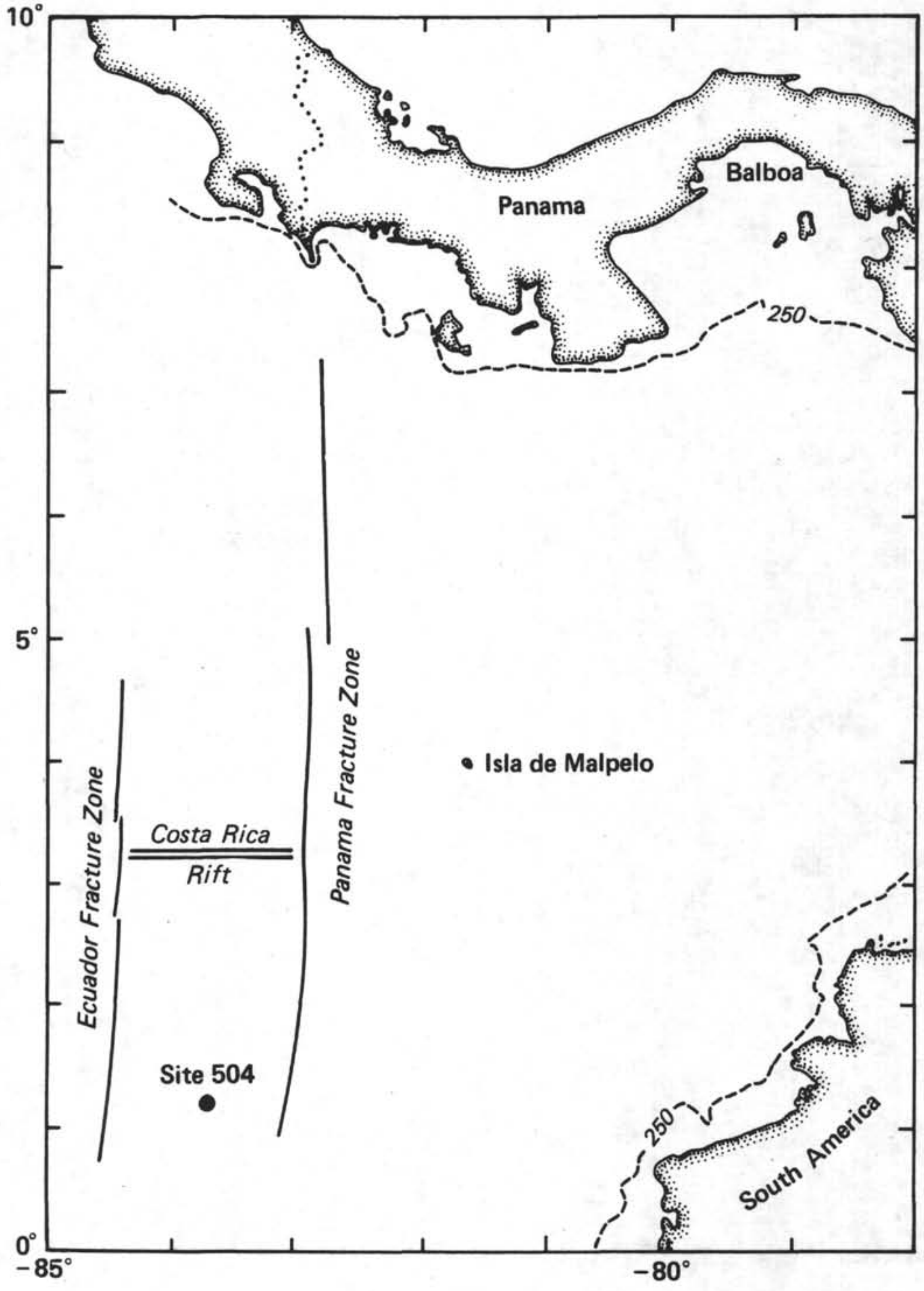

Figure 1. Location of DSDP Hole 504B (from Becker et al., 1985).

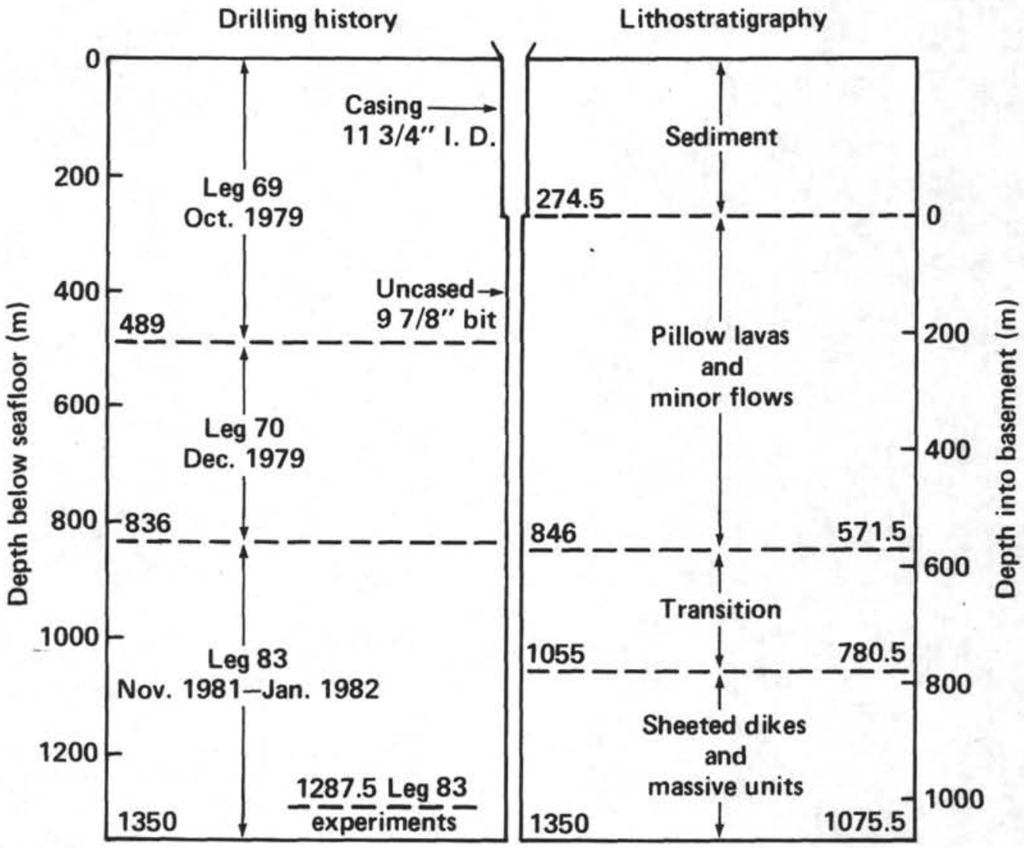

Figure 2. Schematic of the drilling history and lithostratigraphy of Hole 504B (from Becker et al., 1985).

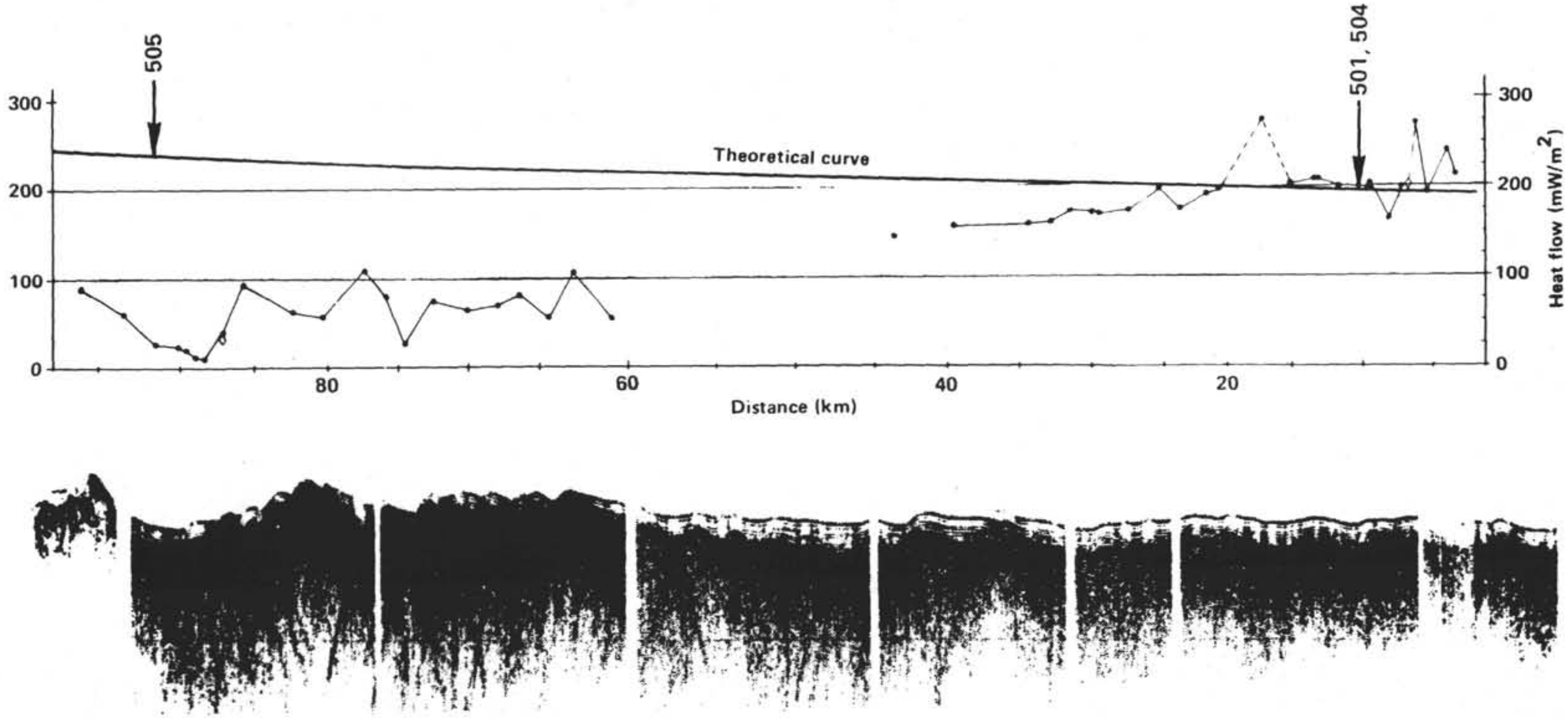

Figure 3. Site survey surface heat flow measurements and seismic profile on the southern flank of the Costa Rica Rift. The spreading axis is about 110 km farther north (left) than this figure shows (from Becker et al., 1985).

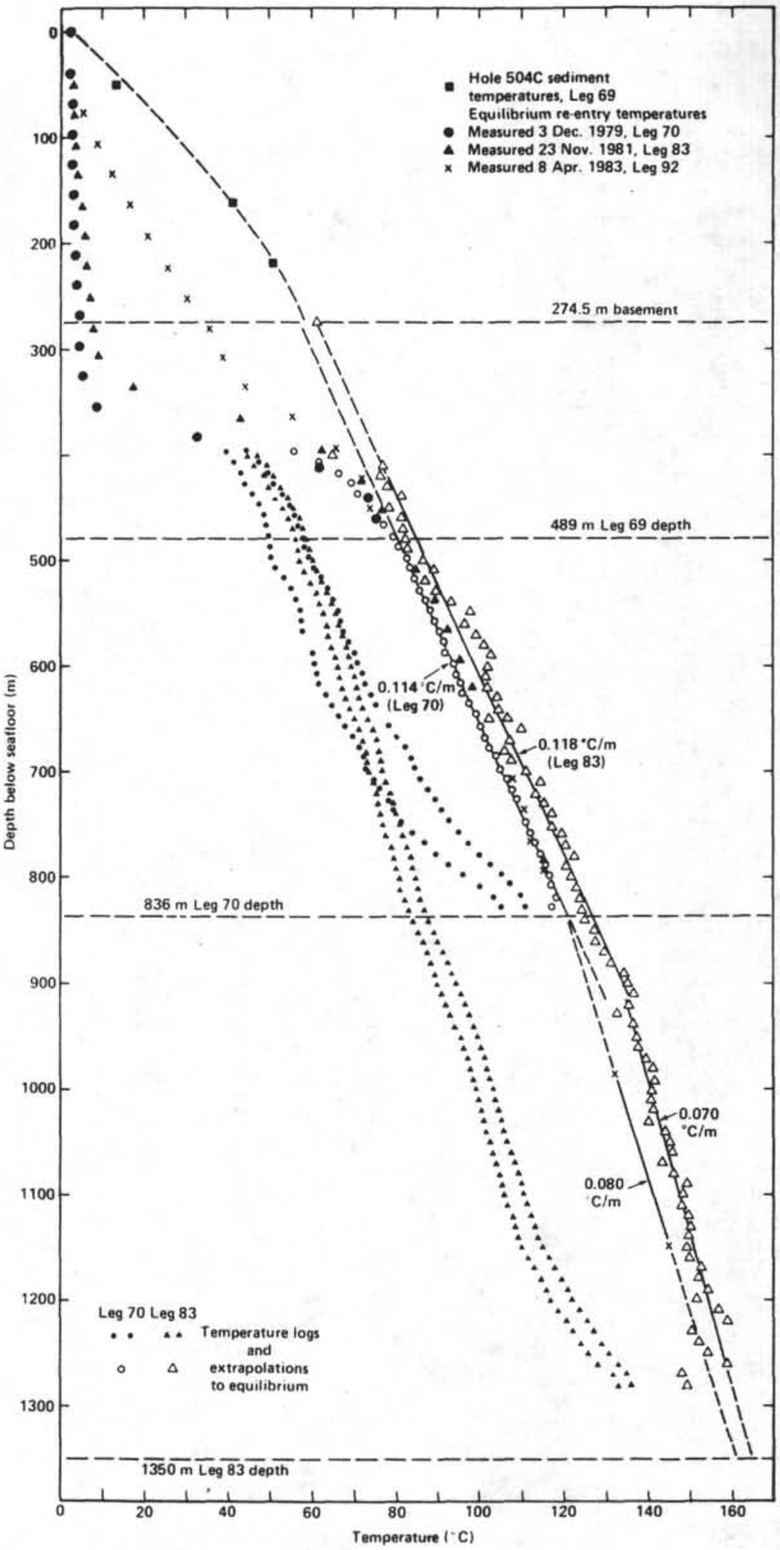

Figure 4. Temperatures measured in Hole 504B. The equilibrium geothermal gradient follows the conductive profile indicated by dashed and solid lines, with an estimated bottomhole temperature of 160°C. The depressed temperatures in the upper 400 m reflect the downhole flow of cold bottom water through the casing and into the uppermost 100 m of basement (from Becker et al., 1985).

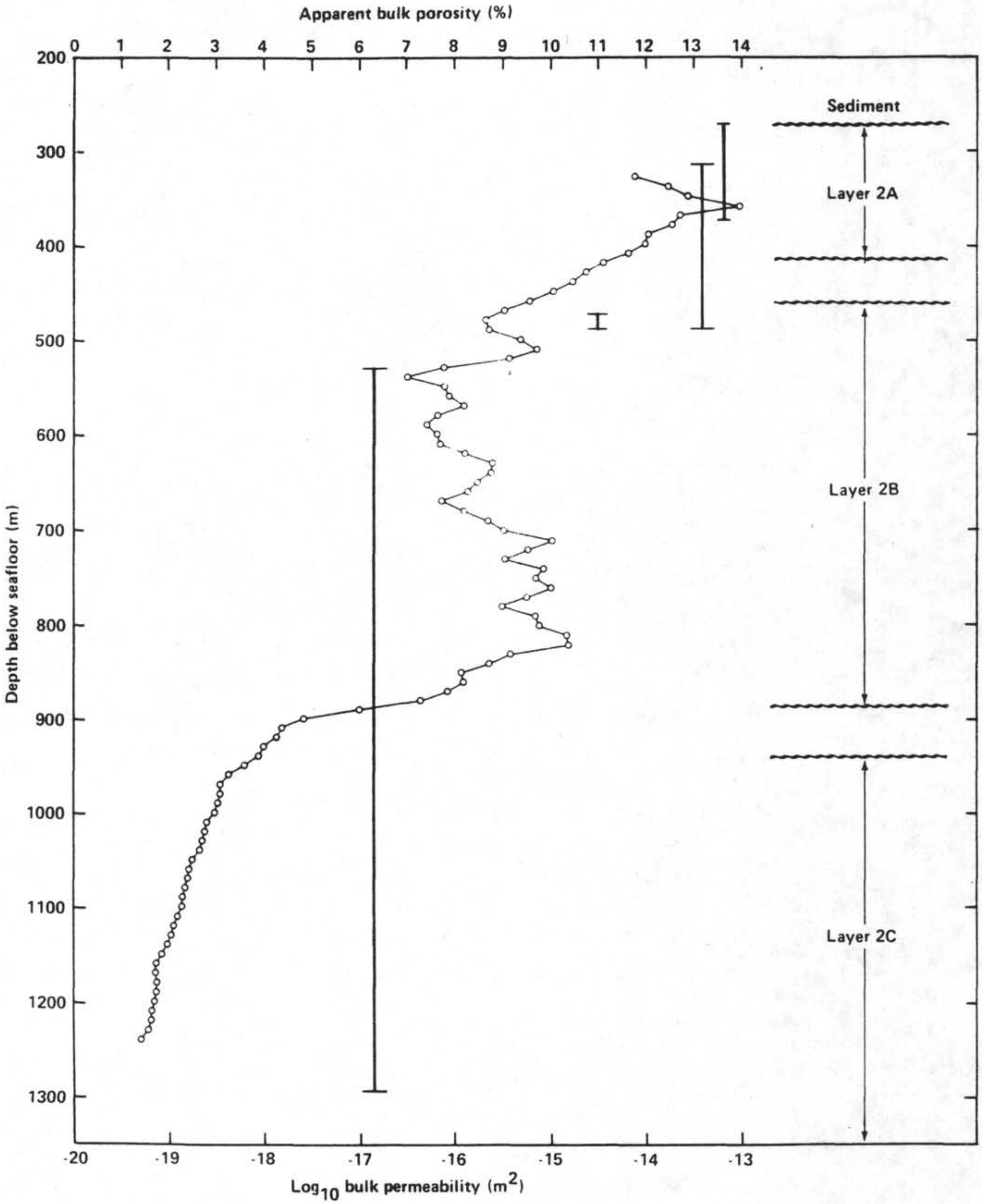

Figure 5. Apparent bulk porosities (circles) of basement in Hole 504B, determined by applying Archie's Law to large-scale electrical resistivities. Also plotted are bulk permeabilities measured over the intervals spanned by the vertical bars (from Becker et al., 1985).

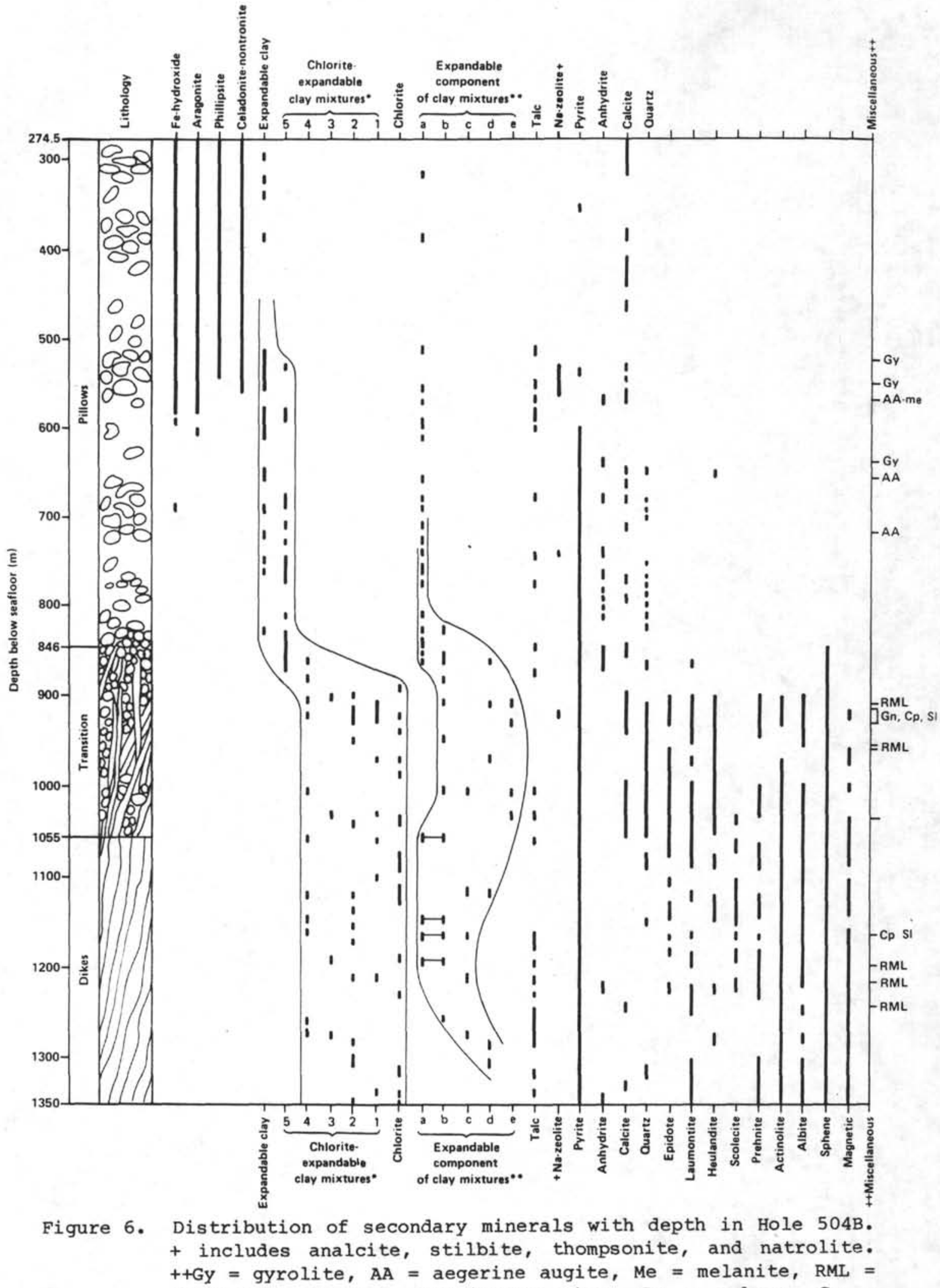

Figure 6. Distribution of secondary minerals with depth in Hole 504B. + includes analcite, stilbite, thompsonite, and natrolite. ++Gy = gyrolite, AA = aegerine augite, Me = melanite, RML = regular-mixed-layer chlorite-smectite, Gn = galena, Cp = chalcopyrite, Sl = sphalerite. * mixtures range from chlorite-rich (Type 1) to expandable layer-rich (Type 5). ** mixtures range from pure smectite (a) to pure vermiculite (e) (from Alt et al., 1985).

SITE NUMBER: DSDP Hole 504B

POSITION: 1°13.62'N 83°43.81'W SEDIMENT THICKNESS: 274.5 m

WATER DEPTH (UNCORR.): 3474 m PRIORITY: 1

PROPOSED DRILLING PROGRAM:

Re-entry into existing re-entry cone. Logging; vertical seismic profiling; special experiments. RCB coring into basement (> 500 m).

SEISMIC RECORD:

From DSDP, and Mottl/Langseth site survey of May, 1986.

HEAT FLOW: yes

LOGGING: yes

OBJECTIVES:

Deepen penetration of Layer 2B; log deep section of oceanic crust; hydrology studies.

BASEMENT TYPE:

Basalt.

<u>SITE NUMBER</u>: MM-1

<u>POSITION</u>: 1°13'N 83°43'W

<u>SEDIMENT THICKNESS</u>: 250-300 m

<u>WATER DEPTH (UNCORR.)</u>: 3500 m

<u>PRIORITY</u>: 1

<u>PROPOSED DRILLING PROGRAM</u>:

Site to be located in downwelling limb approximately 3 km south of DSDP Hole 504B. Double APC to refusal; APC/XCB to basement; water sampling.

<u>SEISMIC RECORD</u>:

From DSDP, and Mottl/Langseth site survey of May, 1986.

<u>HEAT FLOW</u>: yes

<u>LOGGING</u>: yes

<u>OBJECTIVES</u>:

Biostratigraphy; hydrology; heat flow.

<u>BASEMENT TYPE</u>:

Basalt.

SITE NUMBER: MM-2*

POSITION: 1°13'N 83°43'W

SEDIMENT THICKNESS: 275 m

WATER DEPTH (UNCORR.): 3500 m

PRIORITY: 2

PROPOSED DRILLING PROGRAM:

Site to be located in high heat flow zone east of DSDP Hole 504B. APC/XCB to 325 m maximum penetration (approximately 275 m of sediment and 50 m basement); water sampling.

SEISMIC RECORD:

From DSDP, and Mottl/Langseth site survey of May, 1986.

HEAT FLOW: yes

LOGGING: yes

OBJECTIVES:

Hydrology; sediment chemistry; physical properties; lateral P gradients in basement.

BASEMENT TYPE:

Basalt.

*MM-2 and MM-3 are alternate sites.

SITE NUMBER: MM-3*

POSITION: 1°13'N 83°43'W

SEDIMENT THICKNESS: 275 m

WATER DEPTH (UNCORR.): 3500 m

PRIORITY: 2

PROPOSED DRILLING PROGRAM:

Site to be located in high heat flow zone southwest of DSDP Hole 504B. APC/XCB to 325 m maximum penetration (approximately 275 m of sediment and 50 m of basement); water sampling.

SEISMIC RECORD:

From DSDP, and Mottl/Langseth site survey of May, 1986.

HEAT FLOW: yes

LOGGING: yes

OBJECTIVES:

Hydrology; sediment chemistry; physical properties; lateral P gradients in basement.

BASEMENT TYPE:

Basalt.

*MM-2 and MM-3 are alternate sites.

APPENDIX

REGIONAL DRILLING STUDIES AT IPOD SITE 501/504

A Drilling Proposal submitted to the JOIDES Ocean Drilling Program

by M.J. Mottl
Department of Chemistry
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

27 December 1984

Site 501/504 was drilled originally on DSDP-IPOD Legs 68/501 and 69. The site is on 6 m.y.-old crust on the southern flank of the Costa Rica Rift, in the Panama Basin. It was chosen, along with Site 505 on 4 m.y.-old crust 80 km to the north, as the first site specifically drilled to investigate geothermal processes in the oceanic crust. Hole 504B at this site was started on Leg 69 and deepened on Legs 70 and 83 to 1350 m. With 1075.5 m of basement penetration, Hole 504B is by far the deepest hole yet drilled through normal oceanic crust (Anderson, Honnorez et al., 1982). This hole has also been the site of one of the most complete sets of downhole geophysical and geochemical measurements made to date (e.g., Anderson and Zoback, 1982; Becker et al., 1982; Stephen and Harding, 1983). These measurements were continued on Leg 92. Besides the data from five DSDP legs, Site 501/504 has been investigated on several conventional cruises, including the site survey in 1978 and a follow-up in 1982, both using R/V Conrad.

This extensive body of data has shown that the crust at Site 501/504 is presently at a particularly important stage of a ridge-flank hydrothermal system: the thick sediment cover has almost completely sealed the crust from open circulation of seawater at a very young age, and crustal temperatures have re-equilibrated to a predominantly conductive geothermal gradient, yet low-temperature hydrothermal circulation probably continues in a system mostly confined to the porous upper levels of basement. Studies of the alteration of basalts recovered from Hole 504B indicate that several discrete pulses of alteration occurred; the earlier pulses probably occurred at the ridge crest, but only the sequence, not the exact timing, of the later stages could be determined. Thus, Site 504 is an excellent location to study the development of a ridge-crest/ridge-flank hydrothermal system, with emphasis on the sealing effect of the overlying sediment cover.

The outstanding questions can best be addressed by drilling a small number of shallow, closely-spaced holes at Site 501/504, and by additional drilling and experimentation in Hole 504B. In a separate proposal, the Lithosphere Panel is proposing a program of one or more legs to deepen Hole 504B and to perform additional geophysical and geochemical measurements in the hole both before and after renewed drilling. The program I am proposing for regional drilling complements theirs by providing data laterally from Hole 504B, on a scale which is probably comparable to that of the presently active hydrothermal circulation cells. Together, these programs would implement the strategy endorsed in the COSOD report of establishing "natural laboratories," defined by COSOD as "arrays or clusters of holes, some deep, some relatively shallow, grouped together...in particularly critical parts of the ocean floor." They also address two of the twelve top-priority ocean drilling objectives advanced by COSOD: (1) to determine the "character and composition of the deep portion of the oceanic crust," and (2) to determine the "dimensions and characteristics of hydrothermal systems at ridge crests versus those on ridge flanks," and the effect of "the overlying sediment cover, or lack of it" on Orhydrothermal systems.

The present proposal directly addresses the second objective.

BACKGROUND

The original plan for investigating ridge-flank geothermal processes on Legs 68/501 and 69 consisted of drilling at two sites in contrasting heat flow regimes (CRRUST, 1982). The younger Site 505 was situated on 4 m.y.-old crust where the measured conductive heat flow was only about 10% of the total predicted for crust of that age from cooling lithospheric plate models. The older Site 501/504 on 6 m.y.-old crust yielded a regional conductive heat flow about equal to the predicted total. Thus, advective heat removal due to flow of seawater through the crust was inferred to dominate the thermal budget at Site 505. At Site 501/504, the regional heat flow implied that this process was not important there, presumably because the upper surface of the basement had become effectively sealed by deposition of some 275 m of pelagic sediments. Nevertheless, high and low conductive values were measured about the mean in the region surrounding Site 501/504, suggesting that seawater circulation persisted within the basement, at least, beneath the sealed lid. Site 501/504 itself was not known to be situated over one of these heat flow anomalies.

Five holes were drilled at Site 501/504 on Leg 69, approximately along an east-west line over a total distance of 500 m. Perhaps the most surprising discovery from these holes was that the composition of the sediment pore waters showed a large monotonic gradient from east to west, along with the usual vertical gradients (Figures 1, 2). These gradients were interpreted to indicate that a persistent source of highly reacted seawater, enriched in Ca and depleted in Mg, R, and ^{18}O, existed in basement somewhere to the west of Site 501/504 (Mottl et al., 1983a). This source was inferred to be the upflow zone of a hydrothermal circulation cell which carried warm (>60°C) altered seawater upward to the base of the sediment column, whence its chemical signal propagated vertically and horizontally through the sediments by diffusion and possibly also by advection locally through the sediments themselves.

This was an important discovery because the mature nature of the diffusion profiles indicated that this upflow zone had persisted in a fixed location in basement for a period on the order of 10^6 years (Lawrence and Li, 1982). During this time the plate would have moved as much as 35 km southward. Based on theoretical modelling of the extensive heat flow data set of Green et al. (1981) from the southern flank of the Galapagos Rift, Fehn et al. (1983) had predicted that hydrothermal circulation cells in basement on mid-ocean ridge flanks would migrate away from the ridge axis at the same rate as the plate itself, and thus would remain fixed in the plate. This would mean that a given volume of oceanic basement, once out of the axial zone, would always be altered within either an upflow zone or a downflow zone, for as long as circulation through basement persisted. The sediment pore water data from Site 501/504 are the first field evidence which appears to confirm this important hypothesis.

A second surprising discovery concerning hydrothermal circulation through basement at Site 501/504 was made when Hole 504B was logged at the end of Leg 69, after 214 m of basement penetration. Downhole temperature measurements indicated that ocean bottom water was flowing down the hole and into the upper 100 m of basement. This observation was confirmed after re-entry on Legs 70, 83, and 92, which demonstrated that the flow had slowed significantly over a three-year period (Becker et al., 1983). Apparently the hole, after breaking the hydraulic seal composed by the sediment, had penetrated an underpressured region in the upper basement. The cause of this underpressure, and whether it was statically or dynamically maintained, is still uncertain. It may be hydrothermal in origin. Except for the depressed temperatures caused by this downhole flow, the temperature gradients at Site 501/504 are conductive, as measured both in the sediments and in basement. Hole 501, which penetrated 73 m into basement less than 500 m west of Hole 504B, showed no evidence for flow of water downhole.

Thus, the picture which had emerged by the end of Leg 83 was complex and conflicting. While thermal gradients were generally conductive, both the sediment pore water compositions and the downhole flow suggested that hydrothermal circulation might be active in the region of Site 501/504, at least in the shallow basement. These conflicting results are perhaps not surprising, considering the complex pattern of heat flow highs and lows seen in the site survey.

To clarify some of these complexities, a follow-up cruise was undertaken in the spring of 1982 combining precise navigation with heat flow measurements, piston coring, and seismic reflection (Langseth and Mottl, 1982). The conductive heat flow anomalies measured at Site 501/504 are contoured in Figure 3. The drillholes apparently are situated on the edge of a large heat flow high centered 1300 m south of Hole 504B. Associated with this high, which is shown on the north-south profile in Figure 6, is the largest anomaly in sediment pore water chemistry seen anywhere in the area (Figure 5, Core 17). The increasing chemical anomaly observed in the five DSDP holes from east to west (Figures 1, 2) correlates with a similar gradient in the thermal anomaly, shown on an east-west profile in Figure 3. The two cores to the west of the drillholes continue this correlation, showing large chemical anomalies (Figure 5, Cores 13 and 14), while the third core (16) shows neither a chemical nor a thermal anomaly and thus delimits the anomaly on the west in this profile. The chemical-thermal anomalies thus are apparently small in area (a few km^2) and define a complex two-dimensional pattern. This pattern probably reflects a three-dimensional pattern of hydrothermal circulation through basement which, judging from the diffusion profiles shown by the sediment pore waters, has been stable and fixed in the crust for about 10^6 years.

The pore water chemistry profiles shown in the DSDP holes, moreover, strongly suggest that there are highly localized zones of upwelling of warm water through the sediments, situated above the similar zones in basement. This possibility is supported by the seismic reflection profiles in Figures 4 and 6, which indicate that the diagenetic alteration fronts in the sediment column closely parallel the basement contact. The chert front, for example, occurs at about the 55^{o}C isotherm in this area. If the anomalies in conductive heat flow measured at the seafloor were transmitted through the sediments by diffusion alone, the isotherms and diagenetic boundaries should be raised beneath heat flow highs.

It may be that more is known about hydrothermal circulation at Site 501/504 than at any other place along a mid-ocean ridge flank. Because of the large body of previous work, we are in a position to document several important processes and to understand the dynamics of circulation there by drilling a few additional, shallow, well-placed holes.

SCIENTIFIC OBJECTIVES

The objectives of the regional drilling at Site 501/504 are, in order:

1. To test the hypothesis that warm, altered seawater is flowing upward through the sediment section in highly localized zones which correspond to the conductive heat flow highs. This would be done by drilling through the sediments to basement at a point directly centered over two or more of the heat flow highs. Critical measurements would include the profiles for temperature and sediment pore water chemistry.

2. To determine whether the chemical and physical properties of the sediment column and upper basement vary laterally. Specifically, are they affected by diagenetic processes related to the heat flow highs?

3. To determine the nature of water flow through basement at the site, by making a shallow penetration of basement in the same holes designated above. The critical measurement to be made is of the lateral pressure gradient, which is the driving force for hydrothermal flow. Both flow rates and permeability could be calculated from this measurement.

DEFICIENCIES IN PRESENT DATA BASE

Heat flow surveys of Site 501/504 were made as part of the original DSDP site survey and again in 1982 on cruise 23-5 of R/V Conrad (Figure 3). The latter cruise, with M.G. Langseth and M.J. Mottl as co-chief scientists, used bottom transponders for precise navigation and also collected piston cores and seismic reflection data (Figures 4-6). These data suggest two primary drilling targets: the heat flow high 1300 m south-southeast of Hole 504B (Figures 3 and 6) and the heat flow maximum 1700 m west of Hole 504B shown in Figure 4.

Unfortunately, these surveys are insufficient to define the heat flow pattern in enough detail to choose the best additional targets. Langseth and Mottl plan to return to Site 501/504 in May 1986, to collect additional heat flow measurements, piston cores, and seismic reflection data. The piston cores will be analyzed, as before, for physical properties, sediment, and sediment pore water composition. This survey will be positioned specifically to determine optimal locations for ODP drilling to achieve the above objectives. It will also aid greatly in any interpretation of hydrothermal flow processes at the site.

DRILLING REQUIREMENTS

While an optimal program cannot be laid out in detail until an additional heat flow survey is completed, all three objectives should be easily achievable within one 56-day leg.

The first objective, and to some extent the second, could be achieved under favorable circumstances by one well-placed single-bit hole. For the first objective only, this hole could consist of as little as a washdown (without core recovery) accompanied by several temperature measurements and pore water samples taken with the Barnes-Uyeda tool. Hole 504C was drilled in this way on Leg 69 in only 24 hours (see Figure 2).

For the second objective, core recovery would be required from at least one hole. For accurate physical properties measurements, the hydraulic piston corer should be used down to the top of the chert layers at about 230 m depth, as was done in Hole 504. From 230 m to basement at 275 m, the presence of chert will probably require rotary drilling. Rotary drilling and basement penetration obviously would be required to assess the degree of alteration in the shallow basement.

The third objective definitely requires at least two re-entry holes, in order to measure the lateral pressure gradient in the basement. This measurement requires setting the inflatable packer in shallow basement of each hole. While this measurement is more difficult to make, it is also more sensitive and direct than other methods of assessing a hydrothermal flow regime. Measurement of flow rates directly, for example, requires assumptions about reservoir size and permeability to calculate the lateral pressure gradient which is the driving force for the flow. Measurement of the temperature profile to infer flow rates is even less direct, and is not sensitive to small flow rates and pressure gradients.

Thus, while the stated objectives can be achieved incrementally, a full program would consist of re-entry holes, including:

- hydraulic piston coring from 0-230 m below the seafloor;
- rotary drilling through the chert-limestone beds from 230 m to basement at 275 m;

- use of the Barnes-Uyeda tool at least four times per hole during the above drilling, to collect undisturbed profiles of temperature and pore water chemistry in the sediment column;
- rotary drilling to bit destruction in shallow basement;
- logging of the hole to measure temperature, flow rate, and sediment and basement physical properties;
- setting of the packer in basement to measure pressure and permeability.

This full program would require 1-2 weeks per hole, in a water depth of 3450 m. Depending on performance, 3-5 such holes could be drilled on a 56-day leg, including a 2-3 day one-way transit time from Panama City or Guayaquil, Ecuador. Even three holes should easily achieve the stated objectives.

Because the objectives could be achieved incrementally, as outlined above, this program could be considered as a back-up to other drilling which may occur in this area. A hiatus during deeper drilling in Hole 504B, for example, could be used profitably for this program, even in increments as small as 24 hours. Longer periods of time could easily be used to produce proportionately more information.

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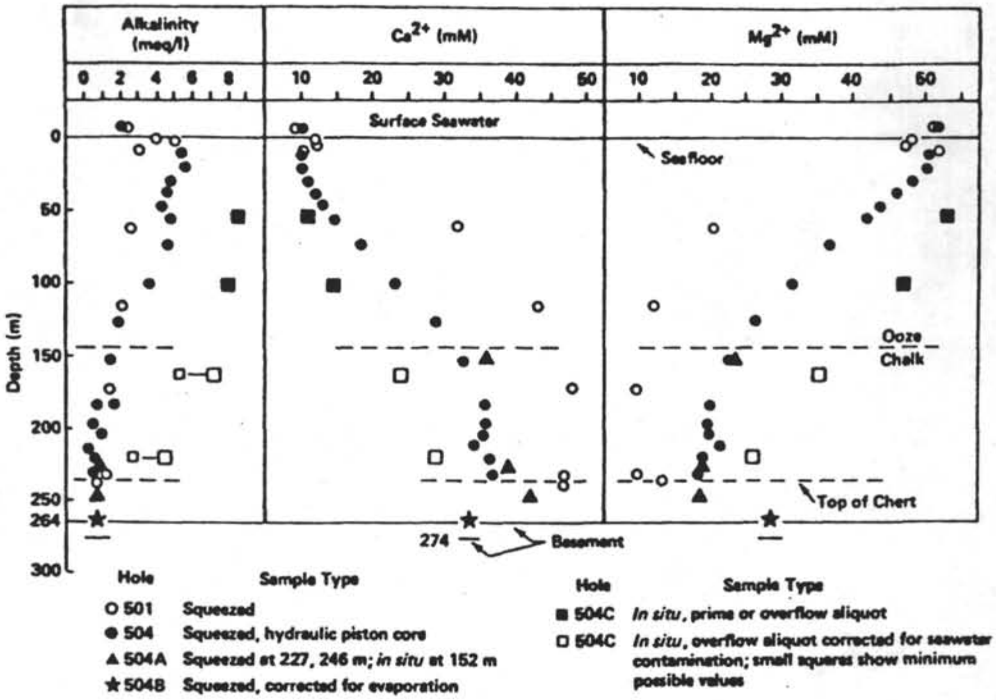

Figure 1 Composition of sediment pore waters from Site 501/504.

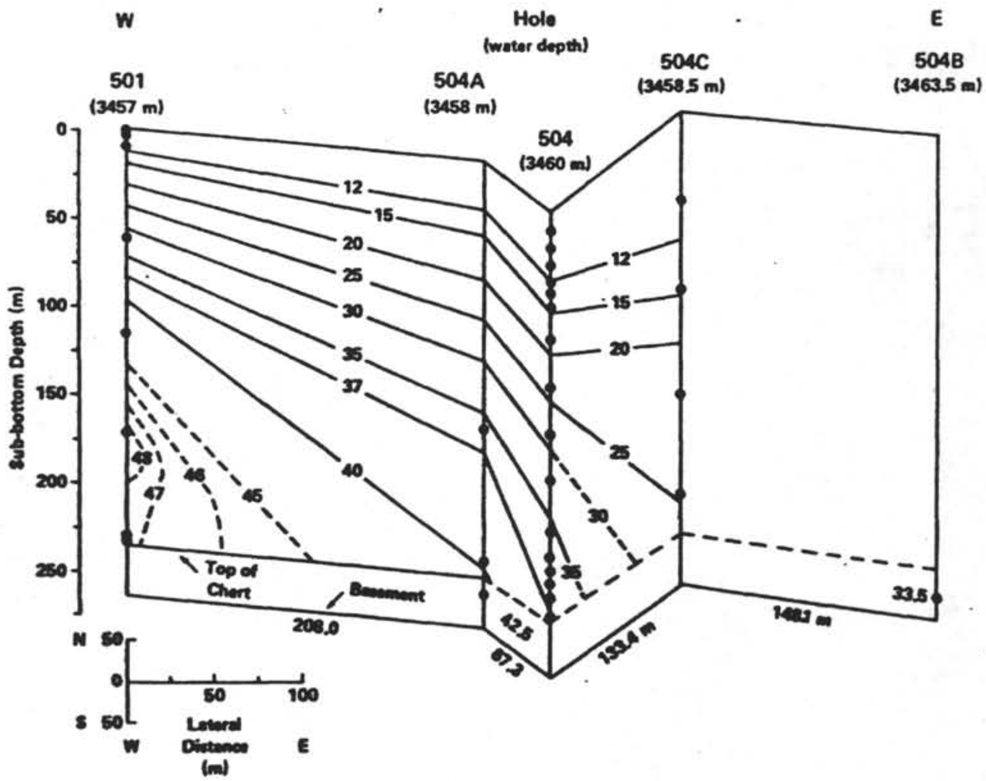

Figure 2 Three-dimensional fence diagram depicting the spatial relationships of the five holes drilled at Site 501/504 and the concentration of Ca^{2+} with depth in the sediment pore waters. The Ca^{2+} concentration is contoured in mmoles/liter. Contours are based on samples, shown as closed circles, from five holes situated approximately along at east-west line over a distance of 464 meters. View is straight north; horizontal and vertical scales are equal, except that the diagram is foreshortened north to south by a factor of 2.

(Both from Mottl et al., 1983a.)

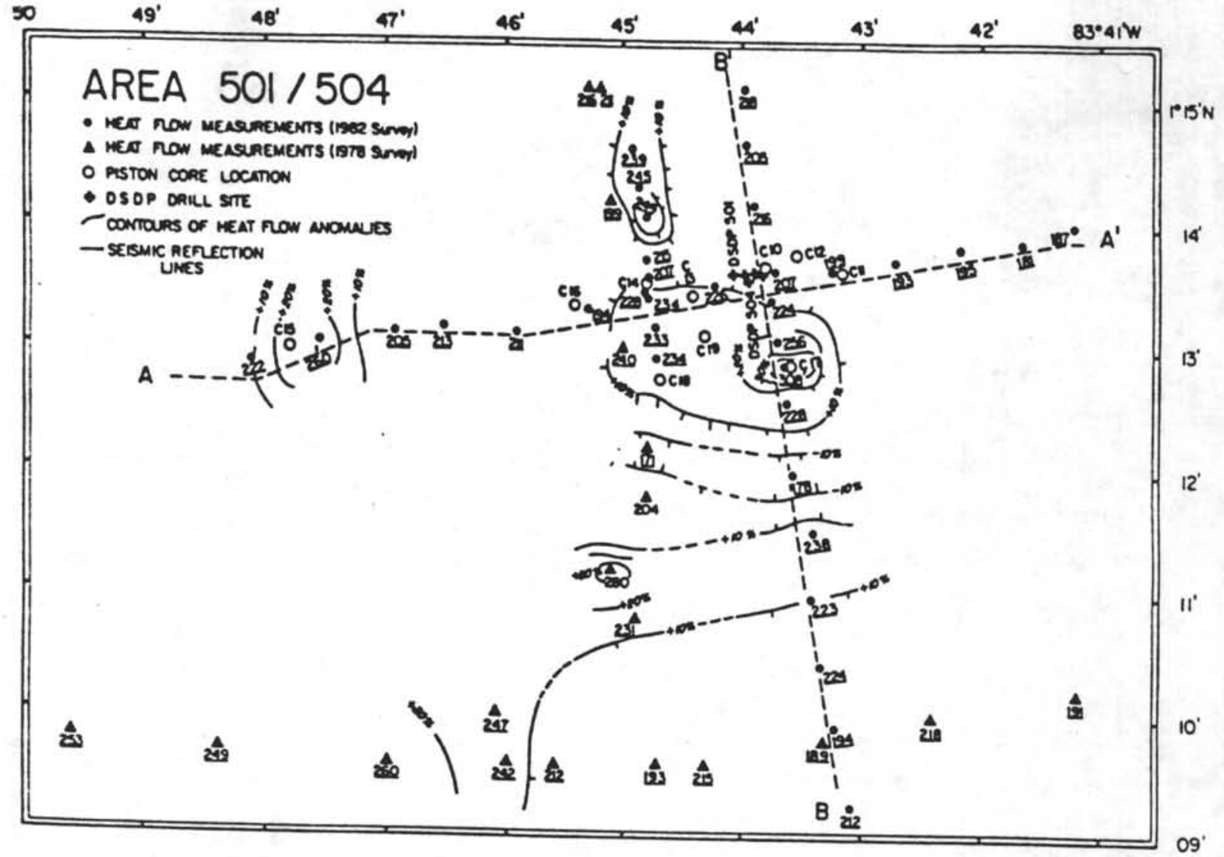

Figure 3. (from Langseth et al., ms.)

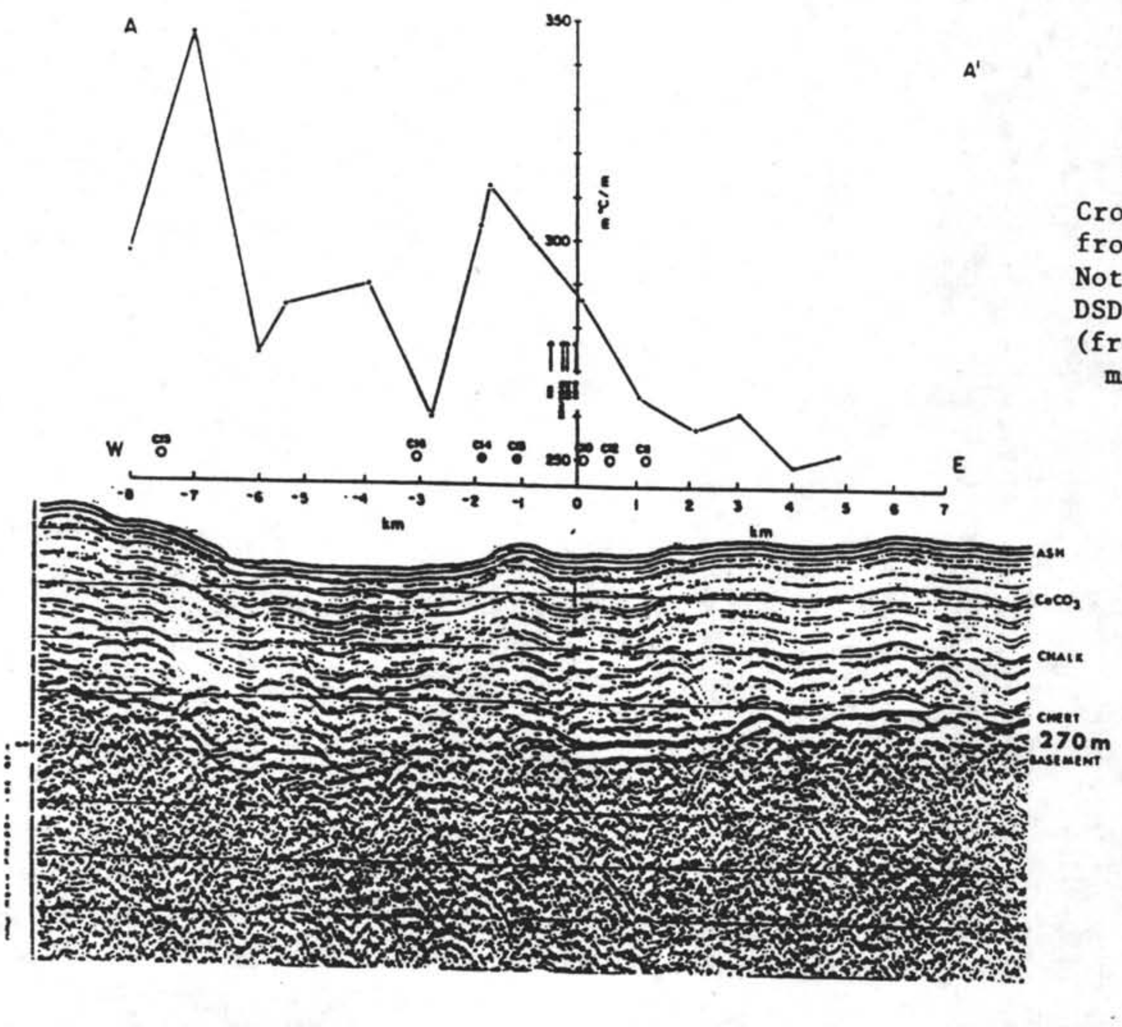

Figure 4.

Cross-section A-A' from Figure 3. Note locations of DSDP Holes. (from Langseth et al. ms.)

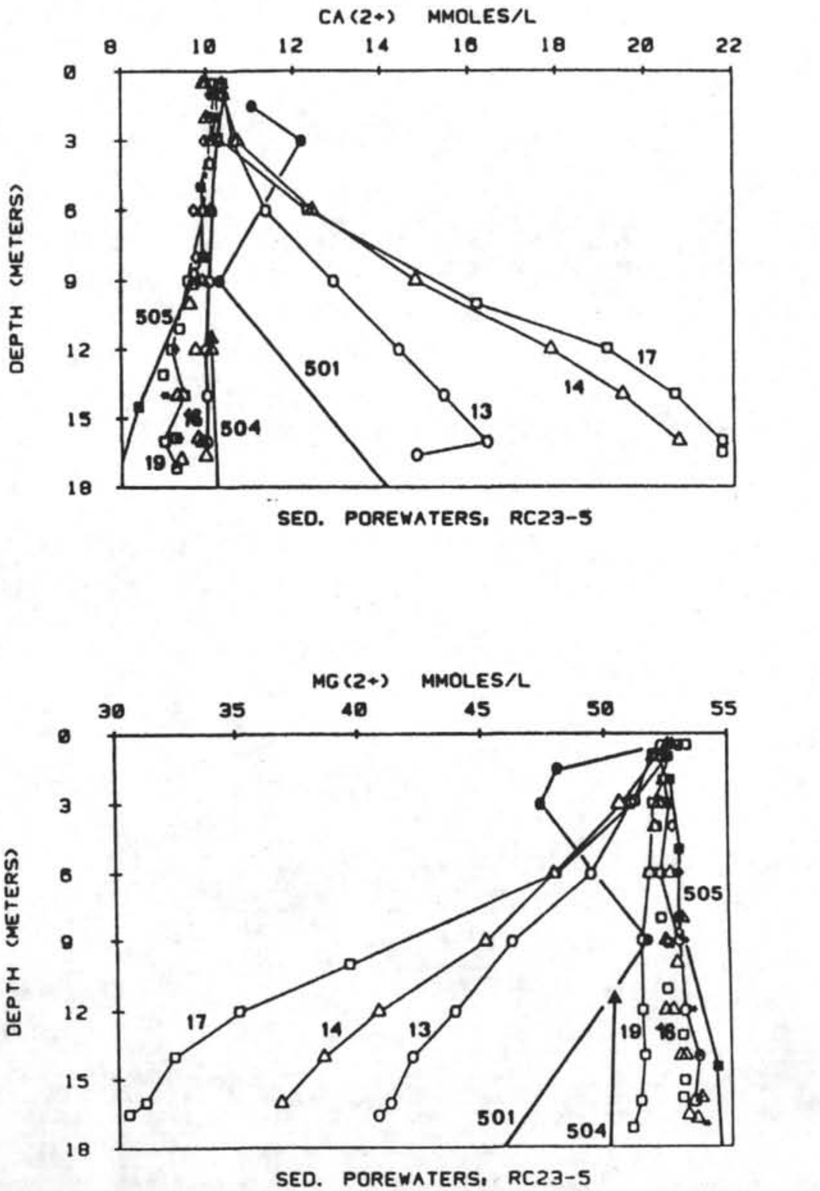

Figure 5. Concentrations of Ca^{2+} and Mg^{2+} vs. depth in sediment pore waters at Site 501/504, including samples from piston cores and from DSDP holes. See Fig. 3 for locations. (from Langseth et al., ms.)

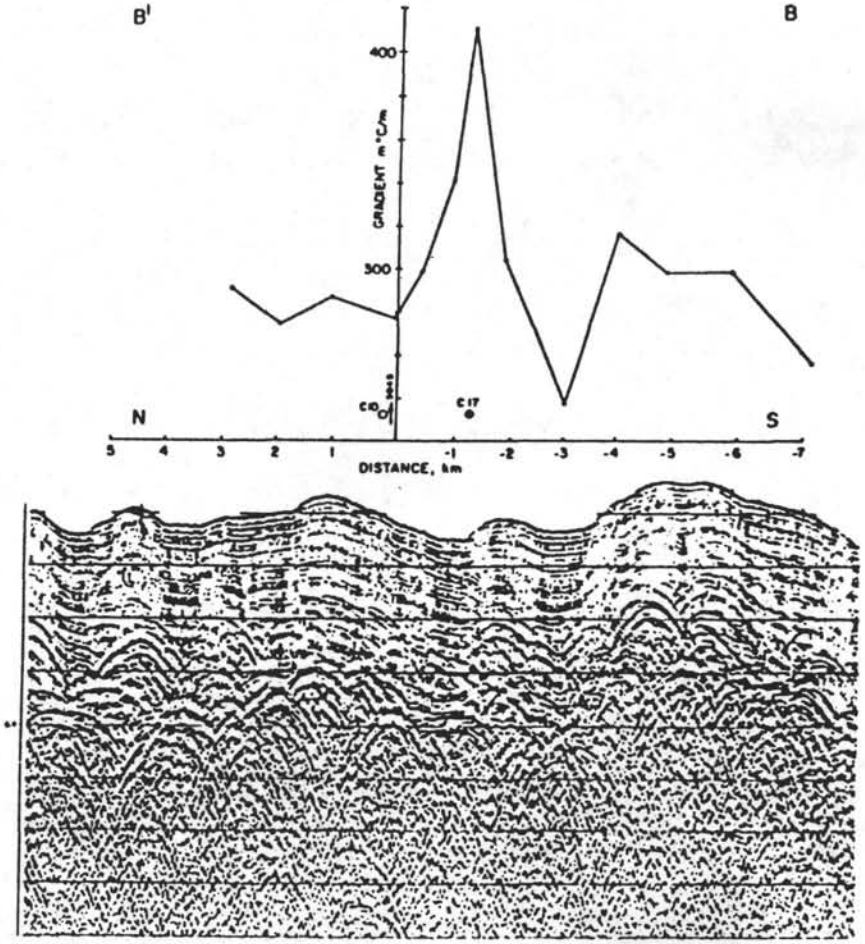

Figure 6. Cross-section B-B' from Figure 3. Note location of Hole 504B. (from Langseth et al., ms.)

LEG 111 PARTICIPANT ACCEPTANCES

As of 25 July 1986

Co-chief:	KEIR BECKER Rosenstiel School of Marine and Atmospheric Sciences University of Miami 4600 Rickenbacker Causeway Miami, FL 33149 USA
Co-chief:	HITOSHI SAKAI Ocean Research Institute University of Tokyo 1-15-1, Minamidai Nakano-ku, Tokyo 164 Japan
ODP Staff Scientist/ Igneous Petrologist:	RUSSELL B. MERRILL Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Petrologist:	ANDREW C. ADAMSON Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Petrologist:	JEFFREY C. ALT Department of Earth and Planetary Sciences Washington University in St. Louis Campus Box 1169 St. Louis, MO 63130 USA
Petrologist:	DANIEL BIDEAU IFREMER Centre de Brest BP 337 29273 Brest Cedex, France

Petrologist: PETER M. HERZIG
Institute of Mineralogy and Economic Geology
Aachen Technical University
Wuellnerstr.2
D-5100 Aachen 1,
Federal Republic of Germany

Petrologist and Pore Water Specialist: HODAKA KAWAHATA
Department of Geology
University of Toronto
Toronto, Ontario M5S 1A1
Canada

Petrologist: HIDEO ISHIZUKO
Department of Geology
Kochi University
Kochi,
780 Japan

Petrologist: JOHN MALPAS
Centre for Earth Resource Research
Department of Earth Sciences
Memorial University
St. John's, Newfoundland
A1B 3X5 Canada

Petrologist and Geochemist: JOEL SPARKS
Department of Geology and Geography
Morrill Science Center
University of Massachusetts
Amherst, MA 01003
USA

Petrologist: STEFAN UHLIG
Institut fur Geowissenschaften und Lithsopharenforschung
Seckenbergstrasse 3
D-6300 Giessen,
West Germany

Pore Water Geochemist: HARUE MASUDA
Ocean Research Institute
University of Tokyo
Nakano-ku, Tokyo 164
Japan

Pore Water Geochemist:	MICHAEL J. MOTTL Hawaii Institute of Geophysics University of Hawaii at Manoa 2525 Correa Road Honolulu, HI 96822 USA
Sedimentologist:	TO BE DETERMINED
Micropaleontologist:	SIMON HOUGHTON Department of Earth Sciences Open University Walton Hall, Milton Keynes MK7 6AA Buckinghamshire, ENGLAND
Physical Properties Specialist:	NIKOLAS I. CHRISTENSEN Department of Geosciences Purdue University West Lafayette, IN 47907 USA
Down-hole Magnetometer Specialist:	HAJIMU KINOSHITA Department of Earth Science Chiba University 1-33 Yayoicho, Chiba 260 Japan
Paleomagnetist:	JANET E. PARISO School of Oceanography University of Washington Seattle, WA 98195 USA
VSP Specialist:	JOSEPH PHILLIPS Department of Geophysics University of Texas at Austin 4920 North IH 35 Austin, TX 78751 USA

Hydro Geophysicist:	ROGER ANDERSON Lamont-Doherty Geological Observatory Palisades, NY 10964 USA
High Temperature Logging Specialist:	ROBERT GABLE Bureau de Recherches Geologiques et Minieres BP 6009 45060 Orleans Cedex, France
Logging Scientist:	MICHAEL A. LOVELL Geology Department University of Nottingham Nottingham NG67 2RD, United Kingdom
Logging Scientist:	ROGER H. MORIN Borehole Geophysics Research Project United States Department of the Interior, Geological Survey Box 25046, M. S. 403 Denver Federal Center Denver, CO 80225 USA
LDGO Logging Scientist:	PHILIPPE PEZZARD Borehole Research Group Lamont Doherty Geological Observatory Palisades, NY 10964 USA
Operations Superintendent:	GLENN FOSS Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Operations Superintendent:	CHARLES HANSON Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA

Schlumberger Logger:	JOHN MARVEL Schlumberger Houston 8460 Gulf Freeway Houston, TX 77023 USA
Laboratory Officer:	TED GUSTAFSON Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Assistant Laboratory Officer/XRF:	BILL MILLS Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Curatorial Representative:	PAULA WEISS Ocean Dilling Program East Coast Repository Lamont Doherty Geological Observatory Palisades, NY 10964 USA
System Manager:	JOHN EASTLUND Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Electronics Technician:	RANDY CURRENT Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Electronics Technician:	DWIGHT MOSSMAN Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA

Chemistry Technician:	LARRY BERNSTEIN Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Chemistry Technician:	TAMARA FRANK Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Yeoperson:	ELSA MAZZULLO Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Photographer:	JOHN WEISBRUCH Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
XRF Technician:	BETTINA DOMEYER Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Marine Technician:	WENDY AUTIO Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Marine Technician:	HENRIKE GROSCHEL Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Marine Technician:	SKIP HUTTON Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA

Marine Technician:	JESSY JONES Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Marine Technician:	MARK NESCHLEBA Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA
Marine Technician:	BRYAN TRIMM Ocean Drilling Program Texas A&M University College Station, TX 77843-3469 USA