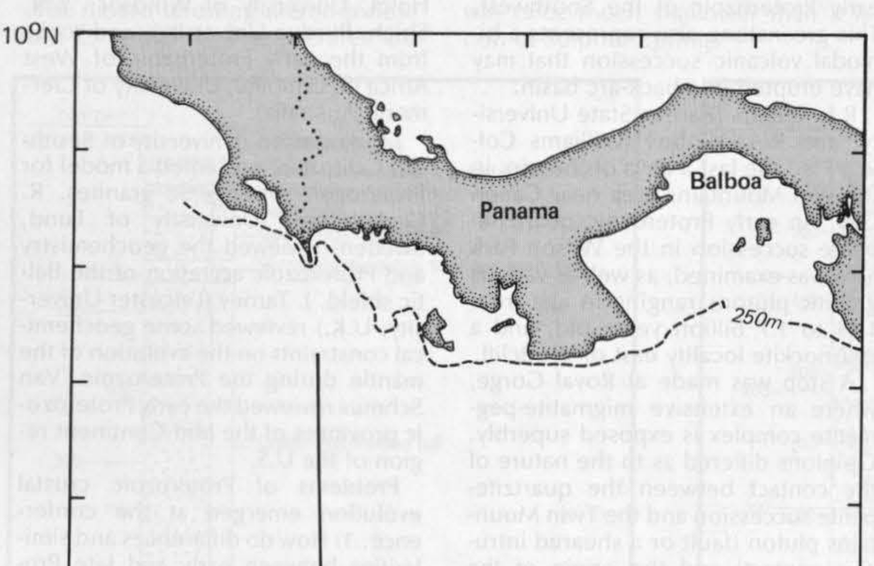
on ODP Leg 111

Costa Rica Rift hole deepened and logged

During Leg 111 of the Ocean Drilling Program, scientists on the drilling vessel *JOIDES Resolution* studied crustal structure and hydrothermal processes in the eastern equatorial Pacific. Leg 111 spent 43 days on its primary objective, deepening and logging Hole 504B, a deep reference hole in 5.9-million-year-old crust 200 km south of the spreading axis of the Costa Rica Rift. Even before Leg 111, Hole 504B was the deepest hole drilled into the oceanic crust, penetrating 274.5 m of sediments and 1,075.5 m of pillow lavas and sheeted dikes to a total depth of 1,350 m below sea floor (mbsf). Leg 111 deepened the hole by 212.3 m to a total depth of 1,562.3 mbsf (1,287.8 m into basement), and completed a highly successful suite of geophysical logs and experiments, including sampling of borehole waters.



This map shows locations of Sites 504, 677 and 678 in the eastern equatorial Pacific. Dashed lines show the 250 m bathymetric contour. (From Ocean Drilling Program)

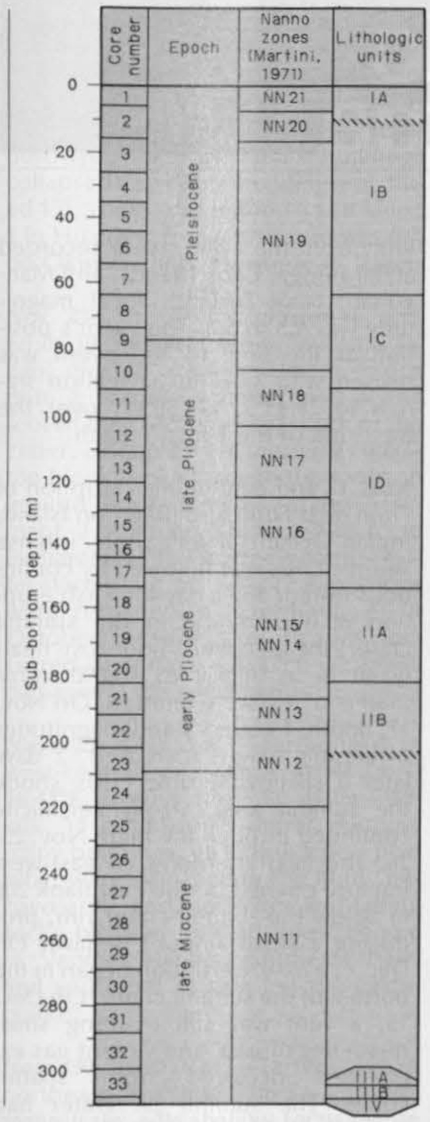
Leg 111 also completed a 5-day program of coring the 200- to 300-m-thick sedimentary sections at Sites 677 and 678, which are located respectively on a local minimum and maximum heat flow near Hole 504B. There were 2 major purposes for this sediment coring: to recover sediment, especially at the low heat flow site, for high-resolution studies of Plio-Pleistocene biostratigraphy; and to obtain sediment pore waters for chemical study of advective versus diffusive exchange between the ocean bottom water and the basement through the sediment cover.

Sites 677 and 678 are located 3 km south and 1.6 km south-southeast of Hole 504B, in water 3,461 and 3,425 m deep, respectively. 2 holes were drilled at Site 677: Hole 677A reached basal sediments and altered basalt at 309.4 mbsf. Hole 677B, which was offset about 20 m from Hole 677A, was terminated at 93.1 mbsf, because time was short. Hole 678A was abandoned after 2 successive failures to obtain a good mudline core. Hole 678B was cored only at specific stratigraphic intervals at 0 to 7.5, 18.2 to 27.7, 95.5 to 105.0, and 169.5 to 171.8 mbsf; material from intervening intervals was washed down. The last core recovered fragments of basal basalt.

Sediments recovered from Site 677 are mostly calcareous nannofossil oozes and chalk with some limestone and chert from lower sections. 3 major sedimentary units and a basal basalt unit are recognized. The sedimentary section of Site 678 may be divided into 4 similar units, although spot coring at this site makes precise comparison with Site 677 difficult. The oldest sediment recovered in Hole 677A has an age of 5.6 to 5.9 million years. The rate of sedimentation is surprisingly constant with a mean value of 42 m in a million years over the last 5.6 million years. The first 0.3 million years of deposition had a much higher rate.

The profiles of sediment pore water composition versus depth differ greatly between Sites 677 and 678. Profiles for Ca and Mg are concave upward at Site 677 and convex upward at Site 678. Alkalinity is also convex-upward at Site 678. Profiles for ammonium, silica, and phosphate are dominated by reactions in the sediments. All species except phosphate show large gradients in the 20 m section above basement at Site 677 and within the top 40 m below the seafloor at Site 678. In the altered basal basalt, pore waters at both sites have almost the same composition.

Those observations indicate that ocean-bottom seawater flows down through the 300-m-thick sediment into basement at the low heat flow Site 677. Significantly altered seawater formed in basement upwells through 180-m-thick sediment into overlying seawater at the high heat flow Site 678. The rate of the flows estimated from the depth-composition profiles is a few millimeters a year at both sites. However, the similarity in composition of pore water from the basal alteration products at both sites suggests that the advective flow rates in sediment are negligible compared to those in basement.



This diagram shows zonal assignments, epoch boundaries, and lithostratigraphy within cores and sub-bottom depth in Hole 677A. Unit I A,B,C: alternating clayey biogenic calcareous siliceous oozes and clayey biogenic siliceous calcareous oozes. Unit II A,B: siliceous nannofossil oozes and chalk. Unit III A,B: cherty limestone and nannofossil chalk. Unit IV: sediments rich in iron oxide and smectite, intermixed with glassy basement basalts. Slanted lines represent volcanic ash layers. (From Ocean Drilling Program)

During the Deep Sea Drilling Project, *Glomar Challenger* made 4 visits to Hole 504B between 1979 and 1983, coring to a total depth of 1,350 mbsf. Before Leg 111, Hole 504B had penetrated 275 m of sediment, 575 m of pillow lavas, and 200 m of transition into 300 m of massive dike units. Leg 111 was expected to core mostly within the sheeted dike complex that forms Layer 2C of the oceanic crust.

The rocks recovered from Hole 504B during Leg 111 are phyric to highly phyric, fine- to medium-grained, olivine tholeiitic basalts, similar in chemical composition to the basalts recovered from the shallow basement at the site during previous DSDP legs. Phenocrysts of olivine, clinopyroxene, plagioclase, and rarely chromian spinel occur in various combinations, including olivine+clinopyroxene and plagioclase+clinopyroxene. Although the basalts were mostly massive units, 5 intrusive dike contacts with chilled glassy margins were also sampled.

Most of the recovered basalt is altered slightly with olivine totally replaced by ± chlorite, ± pyrite, ± talc, ± mixed-layer clay minerals, ± magnetite, or by chlorite ± actinolite. Thin, subhorizontal or subvertical fissures and veins are common; some are filled by ± chlorite, ± actinolite, ± sulfides, ± quartz, ± prehnite, ± laumontite, and ± anhydrite. Actinolite becomes more abundant deeper in the section, implying higher temperatures of alteration.

Hole 504B sat undisturbed for 1,233 days after DSDP Leg 92. Before Leg 111 began coring, undisturbed borehole temperatures were logged continuously, and borehole waters were sampled. The highest measured temperature was 148.9°C at 1,280 mbsf. Deep in the hole, the temperature gradient is basically linear, decreasing from 116°C/km in the pillow lavas to 61°C/km in the dikes. The change in gradient suggests a puzzling reduction in heat flow with depth.

Four samples of borehole waters were collected from 466, 631, 766 and 1,236 mbsf, at temperatures of 81°, 101°, 115°, and 146°C, respectively. The samples show a strong vertical gradient in major chemical composition: magnesium, sulfate, and alkalies decrease with depth, while calcium shows an opposite trend. The samples fall on mixing lines between ocean bottom water and borehole water. This indicates that the chemical composition of the borehole water is controlled by vertical convection in the borehole and exchange of borehole water with the ocean bottom water that flows downhole into the upper 100 to 200 m of basement.

Permeabilities measured in the dike section indicate that the kilometer of basement deeper than 500 mbsf is uniformly impermeable (5 to 20 × $10^{-18} m^2$), so that the only permeable section of basement is the uppermost 100 to 200 m of pillow lavas. In fact, temperature measurement indicates that ocean bottom water flows down the hole and into this zone at a rate of 80 liters an hour.

Hole 504B was logged with an exceptionally complete suite of tools: Schlumberger neutron-activation/gamma-spectroscopy tool, lithodensity tool, magnetometer, electrical resistivity tool, Lamont-Doherty multi-

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channel sonic log, and U.S.G.S. borehole televiewer. When calibrated against properties of recovered basalts, the logs yield a nearly continuous geophysical, geochemical and lithological characterization of the basement.

The neutron-activation tools resolved the relative abundances of major elements Al, Ca, Fe, K, Mg, S, Si, U, and Th, and allowed construction of a normative mineralogy log. The variation in log-determined geochemistry and mineralogy is a response to the original chemistry of the phyric versus aphyric units and to the presence of alteration products such as chlorite, actinolite and clays. The logs show that the alteration products are tightly confined to fractures along boundaries between individual extrusive or intrusive events. In particular, the basalts beneath the stockwork sampled during DSDP Leg 83 at 910 to 930 mbsf are more phyric and contain more aluminum than basalts above the stockwork.

The logs yield a nearly continuous geophysical, geochemical, and lithological characterization.

Both sonic and resistivity logs clearly distinguish individual lithologic units. Deep in the dikes, compressional and shear velocities reach 6.4 and 3.7 km a second, respectively, and electrical resistivity increases to over 1,000 ohm-meters. The borehole televiewer revealed major breakouts in this otherwise massive section, suggesting that some of the drilling problems might have resulted from spalling of wall rocks as stresses were relieved around the newly drilled hole.

Both fracture and total apparent porosity could be determined from electrical resistivities; the latter ranges from about 15% in the upper pillow lavas to less than 1% deep in the dikes. The variation in logged abundances of alteration products correlates with apparent porosities calculated from resistivities, suggesting that some of the apparent porosity may represent original porosity that has been filled by alteration products.

The logged abundances of alteration minerals also correlate with changes in logged magnetic intensities. The logged magnetic inclination changes clearly at about 800 mbsf, from 15° in the pillow lavas above to 8° in the flows and dikes below. This observation is interpreted to indicate that the boundary between pillow lavas and dikes in Hole 504B is a relict of early listric faulting between pillows over the dikes in the rift valley. Such a fault might have been the permeable conduit for circulating hydrothermal fluids that produced the heavily mineralized stockwork at the base of the pillow lavas.

A highly successful vertical sounding profile experiment was done by shooting a geophone clamped about every 10 m up the hole from 1,535 mbsf. The results show 2 important reflectors, one of which might be the contact between the dikes of Layer 2C and the underlying gabbros of Layer 3. The reflectors are about 100 and 450 m deeper than the present depth of the hole and may be within reach of the next full drilling leg to Hole 504B.

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Geologic phenomena

Oct. 2—Ash plume at Suwanosejima (Ryukyu Islands, Japan); people on an airplane saw a white plume 500 to 600 m high; an ash plume was sometimes seen from 30 km northeast of the summit. Explosions have been frequent since the eruption began in 1949.

Early October and continuing—Renewed growth of the lava dome in the summit crater of Merapi (Java) continued into November; several hundred rockfalls a day have been occurring since mid-October.

October and continuing—2 new cones have been growing at Pacaya (southern Guatemala), reaching heights of 3 and 5 m by November; explosions alternated between the cones on Nov. 18 and 23. Narrow lava flows as long as 500 m were seen Nov. 16 on the west flank of MacKenney Cone. Activity from several vents has built new cones in and near MacKenney Crater and fed many lava flows since March 1983.

Nov. 10 and continuing—Explosions at Iliboleng (Lesser Sunda Islands, Indonesia); the first explosions since May 28 occurred Nov. 10, 15 and 24; a gas and ash column emitted early Nov. 24 rose 1,000 m and spread a 1-mm-thick ash layer over 18.7 square kilometers.

Nov. 11—The submarine explosion near the Kermadec Islands reported in February *Geotimes* was probably an earthquake; to people on a yacht, the event sounded like a dynamite blast followed by 2 echoes; no pumice, ash or water discoloration was seen. P and S seismic waves, apparently from the event, were recorded at Rarotonga, Cook Islands, and Mangohao, New Zealand; local magnitude was 4.5 to 5.0. The yacht's position at the time of the event was revised with satellite navigation signals to 24.43°S, 175.50°W, over the west side of the Tonga Trench.

Nov. 12 and continuing—Eruption of Piton de la Fournaise (Réunion Island, Indian Ocean); a very short, intense seismic crisis was followed by continuous tremor and a day-long ash eruption in a pit crater in the summit crater; the pit crater's floor rose nearly 40 m as 30,000 to 40,000 cubic meters of ash were emitted. On Nov. 17, depth, frequency and magnitudes of seismic events increased. 2 days later a shallow seismic crisis shook the summit area; strong seismicity continued through the night Nov. 25-26. The next afternoon an east-west fracture opened on the east flank 200 m below the summit-crater rim, producing a small amount of lava. On Dec. 6, a fissure eruption began in the bottom of the summit crater. On Dec. 15, a vent was still emitting small quantities of lava, and violent gas explosions occurred from spatter cones. The summit pit crater had formed in March (July *Geotimes*); wall collapse and a brief eruption from the pit crater in July had been the last activity at the volcano.

Nov. 12—Big rockslides began at Masaya (western Nicaragua) at midday on the south and west sides of Santiago Crater and the crater floor collapsed; part of the southwest wall collapsed, extending Santiago into adjacent Nindirí Crater. The only seismicity recorded by instruments near