5. SITE 649[1]

Shipboard Scientific Party[2]

HOLE 649A

Date occupied: 12 December 1985, 0520 L

Date departed: 14 December 1985, 1729 L

Time on hole: 59 hr, 44 min (includes 37.5-hr television survey)

Position: 23°22.139′N, 44°57.043′W

Water depth (sea level; corrected m, echo-sounding): 3524.7

Water depth (rig floor; corrected m, echo-sounding): 3535.8

Bottom felt (m, drill pipe): 3528.0

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3535.5

Penetration (m): 7.5

Number of cores: 1

Total length of cored section (m): 7.5

Total core recovered (m): 0.0

Core recovery (%): 0.0

Sediment:
Depth sub-bottom (m): 0.0–7.5
Nature: unknown—none recovered. Probable hydrothermal sulfide deposit.

HOLE 649B

Date occupied: 14 December 1985, 1729 L

Date departed: 14 December 1985, 2050 L

Time on hole: 3 hr, 21 min

Position: 23°22.139′N, 44°57.043′W

Water depth (sea level; corrected m, echo-sounding): 3524.7

Water depth (rig floor; corrected m, echo-sounding): 3535.8

Bottom felt (m, drill pipe): 3528.0

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3534.5

Penetration (m): 6.5

Number of cores: 1

Total length of cored section (m): 6.5

Total core recovered (m): 6.0

Core recovery (%): 92

Sediment:
Depth sub-bottom (m): 0.0–6.5
Nature: hydrothermal sulfide deposit
Age: Holocene
Measured velocity (km/s): not measured

Basement: presumed contact at 6.5 mbsf (no recovery)
Depth sub-bottom (m): 6.5
Nature: unknown—none recovered. Probably basalt.

HOLE 649C

Date occupied: 14 December 1985, 2050 L

Date departed: 15 December 1985, 0030 L

Time on hole: 3 hr, 40 min

Position: 23°22.139′N, 44°57.043′W

Water depth (sea level; corrected m, echo-sounding): 3524.7

Water depth (rig floor; corrected m, echo-sounding): 3535.8

Bottom felt (m, drill pipe): 3529.5

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3533.0

Penetration (m): 3.5

Number of cores: 1

Total length of cored section (m): 3.5

Total core recovered (m): 0.15

Core recovery (%): 4.3

Sediment:
Depth sub-bottom (m): 0.0 to approximately 3.0
Nature: unknown—none recovered. Probable hydrothermal sulfide deposit

Basement:
Depth sub-bottom (m): approximately 3.0
Nature: basalt pillows overlain by rubble
Velocity range (km/s): not measured

HOLE 649D

Date occupied: 15 December 1985, 0030 L

Date departed: 15 December 1985, 1015 L

Time on hole: 9 hr, 45 min

[1] Detrick, R., Honnorez, J., et al., 1988. *Proc. ODP, Init. Repts. (Pt. A)*, 106: College Station, TX (Ocean Drilling Program).

[2] Robert S. Detrick (Co-Chief Scientist), Graduate School of Oceanography, University of Rhode Island, Kingston, RI 02881; Jose Honnorez (Co-Chief Scientist), Rosentiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149) (current address: Institut de Géologie, Université Louis Pasteur, 1 Rue Blessig, 67084 Strasbourg, France; Andrew C. Adamson (Staff Scientist), Ocean Drilling Program, Texas A&M University, College Station, TX 77843; Garrett W. Brass, Ocean Drilling Program, National Science Foundation, 1800 G Street NW, Washington, DC 20550; Kathryn M. Gillis, Department of Geology, Dalhousie University, Halifax, Nova Scotia B3H 3J5, Canada (current address: Département de Géologie, Université de Montréal, C.P. 6128, Succursale A, Montréal, Quebec H3C 3J7, Canada); Susan E. Humphris, Department of Chemistry, Woods Hole Oceanographic Institution, Woods Hole, MA 02543; Catherine Mevel, Laboratoire de Pétrologie Métamorphique, Université Pierre et Marie Curie, 4 Place Jussieu, 75230 Paris 05, France; Peter S. Meyer, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543; Nikolai Petersen, Institut für Geophysik, Universität München, Theresienstrasse 41, D-8000 München 2, Federal Republic of Germany; Martina Rautenschlein, Max-Planck-Institut für Chemie, Abtellung Geochemie, Postfach 3060, D-6500 Mainz, Federal Republic of Germany; Tsugio Shibata, Faculty of Science, Okayama University, 3-1-1 Tsushimanaka, Okayama 700, Japan; Hubert Staudigel, Geological Research Division, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093; Anita L. Wooldridge, Marine Geology and Geophysics, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149; Kiyohiko Yamamoto, Faculty of Science, Tohoku University, Sendai, Miyagi Pref. 980, Japan.

Position: 23°22.139′N, 44°57.043′W

Water depth (sea level; corrected m, echo-sounding): 3524.7

Water depth (rig floor; corrected m, echo-sounding): 3535.8

Bottom felt (m, drill pipe): 3528.5

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3535

Penetration (m): 6.5

Number of cores: 1

Total length of cored section (m): 6.5

Total core recovered (m): 0.0

Core recovery (%): 0.0

Sediment:
Depth sub-bottom (m): 0.0–6.5
Nature: Unknown—none recovered. Section below 4.5 mbsf is very hard (not basement). Probable hydrothermal sulfide deposit.

HOLE 649E

Date occupied: 15 December 1985, 1115 L

Date departed: 16 December 1985, 0700 L

Time on hole: 19 hr, 45 min

Position: 23°22.139′N, 44°57.043′W

Water depth (sea level; corrected m, echo-sounding): 3524.7

Water depth (rig floor; corrected m, echo-sounding): 3535.8

Bottom felt (m, drill pipe): 3530.5

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3539.4

Penetration (m): 8.9

Number of cores: 1

Total length of cored section (m): 8.9

Total core recovered (m): 0.1

Core recovery (%): 1.1

Sediment:
Depth sub-bottom (m): 0.0–8.9
Nature: hydrothermal sulfide deposit
Age: Holocene
Measured velocity (km/s): not measured

HOLE 649F

Date occupied: 16 December 1985, 1015 L

Date departed: 17 December 1985, 0400 L

Time on hole: 17 hr, 45 min

Position: 23°22.139′N, 44°57.043′W

Water depth (sea level; corrected m, echo-sounding): no value

Water depth (rig floor; corrected m, echo-sounding): no value

Bottom felt (m, drill pipe): 3515.5

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3528.5

Penetration (m): 13.0

Number of cores: 1

Total length of cored section (m): 13.0

Total core recovered (cm^3): 4

Core recovery (%): <1

Sediment:
Depth sub-bottom (m): 0.0–13.0
Nature: hydrothermal sulfide deposit
Age: Holocene
Measured velocity (km/s): not measured

HOLE 649G

Date occupied: 17 December 1985, 0430 L

Date departed: 17 December 1985, 1745 L

Time on hole: 13 hr, 15 min

Position: 23°22.160′N, 44°57.072′W

Water depth (sea level; corrected m, echo-sounding): no value

Water depth (rig floor; corrected m, echo-sounding): no value

Bottom felt (m, drill pipe): 3518.8

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3527.8

Penetration (m): 9.0

Number of cores: 1

Total length of cored section (m): 9.0

Total core recovered (m): 0.15

Core recovery (%): 1.7

Sediment:
Depth sub-bottom (m): 0.0–9.0
Nature: hydrothermal sulfide deposit with massive sulfides 8.5–9.0 mbsf
Age: Holocene
Measured velocity (km/s): not measured

HOLE 649H

Date occupied: 17 December 1985, 1745 L

Date departed: 17 December 1985, 2100 L

Time on hole: 3 hr, 15 min

Position: 23°22.160′N, 44°57.072′W

Water depth (sea level; corrected m, echo-sounding): no value

Water depth (rig floor; corrected m, echo-sounding): no value

Bottom felt (m, drill pipe): 3521.8

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3524.8

Penetration (m): 3.0

Number of cores: 1

Total length of cored section (m): 6.5[a]

Total core recovered (m): 0.06[a]

Core recovery (%): 0.9[a]

Sediment:
Depth sub-bottom (m): 0.0–3.0
Nature: hydrothermal sulfide deposit
Age: Holocene
Measured velocity (km/s): not measured

Basement: presumed contact at 3.0 mbsf (no recovery)
Depth sub-bottom (m): 3.0
Nature: unknown—none recovered. Probably basalt.

[a] Values are for Holes 649H through 649J combined. Core barrel was not retrieved between holes.

HOLE 649I

Date occupied: 17 December 1985, 2100 L

Date departed: 17 December 1985, 2331 L

Time on hole: 2 hr, 31 min

Position: 23°22.160′N, 44°57.072′W

Water depth (sea level; corrected m, echo-sounding): no value

Water depth (rig floor; corrected m, echo-sounding): no value

Bottom felt (m, drill pipe): 3521.8

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3523.8

Penetration (m): 2.0

Number of cores: 1

Total length of cored section (m): 6.5[a]

Total core recovered (m): 0.06[a]

Core recovery (%): 0.9[a]

Sediment:
Depth sub-bottom (m): 0.0–2.0
Nature: hydrothermal sulfide deposit
Age: Holocene
Measured velocity (km/s): not measured

Basement: presumed contact at 2.0 mbsf (no recovery)
Depth sub-bottom (m): 2.0
Nature: unknown—none recovered. Probably basalt.

HOLE 649J

Date occupied: 17 December 1985, 2331 L

Date departed: 18 December 1985, 0700 L

Time on hole: 7 hr, 29 min

Position: 23°22.160′N, 44°57.072′W

Water depth (sea level; corrected m, echo-sounding): no value

Water depth (rig floor; corrected m, echo-sounding): no value

Bottom felt (m, drill pipe): 3517.8

Distance between rig floor and sea level (m): 11.1

Total depth (rig floor; m): 3519.3

Penetration (m): 1.5

Number of cores: 1

Total length of cored section (m): 6.5[a]

Total core recovered (m): 0.06[a]

Core recovery (%): 0.9[a]

Sediment:
Depth sub-bottom (m): 0.0–1.5
Nature: hydrothermal sulfide deposit
Age: Holocene
Measured velocity (km/s): not measured

Basement: Presumed contact at 1.5 mbsf (no recovery)
Depth sub-bottom (m): 1.5
Nature: unknown—none recovered. Probably basalt.

Principal Results: Site 649 was occupied from 12 to 18 December 1985 on the Mid-Atlantic Ridge in an area between 23°22.14′ to 23° 22.16′N and 44°57.04′ to 44°57.07′W, about 25 km south of the Kane Fracture Zone. We surveyed a major active hydrothermal field, the Snake Pit hydrothermal area, which covered about 40,000 m^2. The Snake Pit is on the western half of a small terrace near the crest of a median ridge in this part of the rift valley, where we observed one large active chimney emitting "black smoke." The chimney is more than 11 m high and several meters in diameter, surrounded by a thick debris apron. Two other probably active chimneys and many "decorated" inactive vents were also found surrounded by debris.

Using various coring systems, we drilled 10 shallow holes in 3525 m of water. A total of 61 m of hydrothermal precipitates and a few centimeters of the underlying basement were penetrated; average recovery was 12%. Holes 649F, 649G, 649D, and 649A and 649B were drilled at increasing distances (<1, 3, 9, and 17 m) away from a large active "black-smoker" chimney. Hole 649C was drilled close to a small inactive chimney. Hole 649E was drilled 20 m south of the "black smoker," and Holes 649H, 649I, and 649J were spudded about 65–80 m west of the active vent.

The hydrothermal precipitates are made up of essentially unaltered iron, copper, and zinc sulfides, identified as chalcopyrite and ISS (also called isocubanite or chalcopyrrhotite), pyrite, sphalerite, and pyrrhotite, in decreasing order of abundance, with traces of marcasite, covellite, and bornite. The thickness of the sulfide deposit decreases from >13 m at the foot of the active chimney (Hole 649F) to <3 m, 17 m away (Holes 649A and 649B). Basement rock consists of unaltered aphyric pillow basalt with some olivine and plagioclase phenocrysts. The basalt from this site is rather uncommon for the Mid-Atlantic Ridge Kane (MARK) area because it is more primitive (higher MgO content) than that from Sites 648 and 669 and from surrounding dredge hauls.

BACKGROUND AND OBJECTIVES

The existence of submarine hydrothermal systems along actively spreading mid-ocean ridges was first proposed by geophysicists to explain the significant discrepancy between the conductive heat-flow measurements at spreading centers and the heat flux predicted by thermal models of the lithosphere (Lister, 1972; Williams and Von Herzen, 1974; Anderson et al., 1977). The extreme variability of conductive heat-flow measurements near ridge crests also suggests convective heat loss (Elder, 1965; Lister, 1972). Skornyakova (1964) was probably the first to speculate that submarine hydrothermal activity produced the iron- and manganese-rich metalliferous sediments found along the East Pacific Rise (EPR). The same conclusion was independently reached by Bonatti and Joensuu (1966) and Bostrom and Peterson (1966), who studied iron and manganese concretions and particulate suspensions collected from Pacific seamounts and the EPR. The effects of hydrothermal activity on dredged oceanic crustal rocks from the Mid-Atlantic Ridge (Melson and van Andel, 1966; Bonatti et al., 1975; Humphris and Thompson, 1978) and the Carlsberg Ridge (Cann, 1969) were also described. Pyrite concretions (Bonatti et al., 1976a) and disseminated iron and copper sulfide mineralizations accompanying greenschist facies paragenesis were also described in metabasalts from the Romanche Fracture Zone (Bonatti et al., 1976b). These hydrothermal mineralizations and the recrystallization of their host rocks were explained as being the result of high-temperature reactions between hydrothermal solutions and the oceanic crust at spreading centers.

Not until 1977, however, were the first active hot springs directly observed at the Galapagos Spreading Center (Lonsdale, 1977; Corliss et al., 1979), and only in 1979 were the first high-temperature, "black-smoker" vents discovered in the Rise area at 21°N on the EPR (Spiess et al., 1980). In the Rise area, hydrothermal fluids flow out of chimneys up to several meters high, which are constructed of precipitated metallic sulfides (Finkel et al., 1980; Haymon and Kastner, 1981). A single vent can consist of as many as a dozen discrete chimneys coalesced to form a large sulfide mound. Water, blackened by sulfide precipitates, jets out of these chimneys at rates of 1–3 m/s at temperatures of up to 350°C (Spiess et al., 1980). Subsequent discoveries have revealed evidence of high-temperature hydrothermal discharge on the EPR near 13°N, 11°N, and 20°S, in the Guaymas Basin of the Gulf of California, and along the Juan de Fuca Ridge

[a] Values are for Holes 649H through 649J combined. Core barrel was not retrieved between holes.

(Lonsdale et al., 1980; Malahoff, 1982; Normark et al., 1982; Simoneit and Lonsdale, 1982; Francheteau and Ballard, 1983). All these vent areas are colonized by chemoautotrophic bacteria, which flourish on nutrients within the hydrothermal fluids, and provide the basis of a food chain for a unique and distinctive biological community consisting of crabs, Vesicomyid clams, large sessile Vestiminifera tube worms, and other exotic species (Corliss et al., 1979; Jannasch and Wirsen, 1979).

Although more than a dozen active, hydrothermal vent areas have now been observed along the intermediate- and fast-spreading centers in the Pacific and in back-arc basins and other subduction-related settings, such as the Lau Basin and the Marianas Trough, until recently, extensive surveys revealed no evidence of such activity along the slow-spreading Mid-Atlantic Ridge. For example, in the Trans-Atlantic Geotraverse (TAG) area, near 26°N, several studies during the past 13 yr (Rona, 1980) found abundant evidence of low-temperature activity. Manganese and nontronite precipitates were discovered in the TAG and French-American Mid-Ocean Undersea Study (FAMOUS) areas (Hoffert et al., 1978; Thompson et al., 1985), but no indication of the high-temperature vents was found until recently. In the FAMOUS area near 37°N, detailed studies involving bottom-water temperature measurements from both deep-tow vehicles and submersibles found no evidence of water-temperature anomalies attributable to hydrothermal circulation (Fehn et al., 1977). However, bottom photographs taken in May 1985 during a SeaMARC I survey of the rift valley south of the Kane Fracture Zone reveal the presence of pockets of greenish white, mottled hydrothermal sediment near the crest of a young, north–northeast-trending volcanic ridge in the middle of the rift valley (Detrick et al., 1985; Kong et al., 1985). The sediment ponds were populated by crabs and small spindly worms that suggest recent hydrothermal activity. These photographs were the first convincing evidence of an active hydrothermal area on the Mid-Atlantic Ridge. In July 1985, just 2 months later, the first "black smokers" on the Mid-Atlantic Ridge were discovered in the TAG area at 26°N (Rona et al., 1986). Little was known about either area before Leg 106, but these discoveries stirred considerable scientific interest because they provided the first opportunity to study active hydrothermal processes at a slow-spreading ridge (< 2 cm/yr).

Toward the end of Leg 106, when deteriorating hole conditions forced us to terminate drilling operations at Site 648, we decided to spend the remaining site time (about 6 days) drilling the hydrothermal area described by Detrick et al. (1985), about 25 km south of the Kane Fracture Zone. Because of the amount of available time, the objectives of Site 649 were limited to (1) surveying the area using the Colmek video camera and Mesotech sonar system to locate an active vent area and (2) drilling several unsupported, "bare-rock" holes using the Navidrill coring motors to sample a cross section of the hydrothermal deposits in the area and the underlying basement rocks.

Scientific Objectives

A variety of important scientific questions, addressed by drilling in an active hydrothermal area on the Mid-Atlantic Ridge, includes

1. establishing the character, extent, and duration of hydrothermal activity at a slow-spreading ridge;
2. determining the thickness, lateral variation, and mineralogy of the hydrothermal precipitates deposited on the seafloor at different distances from an active vent;
3. understanding the metallogenesis of massive sulfide ore bodies within the oceanic crust and their relationship to magmatic activity;
4. developing a better understanding of basalt–seawater interactions and their effect on the overall geochemical balance in the oceans;
5. quantifying the physical parameters (crustal permeability, pore pressure, depth of circulation, flow velocities, and so forth) that control the hydrodynamics of hydrothermal fluids in the crust;
6. improving geophysical models of the thermal structure of mid-ocean ridges; and
7. investigating the effects of basic hydrothermal parameters (e.g., solution composition, flow history, and temperature) on bacterial productivity, and investigating the biomass and character of the hydrothermal vent community.

In addition to providing information about these specific problems, drill holes in a hydrothermal area are ideal sites for emplacement of permanent downhole instruments for monitoring long-term seismic activity and variations in crustal permeability, pore pressure, and chemistry. This information is needed to establish the temporal, as well as spatial, interrelationships of the various physical, chemical, and biological processes associated with hydrothermal activity at mid-ocean ridges.

GEOLOGIC SETTING: HYDROTHERMAL AND BIOLOGICAL ACTIVITY

Site 649 is about 25 km south of the Kane Fracture Zone on the crest of the young, north–northeast-trending volcanic ridge identified on Sea Beam maps of the northern part of the rift valley (Fig. 1). This ridge stands several hundred meters high and is near the middle of the central magnetic anomaly (Fig. 2). The SeaMARC I survey revealed the presence of a small terrace near the crest of this ridge, and the site survey team lead by W.B.F. Ryan (Lamont-Doherty Geological Observatory) and L. Mayer (Dalhousie) deployed a navigation beacon here (beacon site 3) to mark this area for possible drilling on Leg 106. Bottom photographs taken by the site-survey team revealed a pocket of greenish white, mottled sediment populated by crabs and small spindly worms, suggesting recent hydrothermal activity (Kong et al., 1985). This discovery, made in May 1985, was the first convincing evidence of an active hydrothermal area on the slow-spreading Mid-Atlantic Ridge.

This area was not chosen as the primary drilling target for Leg 106 mainly because of the potential difficulty of locating a bare-rock guidebase in such a small target area. The terrace is < 100 m wide and may not be more than 200 m long. Additionally, we were concerned about the presence of what appeared to be large amounts of surficial rubble and extensive fissuring along the crest of the ridge and their effect on drilling conditions. However, when we were forced to terminate drilling operations at Site 648, we decided to spend the remaining site time (about 6 days) surveying and possibly drilling the hydrothermal area around beacon site 3.

Survey of Hydrothermal Area

On arrival at beacon site 3 early 12 December, we began a 36-hr survey of the area east and south of the beacon using a Colmek video camera system and the high-resolution Mesotech color sonar (Fig. 3). Both instruments were mounted on a frame and towed using a standard 0.68-in. armoured coaxial cable. We used the drill ship's dynamic-positioning system to determine position relative to the navigation beacon. The survey procedure was similar to that employed at Site 648 (see Site 648 chapter, this volume), the only significant difference being that a navigation beacon was mounted on the camera frame so that the frame position relative to the ship could be continuously monitored. Offsets of as much as 60–80 m were observed when the ship was

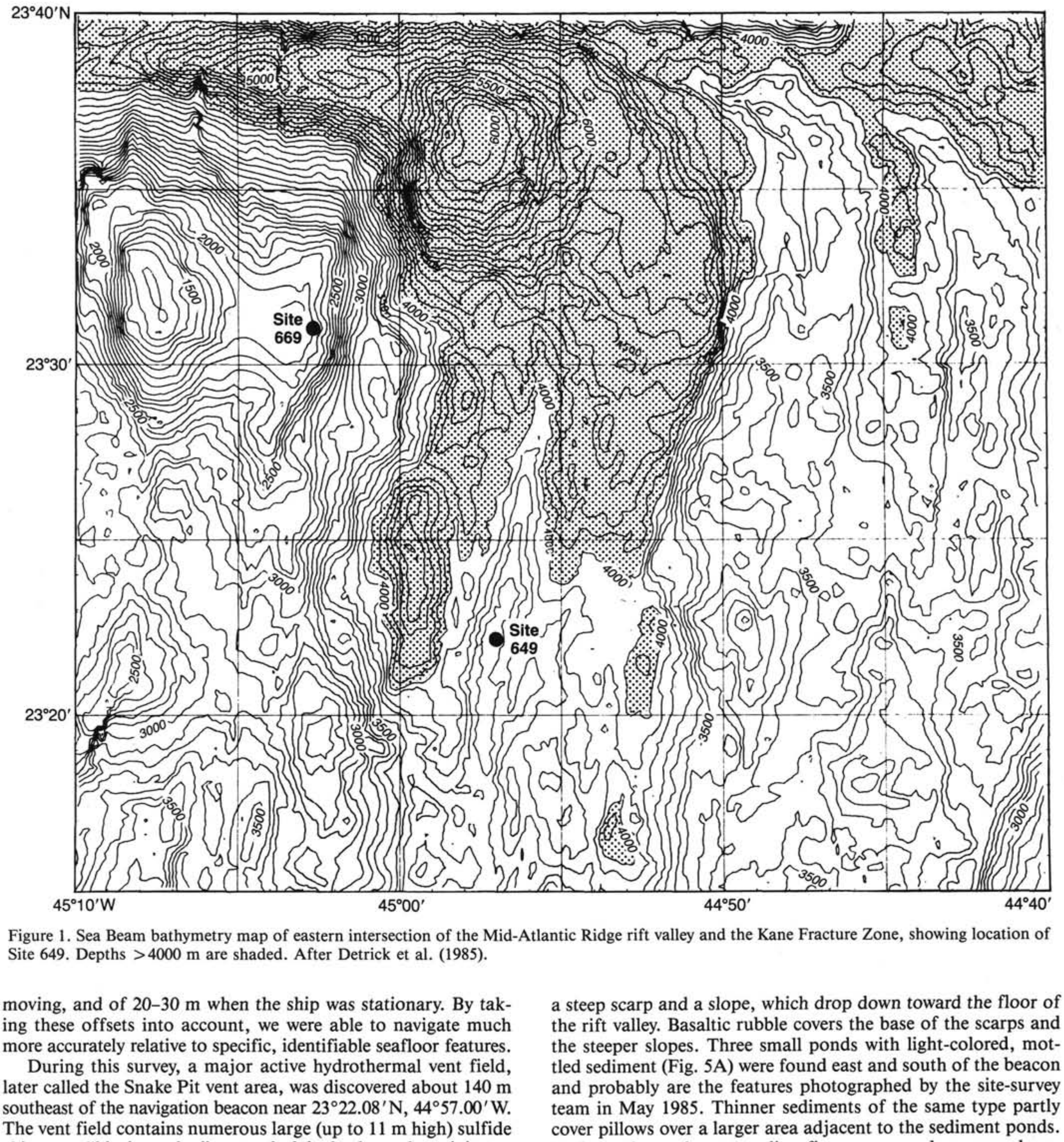


Figure 1. Sea Beam bathymetry map of eastern intersection of the Mid-Atlantic Ridge rift valley and the Kane Fracture Zone, showing location of Site 649. Depths >4000 m are shaded. After Detrick et al. (1985).

moving, and of 20–30 m when the ship was stationary. By taking these offsets into account, we were able to navigate much more accurately relative to specific, identifiable seafloor features.

During this survey, a major active hydrothermal vent field, later called the Snake Pit vent area, was discovered about 140 m southeast of the navigation beacon near 23°22.08′N, 44°57.00′W. The vent field contains numerous large (up to 11 m high) sulfide chimneys, "black-smoker" vents, dark hydrothermal precipitates, and a unique biological community. This was only the second time that "black smokers" had been reported from the slow-spreading Mid-Atlantic Ridge ("black smokers" were also reported from the TAG hydrothermal area in July 1985 by Rona [1985]) and the first time that an Atlantic vent area had been surveyed in any detail and monitored in realtime.

A geological map constructed from an analysis of the survey video tapes is shown in Figure 4. We found a narrow summit terrace, made up of pillow lavas and basaltic rubble, about 100 m wide and at least a few hundred meters long. This terrace is bordered on the west by two narrow ridges and on the east by a steep scarp and a slope, which drop down toward the floor of the rift valley. Basaltic rubble covers the base of the scarps and the steeper slopes. Three small ponds with light-colored, mottled sediment (Fig. 5A) were found east and south of the beacon and probably are the features photographed by the site-survey team in May 1985. Thinner sediments of the same type partly cover pillows over a larger area adjacent to the sediment ponds.

A north-northeast-trending fissure, as much as several meters wide, was observed running down the center of the terrace (Figure 5B). This fissure, later called the Snake Pit fissure, appears to mark the eastern boundary of a major active hydrothermal vent field. To the east of this fissure, very young-looking bulbous and elongate pillow lavas crop out. These basalts are largely free of sediment or any hydrothermal encrustations. West of this fissure, a major vent field stretches approximately east–west for at least 200 m, although the western limit of the vent area is not well constrained by our survey. The vent field consists of numerous chimneys and mounds, many displaying the spectacular dendritic, tubular structures and elaborate orna-

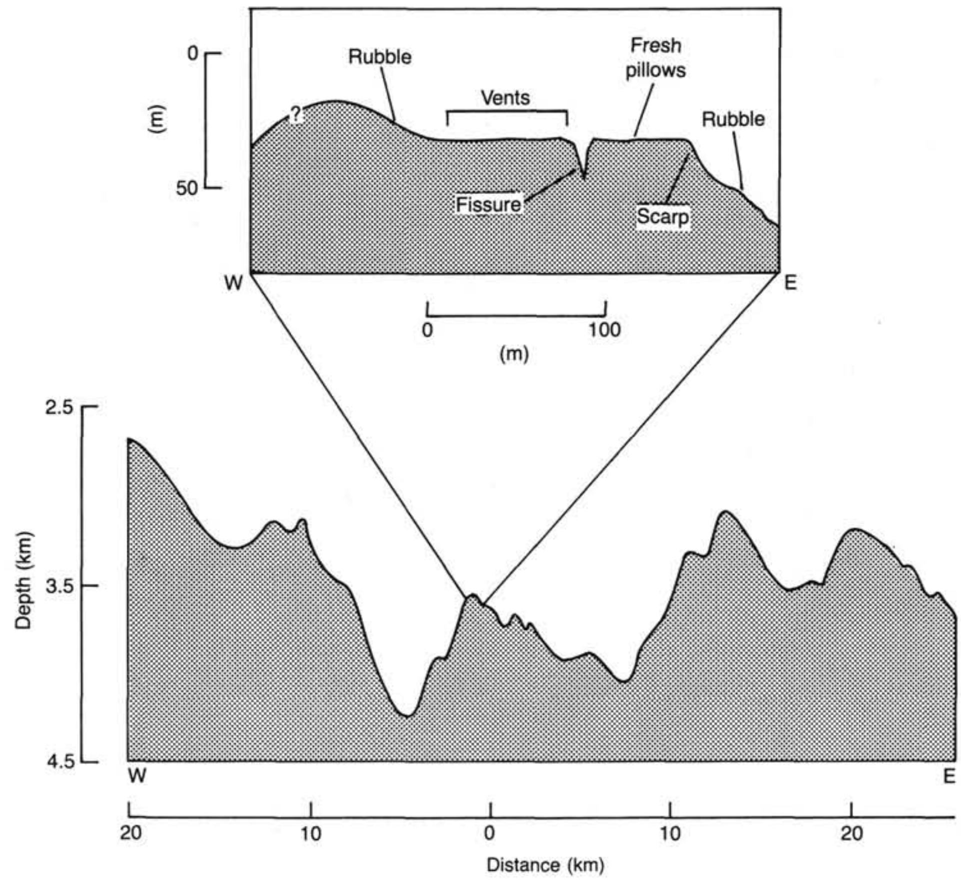


Figure 2. Center beam (Sea Beam bathymetry) profile across the rift valley near Site 649. After Detrick et al. (1985).

mentation observed in chimneys on the East Pacific Rise and Juan de Fuca Ridge (Fig. 5C and 5D). Three types of chimney morphologies can be distinguished: (1) mushroom type on large edifices as high as 11 m, (2) tree type on smaller, delicate chimneys of about 3–4 m high, and (3) finger type on mostly medium-sized vents, 5–10 m high (Fig. 6A through 6C).

The largest concentration of vents seems to be within about 40 m of the Snake Pit fissure, although most of these vents appear to be extinct. The largest and most active vents are in the central and western parts of the field. A blanket of hydrothermal precipitates, encrustations, and chimney debris extends over a much wider area (Fig. 4) and covers all basement rocks completely. An extinct vent surrounded by hydrothermally encrusted basaltic rubble is as far away as 100 m south of the main vent field. The hydrothermal encrustations commonly display striking shapes and fingerlike extensions. In some places, the chimney debris could easily be mistaken for lightly sedimented basaltic rubble in the black-and-white video images.

One extremely large "black-smoker" vent was discovered about 130 m south-southeast of the navigation beacon in the middle of the vent area (Fig. 4). We observed large plumes of "black smoke" rising from the top of the chimney and lesser amounts seeping out of several secondary vents on the chimney walls (Fig. 5E and 5F). Many sea anemones covered the seafloor near the vent. The dimensions of this vent are difficult to estimate, but the chimney is at least 11 m high and several meters in diameter. A large talus apron of debris at the base of the vent is at least 13 m thick, as indicated from the video and sonar surveys and the drill hole data. Thus, the overall size of the hydrothermal deposit related to this one active vent is at least 14 m high and 30 m wide. Fragments of the "black-smoker" chimney inadvertently collected by the television camera frame are discussed in a later section. Although only one "black smoker" was directly observed, evidence (turbid water, large concentrations of sea anemones, and other biological life) of at least two more active vents appears in the western part of the surveyed area (Fig. 4). In summary, the number of vents and the extent of the hydrothermal precipitates indicate that this is a major and highly active hydrothermal system.

The vent field is also associated with a diverse biological community, surprisingly different from that observed at the Pacific vents. No clams or large sessile tube worms were observed near the vents. The most common forms of life spread over the whole Snake Pit vent area were large shrimp and long (30–60 cm), flat, snakelike swimmers (possibly eels), which have given the vent field its name, the Snake Pit. Sea anemones populated the talus slopes of the active hydrothermal vent; great numbers of shrimp congregated on rock surfaces close to the active "black-smoker" vent. Only a few crabs were observed, but more were seen in the still photographs taken by the site-survey team in May 1985.

Using an ingenious biological sampling device welded to the camera frame and built with a 55-gallon drum and some insect screening, we collected several samples during the final coring operation at this site. The collected material consisted of one fish, about 30 cm long, identified as *Bathylaco nigricans*, four large (5–7.5 cm long) eyeless white shrimp, and several small pink and white shrimp.

In general, the biological community observed here appears to consist of smaller, more mobile organisms than those previously found at submarine hydrothermal vents on the fast-spread-

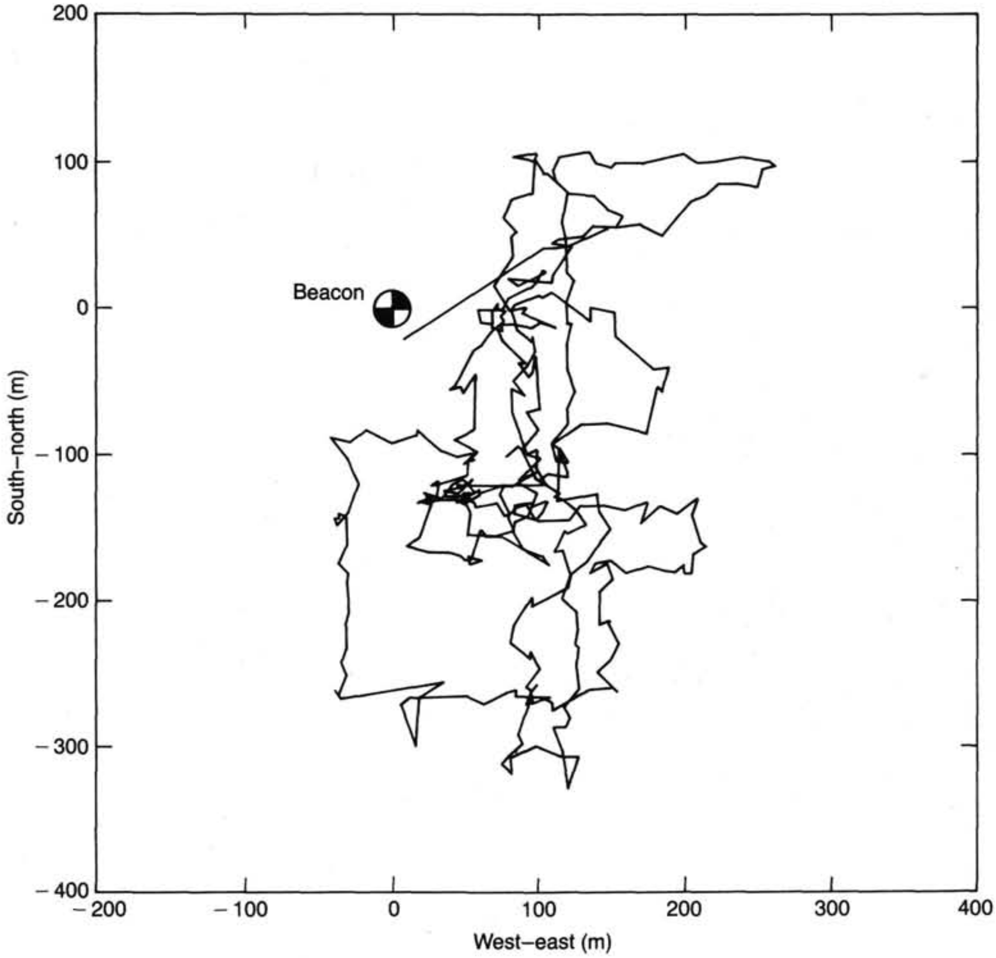


Figure 3. Location of video and sonar coverage obtained during the survey of the Snake Pit hydrothermal area.

ing East Pacific Rise. This might be an evolutionary adaptation to the shorter life and larger spatial separation of vents at the slow-spreading Mid-Atlantic Ridge, which favors the smaller, swimming organisms of the Atlantic over the larger, sessile clams and tube worms of the Pacific vents.

OPERATIONS

The ship arrived at beacon site 3 (23°22.15′N, 44°57.15′W) early 12 December 1985, and the beacon was successfully activated at 0520 hr. At 1105 hr, a 36-hr survey began using the Colmek television camera and the Mesotech sonar around the beacon site. As at Site 648, both instruments were mounted on a frame and towed using a standard 0.68-in. armoured coaxial cable. The drill ship's dynamic-positioning system was used to determine position relative to the navigation beacon. The survey procedure was similar to that employed at Site 648 (see Site 648 chapter, this volume). The only significant difference was that a navigation beacon was mounted on the camera frame so that the position of the frame relative to the ship could be continuously monitored. Offsets of as much as 60–80 m were observed when the ship was moving and 20–30 m when the ship was stationary. By taking these offsets into account, we could much more accurately navigate relative to specific, identifiable seafloor features.

A hydrothermal vent field consisting of numerous chimneys and mineralized mounds was discovered 140 m southeast of the beacon during this survey. We decided to use the remaining time on site to drill several unsupported, "bare-rock" holes with the Navidrill coring motors. Ten holes were drilled during the next 4 days. Tables 1 and 2 summarize drilling operations at Site 649. The relative positions of Holes 649A through 649G are shown in Figure 7. What follows is a brief description of drilling at each hole.

Hole 649A is about 17 m east of the active "black-smoker" chimney discovered during the site survey. The seafloor was tagged at 3528 mbsf, and the hole was spudded at 1355 hr on 14 December. A 7.5-m-deep hole was punched in 45 min into a very soft formation, probably a hydrothermal deposit. We had no recovery, probably because we were using a hard-rock core catcher; we encountered no hard formation. The core barrel could not be retrieved because of overshot latching problems.

Hole 649B is near Hole 649A. The seafloor was tagged at 3528 mbsf, and the hole was spudded at 1729 hr on 14 December. A 6.5-m hole was cored, yielding 90% recovery. The upper 6.0 m took about 20 min to drill. The recovered material was a hydrothermal iron, copper, and zinc sulfide deposit with a minor amount of talc. A hard formation (probably basement rock, indicated by the recovery of fresh basaltic glass shards) near the bottom of the core was then encountered at 6 mbsf, and the last 0.5 m of hole took an additional 30 min to core; the drill bit was torquing and sticking, thus requiring a final 30,000-lb overpull.

Hole 649C was spudded 6 m north of the first two holes at the base of a small, inactive chimney. The seafloor was tagged at 3529.5 m, and the hole was spudded-in at 2050 hr on 14 De-

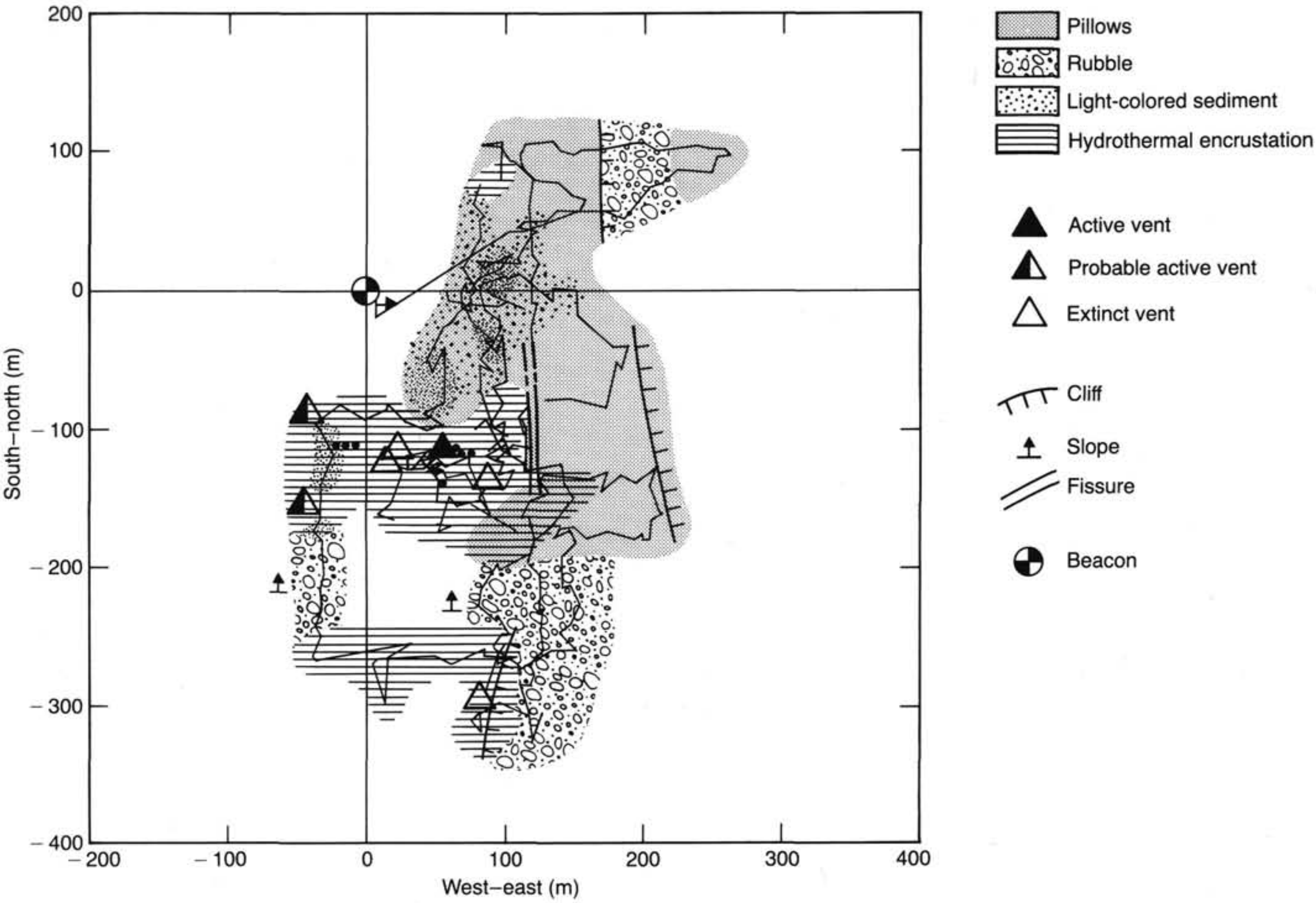


Figure 4. Geologic map of the Snake Pit hydrothermal area constructed from the video and sonar survey. Location of drill holes at Site 649 shown by black dots.

cember. A 3.5-m-deep hole was cored in 1 hr and 20 min. First, an unrecovered l-m-thick, soft formation was washed through almost instantaneously; then 3 m of fresh basalt rubble (four pieces representing a 4.3% recovery) was cored in 15 min. Afterwards, the hole caved in, causing difficult coring through the fill (requiring a 10,000-lb overpull) during the remaining hour.

Hole 649D was spudded in on 15 December at 0030 hr, about 8 m west of Holes A, B, and C. The seafloor was tagged at 3528.5 m, and a 6.5-m-deep hole was drilled into successively soft (uppermost 4.5 m, cored in 25 min) and firmer (2 m, cored in 20 min) formations, probably corresponding to a hydrothermal deposit of alternating unconsolidated and more massive sulfides. No samples were recovered because the inner core barrel parted at a welded connection. The drill string was pulled out of the hole at 0320 hr on 15 December and tripped to the surface.

Hole 649E was cored with a new coring motor and another 10½-in. drill bit. The seafloor was tagged at 3530.5 m at 1910 hr on 15 December, 20 m south and 5 m west of Hole 649D (i.e., about 20 m south and 4 m east of the active hydrothermal chimney). The uppermost meter was immediately washed, and an initially firm formation was cored for 20 min, followed by a rapid penetration into 5.5 m of a soft formation for 5 min. Below this, a second firm formation, 1.5 m thick, was encountered and drilled for 7 min. A total of 32 min was required to core the entire 8.9-m-deep hole. Unfortunately, we were unable to retrieve the core barrel because the pick-up sleeve was not in the barrel but was inadvertently left on the top drive block. We pulled out of the hole at 2330 hr on 15 December and tripped to the surface. About 100 cm^3 of fine cuttings of iron, copper, and zinc sulfides were found in the core catcher, representing a recovery of about 1%.

Hole 649F was spudded at 1930 hr on 16 December into the pedestal of hydrothermal debris at the foot of the large (>11-m-high) "black smoker" discovered during the site survey. This hole is the closest one to this active vent. The seafloor was tagged at 3515.5 m, and a 13-m-deep hole was cored using the XCB system and a drilling motor. After we washed through the uppermost meter, we rapidly cored the relatively soft hydrothermal deposit and a few firmer, but thiner, formations momentarily slowed the penetration. We pulled out of the hole at 2109 hr and tripped to the surface. Only a few grams of chlorite and disseminated iron, copper, and zinc sulfides were extracted from holes in the core cutter. The low recovery was ascribed to the cored material being washed out as the drill bit advanced into the formation, even though the core barrel was located ahead of the motor.

Hole 649G, situated only 3 m away from the active hydrothermal vent, was spudded at 1545 hr on 17 December at a depth of 3518.8 m and was cored down to 3527.8 m in 1 hr and 55 min with a coring motor and a 10½-in. drill bit. The uppermost 2 m was immediately washed, and the following 6.5 m was drilled at the rate of 1 m every 10 min. The remaining time was spent drilling the last 0.5 m of the hole into a much firmer formation. The drill string was pulled out of the hole at 1745 hr on 17 December. Recovery (<2%) consists, from top to bottom, of fine iron, copper, and zinc sulfide cuttings, three large pieces of

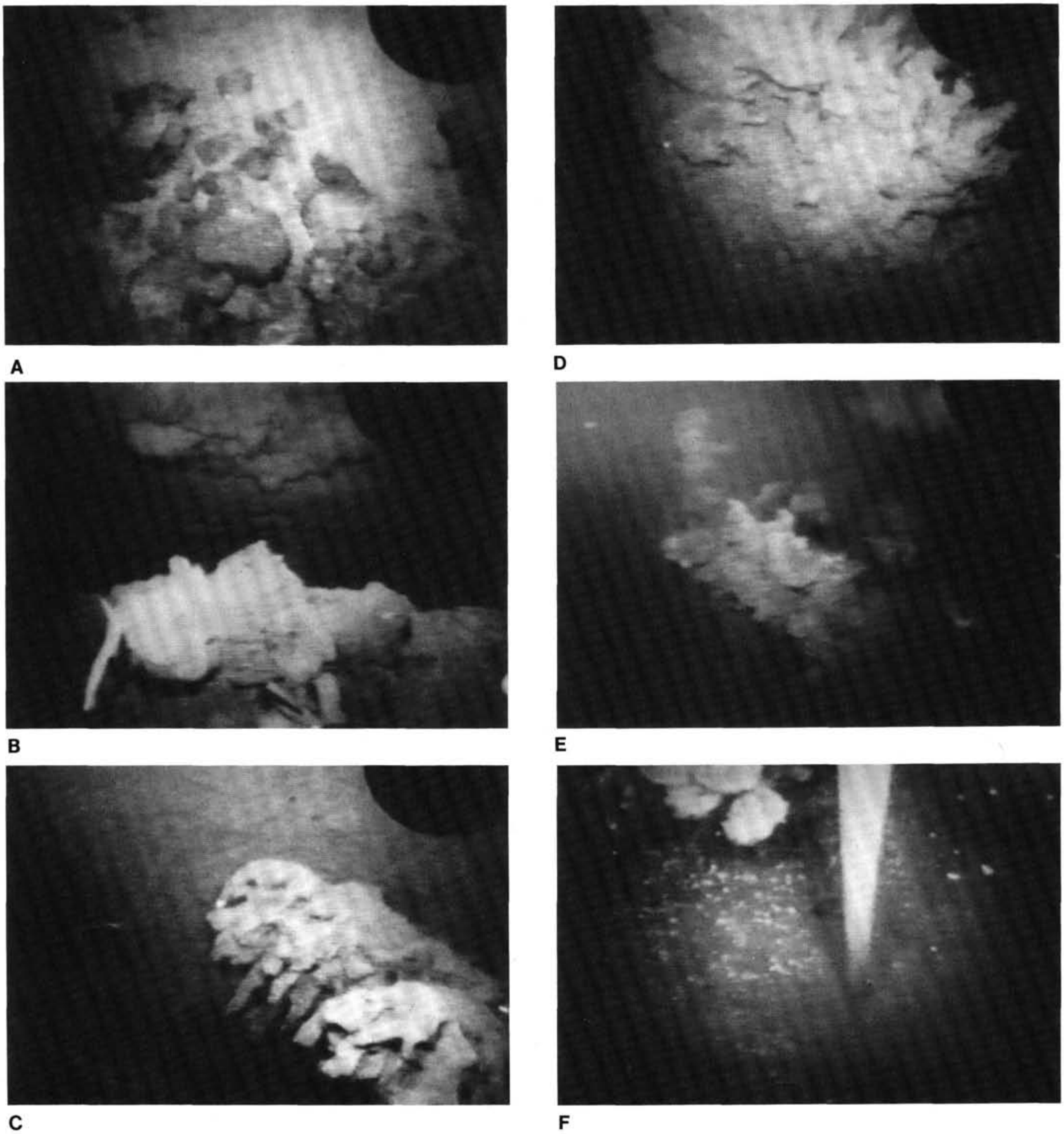


Figure 5. Photographs from television-sonar system obtained during the survey: A. White, mottled sediment pond; B. Snake Pit fissure, encrusted lavas; C. Chimney; D. Chimney; E. "Black smoker;" F. "Black smoker."

massive iron and copper sulfides, one of which displays drilling features, and a piece of a softer unidentified rock with disseminated iron, copper, and zinc sulfides.

Hole 649H is 65–70 m west of the vent, and Holes 649I and 649J are 5 m south and 10 m west of Hole 649H, respectively. All three holes were spudded into what had been thought to be a dark hydrothermal sediment pond but actually was a gentle slope of hydrothermal mounds covered with relatively small-sized rubble. This rubble was friable and, upon being spudded, was observed to crumble under the impact of the drill bit.

The coring motor and a 10½-in. drill bit were used in Holes 649H, 649I, and 649J. In addition, the television-sonar system frame was fitted with a novel biological-sampling device (BSD). The first hole was spudded at 2030 hr on 17 December in a water depth of 3521.8 m. After drilling 3 m of soft hydrothermal deposits in 26 min, we encountered a firmer formation and

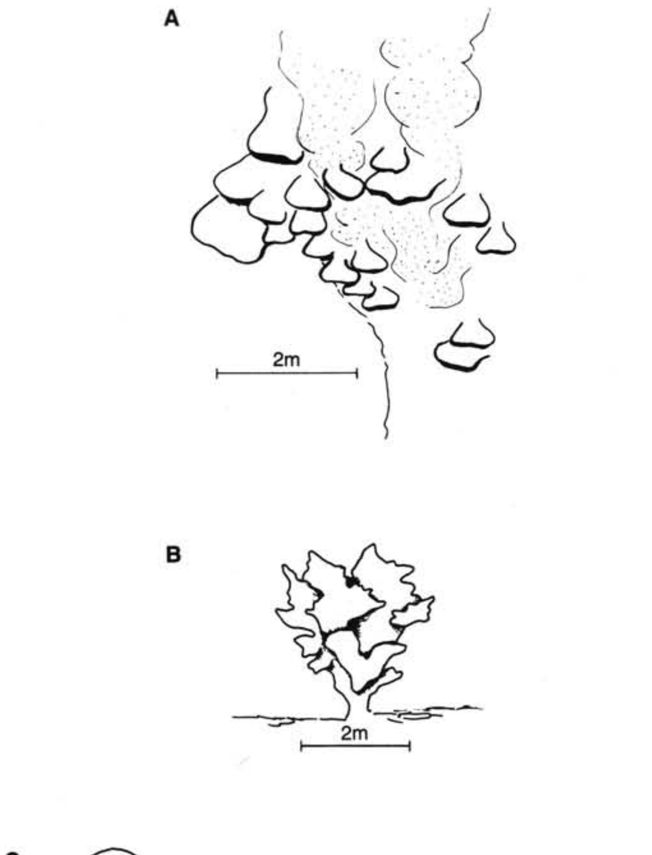


Figure 6. Hydrothermal chimney morphologies: A. Mushroom type; B. Tree type; C. Finger type.

stopped drilling to prevent loss of material already recovered (the core barrel was fitted with a core catcher for soft formations). The drill string was moved, and Hole 649I was spudded at the same water depth. Two meters were cored in 8 min, after which a firmer formation was again encountered. The drill string was moved once more, and the seafloor was tagged at 3517.8 m; Hole 649J was drilled down to 1.5 mbsf in 8 min. Again we encountered a stiffer formation. We pulled the drill string out of the hole at 2340 hr on 17 December. We recovered approximately 100 cm^3 of a fine-cutting slurry, which is made up of the same iron, copper, and zinc sulfides recovered in the other holes.

The television-sonar system frame and the BSD were recovered at 0200 hr on 18 December. Collected material consists of one fish, *Bathylaco nigrican* (about 30 cm long), four large (5–7.5 cm long), eyeless white shrimp identified as two new species of caridean shrimp, *Rimicaris exoculata* and *Rimicaris chacei* (Williams and Rona, 1986), and several small pink and white shrimplike crustaceans. The large white shrimp are thought to be from the vent area.

LITHOSTRATIGRAPHY

Ten holes were drilled at Site 649; Figure 7 shows their location relative to an 11-m-high active "black-smoker" chimney. Holes 649H through 649I were drilled from 65 to 70 m west of the vent in a hydrothermally sedimented area. Several different coring systems were used to retrieve 6.47 m of hydrothermal sulfide cuttings, one piece of massive sulfides, and three pieces of basalt. Holes varied in depth from 1.5 to 13.0 m (Table 2), penetration being determined by the length of the core barrel or by resistance of the formation to coring. In most places, drilling was terminated when basement was presumed to have been reached, the aim of drilling being to get a number of undisturbed stratigraphic sections through an active "black smoker." Recovery rates were disappointingly low, varying from zero to a few percent, except in Hole 649B, where recovery was 92%. The low recovery was attributed to (1) the variation in hardness of the formation being drilled, which varied from hard massive sulfides to soft hydrothermal sandlike deposits, and (2) the difficulty in selecting a core catcher to catch both types. Using the television-sonar system, we could often see the material being cored slowly draining from the core barrel as the pipe was lifted from the hole. All holes were drilled by first punching the drill pipe into the upper soft layers of the deposit and then, when resistance increased, by using Navidrill coring motors.

The lithostratigraphy of the various holes drilled at this site is shown in Figure 8, a stylized diagram based on the resistance of the formation to drilling. "Formation hardness" is a relative term based on the behavior of the drill string and on the length of time taken to drill sections of hole. It is not based on calculated penetration rates. The diagram (Fig. 8) shows how the "formation hardness" changes downhole and where such changes occur. The low recovery does not allow us to assign a certain lithologic type to a particular "formation hardness."

Material recovered from all holes except Hole 649C consists of the various components or products of a hydrothermal "black smoker" (Fig. 8). Hole 649C yielded several pieces of basaltic rubble. The basement and overlying hydrothermal deposits are described separately in following text.

Basement Rock

Two large pieces and several small fragments of basaltic rubble, two of which have fresh glassy margins, were recovered from Hole 649C. The basalts are all fine grained and aphyric and have some plagioclase phenocrysts. They appear fresh with only a trace of yellow-green clays on surfaces. The rubble may have been cored from the upper surface of a pillow flow but probably represents basalt rubble overlying basement rock (Fig. 8). None of the associated hydrothermal deposits were recovered.

Several glass shards found in the hydrothermal deposit recovered from Hole 649B are aphyric with a few small olivine phenocrysts, which presumably represent basement rock. Drilling

Table 1. Operations summary, Site 649.

Hole no.	Location S[a]	Location E[a]	Location Distance[b]	Date (Dec. 1985)	Time	Total depth (m)	Hole length (m)	Coring time (min)	Recovery (%)	Lithology	Drilling system	Driller's record[c]
649A	105	95	5 m E of vent	14	1355	3528-3535.5	7.5	45	0	?	Coring motor and 10½-in. bit; hard formation. CC	1 m instantaneous penetration, 1.5 m in 4 min, 1 m in 3 min, 4 m in 11 min
649B	105	95	5 m E of vent	14	1729	3528-3534.5	6.5	72	92	Fe, Cu, Zn sulfide, talc	Coring motor and 10½-in. bit; soft formation. CC	1 m instantaneous penetration, 5 m in 20 min, the last 0.5 m in 30 min, 30,000-lb overpull, sticking, torquing
649C	99	95	5 m E, 6 m N of vent	14	2050	3529.5-3533	3.5	80	4.3	Pillow basalt, rubble	Coring motor and 10½-in. bit; soft formation. CC	1 m instantaneous penetration, 2.5 m in 15 min, hole caved in, torquing 10,000-lb overpull, CC jammed. Lost hole up to seafloor
649D	105	87	9 m E of vent	15	0030	3528.5-3535	6.5	45	0	?	Coring motor and 10½-in. bit; soft formation. CC	4.5 m in 25 min, then harder formation, cut last 2 m in 20 min, inner barrel parted at weld. POOH 0320 hr on 15 Dec.
649E	125	82	4 m E, 20 m S of vent	15	1910	3530.5-3539.4	8.9	32	1.1	Fe, Cu, Zn sulfide	Coring motor and 10½-in. bit	1 m instantaneous penetration, 20 min in harder formation, 5.5 m in 5 min, last 1.5 m firmer in 7 min
649F	105	78	At foot of vent	16	1930	3515.5-3528.5	13	90	<1	Chlorite	Drilling motor and XCB	1 m instantaneous penetration, 0.5 m in 5 min, 1 m in 5 min, 2 m in 15 min, firmer down to bottom, 5,000-lb drag. POOH 2109 hr on 16 Dec.
649G	105	81	3 m E of vent	17	1545	3518.8-3527.8	9	115	1.7	Fe, Cu, Zn sulfide; massive sulfide	Coring motor and 10½-in. bit; hard formation. CC	2 m instantaneous penetration, then 1 m per 10 min firm next 6.5 m down, last 0.5 m in 20 min., POOH 1745 hr on 17 Dec.
[d]649H	100	0	65-70 m W, 5 m N of vent	17	2030	3521.8-3524.8	3	26	≪1	Fe, Cu, Zn sulfide	Coring motor and 10½-in. bit; hard formation. CC	3 m in 26 min, then stiff
[d]649I	105	0	5 m S of 649H	17	—	3521.8-3523.8	2	8	≪1	Fe, Cu, Zn sulfide	Coring motor and 10½-in. bit; hard formation. CC	2 m in 8 min, then stiff
[d]649J	100	0	10 m W of 649H	17	—	3517.8-3519.3	1.5	8	≪1	Fe, Cu, Zn sulfide	Coring motor and 10½-in. bit; hard formation. CC	1.5 m in 8 min, then stiff, POOH 2340 hr on 17 Dec.

[a] Meters south and east of beacon 3.
[b] Location with respect to vent in meters.
[c] POOH = pulled out of hole.
[d] Core barrel not retrieved between these holes.

Table 2. Coring summary, Site 649.

Hole	Core no.	Date (Dec. 1985)	Time on deck	Total depth (m) top	Total depth (m) bottom	Sub-bottom depths (m)	Advanced (m)	Length cored (m)	Length recovered (m)	Recovery (%)
649A	106-649A-1D	14	1530	3528	3535.5	0.0–7.5	7.5	7.5	0.0	0.0
649B	106-649B-1D	14	1950	3528	3534.5	0.0–6.5	6.5	6.5	6.0	92
649C	106-649C-1D	14	2320	3529.5	3533	0.0–3.5	3.5	3.5	0.15	4.3
649D	106-649D-1D	15	1000	3528.5	3535	0.0–6.5	6.5	6.5	0.0	0.0
649E	106-649E-1D	16	0830	3530.5	3539.4	0.0–8.9	8.9	8.9	0.1	1.1
649F	106-649F-1X	17	0350	3515.5	3528.5	0.0–13.0	13.0	13.0	4 cm^3	<1
649G	106-649G-1D	17	2005	3518.8	3527.8	0.0–9.0	9.0	9.0	0.15	1.7
649H	106-649H-1D	18	0600	3521.8	3524.8	0.0–3.0	3.0	3.0	[a]0.06	[a]0.9
649I	106-649I-1D	18	0600	3521.8	3523.8	0.0–2.0	2.0	2.0		
649J	106-649J-1D	18	0600	3517.8	3519.3	0.0–1.5	1.5	1.5		

[a] Meters recovered and recovery percentage combined for Holes 649H through 649J. Core barrel was not retrieved between holes.

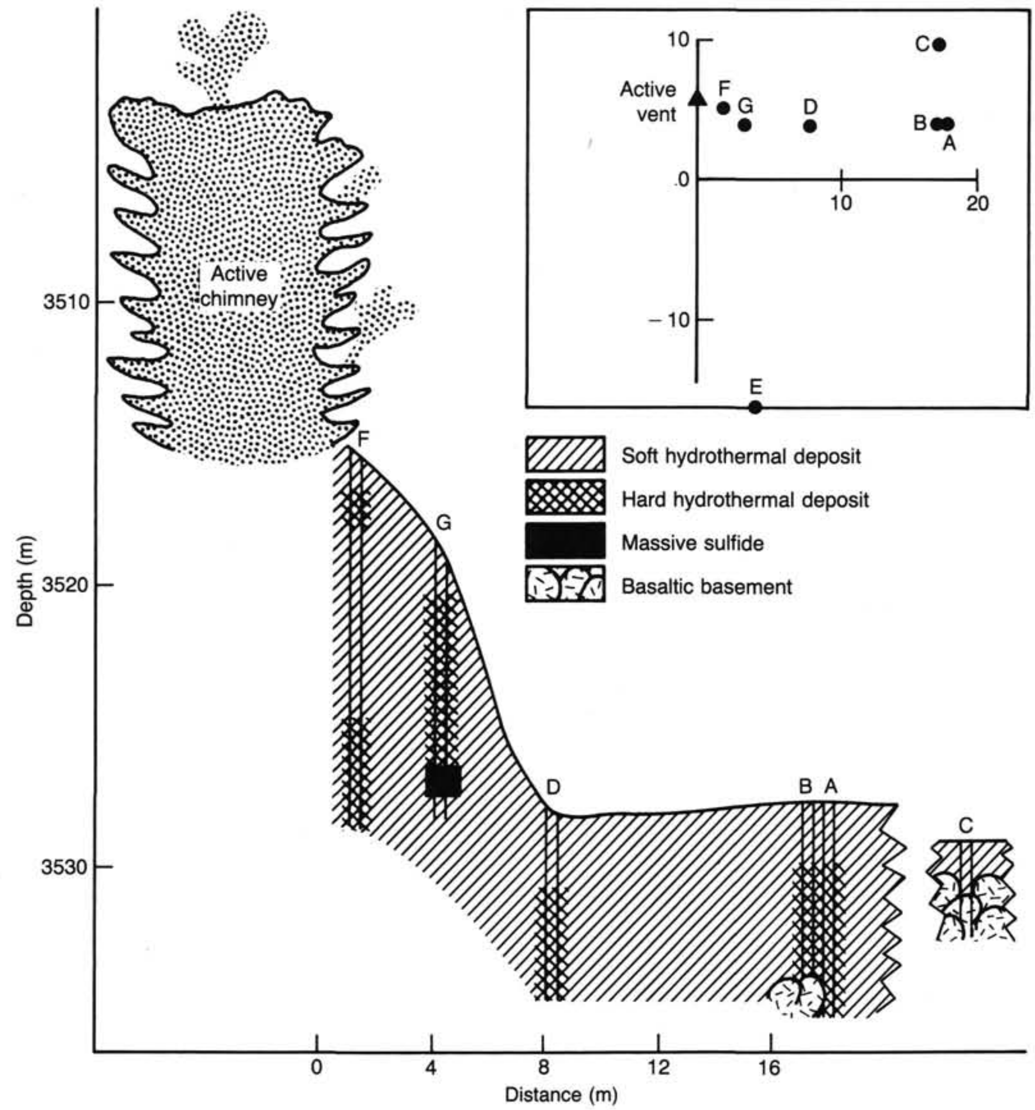


Figure 7. Location of Holes 649A through 649G shown in relation to active "black smoker."

resistance increased dramatically at about 6.0 mbsf, interpreted as being the start of basement (Fig. 8).

Basement rock was presumed to have been reached in Holes 649H through 649J, although no basalt or glass was recovered in the single core retrieved from these holes.

Hydrothermal Deposits

Figures 7 and 8 show the lithologies and the position of the holes drilled at this site in relation to a large, active "black smoker." Hole 649B, which yielded 6 m of core, although badly

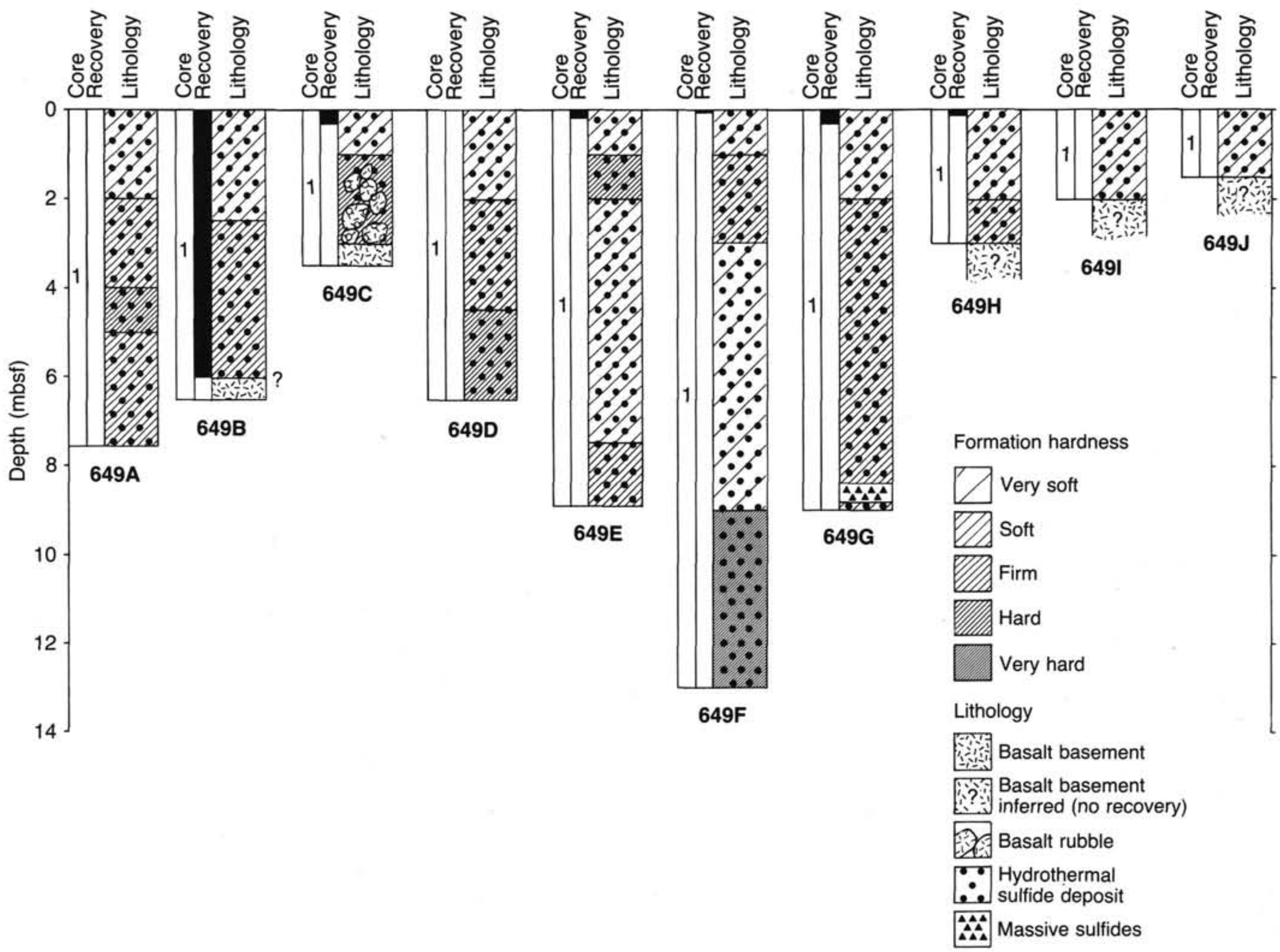


Figure 8. Site 649 lithostratigraphy. "Formation hardness" is a relative term based on the behavior of the drill string and on the length of time taken to drill sections of hole.

disturbed by drilling and subsequent removal from the core barrel, gives us an almost complete average section from seafloor to basement. The other holes offered only limited amounts of material (Table 2); it is unclear, except in Hole 649G, from which horizon the material was cored. Here, however, massive sulfides were recovered presumably from a very hard interval toward the bottom of the hole (Fig. 8).

Hole 649B yielded a section through a hydrothermal sulfide deposit composed of chalcopyrite, sphalerite, pyrite, pyrrhotite, and marcasite with small aggregates of talc. Grain size increases down the core from medium- to coarse-grained silt at the top to very coarse-grained and pebble-sized fragments at the bottom. Fragments are irregularly shaped and evidently represent chipped and broken cuttings from more competent horizons. These presumably correspond to the harder formation below about 2.5 mbsf (Fig. 8) recognized from drilling. Most of the material in the core is black in the hand specimen; only the large fragments are brassy yellow and can clearly be identified as chalcopyrite or pyrite. The talc is a pale gray green and forms small aggregates throughout the core. Material cored from the other holes is composed of the same black hydrothermal deposit, commonly in the form of a coarse-grained sand with small fragments of sulfides.

Hole 649G produced about 0.15 m of massive sulfides (chalcopyrite, sphalerite, and pyrite) showing evidence of having been drilled, fine-grained sand, and a grayish soft material thought to be talc. The talc stratigraphically underlies the massive sulfides. An extremely hard horizon was drilled at about 8.5 mbsf, which is thought to correspond to the massive sulfides. The first piece of the deposit recovered from this hole shows layering of well-crystallized sulfides with light-gray clays.

Discussion

Holes 649A through 649G lie along a rough transect from the edge of a hydrothermal mound to the base of an active "black-smoker" chimney (Fig. 7). Several of these holes were drilled only a few meters apart, and their variable resistance to drilling clearly demonstrates the heterogeneity in structure of the vent deposits. In all holes, the upper 1 to 2 m of the deposit is soft, allowing for easy penetration of the drill string. From the evidence gained at Hole 649B, this horizon would appear to comprise very fine-grained sulfides and some organic material. Resistance to drilling increased with depth, but by no means uniformly. In Holes 649A, 649E, and 649F, relatively soft horizons at depth are covered by a hard formation. Figure 8 shows only the major changes in "formation hardness"; thin softer and firmer horizons occur within each of the thicker layers shown. The increased massive sulfide component of the deposit evident toward the bottom of Hole 649B is clearly related to an increased resistance to drilling. Presumably, hard horizons in the other holes represent a higher proportion of massive sulfide forming the deposit but are probably not equivalent to the horizon from which came the large lumps of pure brassy yellow sulfide described from the bottom of Hole 649G. These hard horizons came from a section consisting of numerous thin lenses of well-crystallized sulfides, similar to the uppermost piece recovered from Hole 649G.

The lithology and distribution of the holes at this site allow us several conclusions about the structure of hydrothermal vents, including

1. The upper 1-2 m of the deposit is soft (and very fine grained).
2. The deposit is complexly layered, consisting of hard and soft horizons of varying thickness (lenses?); softer layers are composed of finer grained sulfides with clays; harder horizons are composed of more massive sulfides, which formed coarse-grained cuttings and pebble fragments during drilling.
3. The sulfides seem to become more common with depth.
4. The vents are both laterally and vertically highly heterogeneous in structure.
5. The hydrothermal deposit on the apron is >7.5 m thick (Hole 649A) and >13 m thick at the base of the chimney (Hole 649F).

PETROGRAPHY

Several glass shards having freshly broken conchoidal surfaces, varying in size from 1 to 7 mm, were found in the highly disturbed hydrothermal deposit of Core 106-649B-1D. These fragments are aphyric with a few small olivine phenocrysts, and typically contain 1%-5% vesicles; one sample is highly vesicular (about 20%). The vesicles are about 0.1 mm in diameter, round, and void.

Five fragments of basaltic rubble were recovered, mostly from the core catcher, in Core 106-649C-1D. Two samples have glassy margins. The basalts are all fine-grained (averaging <0.1 mm in grain size) and aphyric with some plagioclase phenocrysts. They appear fresh and have only trace amounts of yellow-green clays on clast surfaces.

Observations on thin sections of the two larger pieces from Core 106-649C-1D reveal variolitic groundmass textures indicating proximity to pillow margins. Sample 106-649C-1D-1, 2-4 cm, is mostly cryptocrystalline with 65% mesostasis. Groundmass plagioclase (about 20%) occurs as acicular crystals (some as large as 0.4 mm) in radiating sheaths with clinopyroxene (10%). Olivine (about 5%) forms equant, hopper, lantern-shaped, and acicular crystals, some being as large as 0.21 mm, typical of quench crystallization. Vesicles (about 1%) are round and void and range in size from 0.15 to 0.6 mm.

Sample 106-649C-1D-1, 9-11 cm, is microcrystalline with only 11% cryptocrystalline mesostasis, and the groundmass crystal morphologies and maximum crystal sizes are similar to the previous sample. Modal analysis of this sample indicates the following proportions: plagioclase—41%; clinopyroxene—40%; olivine—7%; vesicles—<1%; segregation vesicles—<1%; mesostasis—11%; and secondary minerals—<1%. Vesicles, ranging in size from 0.1 to 0.5 mm, are round and void, except the segregation vesicles, which are partly or completely filled with microcrystalline groundmass. Secondary minerals include trace amounts of reddish brown clays or iron hydroxides in the groundmass and in small fractures.

Site 649 basalts are distinct from those recovered at Site 648 in that very few phenocrysts occur and olivine (5%-7% compared with <2%) in the groundmass is more abundant, which suggests that the Site 649 basalts are more primitive. In addition, olivine having distinct quench crystal morphologies appears to have been the first phase to nucleate in the basalts from Site 649, which indicates that the chemical composition of these lavas falls well within the liquidus field of olivine.

Chemical analysis of a sample of basalt recovered from Hole 649C is presented in Table 3. This sample is more primitive (higher MgO content) than those recovered from Site 648 and is most similar to a group of aphyric basalts recovered from Hole 396B (Dungan et al., 1978). Highly unfractionated basalts with 9%-10% MgO have also been reported in dredge hauls from this region (Bryan et al., 1981).

MINERALOGY

Sulfide phases are by far the most abundant phases in all the cores recovered.

Chimney material is not competent and was easily broken by the drill string. A sample from the active vent was fortuitously recovered by the camera frame during the survey; however, it might not be representative of the whole edifice.

Hole 649B produced 6 m of cuttings from a soft hydrothermal deposit. The cutting size varies from a fine sand to angular fragments as long as a few centimeters. The coarsest fragments are concentrated in the bottom of Section 106-649B-1D-8, and the finest on top in Section 106-649B-1D-1 of the core, but the original stratigraphy may have been disturbed during drilling and during the process of extracting the core out of the liner. Sulfides (mostly chalcopyrite, sphalerite, and pyrite) predominate; small aggregates of soft talc and unidentified material mixed with sulfides are scattered in the whole core, as well as are a few oxidized reddish crust fragments. Organic debris (tubes, crustacean legs, or antennas?) and fresh basaltic glass shards also occur.

Hole 649E yielded 4 cm^3 of material similar to that in Hole 649B.

At Hole 649F, only some sulfide sand and a soft grayish chloritic mineral were extracted from the core cutter and the core catcher.

Massive sulfides (chalcopyrite, sphalerite, and pyrite) were recovered in Hole 649G along with grayish soft material (talc) mixed with sulfides and fine-grained sand.

Table 3. Site 649 whole-rock analysis.

Sample 106-649C-1D-1, 2-4 cm	
Analyst	WHOI
SiO_2	49.70
TiO_2	1.43
Al_2O_3	15.89
Fe_2O_3	9.98
MnO	0.16
MgO	8.42
CaO	11.24
Na_2O	2.61
K_2O	0.11
P_2O_5	0.17
Total	99.67
Loss on ignition	0.11
Mg value	0.650
Rb	2.0
Sr	150
Y	33
Zr	107
Nb	3.4
Ni	142
Cr	288
V	254
Zn	79
Co	44
Cu	88

Holes 649H, 649I, and 649J produced only sandy material with small chunks of sulfides in the core catcher.

Mineral Identification

Five sulfide species were identified on board the ship: chalcopyrite, sphalerite, pyrite, pyrrhotite, and marcasite. The presence of wurtzite, which has major X-ray-diffraction (XRD) peaks similar to sphalerite, could not be ruled out. The relative abundances (estimated from the XRD peak surfaces) vary among the different locations (Table 4).

The XRD pattern of the material recovered from the active vent (on the camera frame) shows sphalerite, pyrite, and, to a lesser extent, pyrrhotite as predominant phases and only traces of chalcopyrite and marcasite (Fig. 9).

Observations of polished sections and XRD patterns on powdered mixtures show that the mineralogy is fairly constant in Hole 649B: ISS (intermediate solid solution in the copper-iron-sulfide system, also known as isocubanite, or chalcopyrrhotite) and chalcopyrite, pyrite and marcasite, sphalerite, and pyrrhotite in decreasing order of abundance. X-ray-diffraction patterns for ISS and chalcopyrite cannot be differentiated on the bulk sample X-ray diagrams obtained on board, which also show sphalerite, pyrite, and marcasite (Fig. 10). Pyrrhotite does not show because it is probably not abundant enough. However, it predominates in X-ray diagrams of magnetically separated powders (Fig. 11), accompanied by minor amounts of chalcopyrite and sphalerite (see Appendix, this chapter, for separation procedures). Pyrrhotite is known as a magnetic sulfide, but it is somewhat surprising that sphalerite and chalcopyrite should be extracted magnetically because they are not ferrimagnetic. Chalcopyrite and sphalerite are sometimes intergrown with pyrrhotite and thus are present in the magnetic separate. This sphalerite, however, contains an appreciable amount of iron (up to about 20 atomic %) that could possibly give the mineral ferrimagnetic properties.

Onshore scanning electron microscope (SEM) photographs and microprobe data also indicate the presence of opal as small balls, a few micrometers in diameter, perched on the sulfide grains.

The sandy fraction from Hole 649F consists of chalcopyrite and minor amounts of sphalerite and pyrite.

In Hole 649G, the massive sulfide is composed essentially of ISS and chalcopyrite and minor amounts of sphalerite and pyrite (Fig. 12). Observation of polished sections shows that pyrrhotite also occurs as a minor phase, explaining why the sample is magnetic. An independent way to check the existence of pyrrhotite is to determine the thermomagnetic curve. This curve, measured for a small piece of the massive sulfide (Fig. 13), shows the typical shape for pyrrhotite at a Curie temperature of approximately 310°C. At higher temperatures, the material transforms into magnetite. The sandy fraction is similar to the bulk samples from Hole 648B.

Hole 649H is characterized by the presence of pyrrhotite in the two samples analyzed. The sulfide fragment consists of dominant amounts of sphalerite, pyrrhotite, and minor amounts of chalcopyrite (Fig. 14). In the sandy fraction, pyrrhotite and chalcopyrite predominate; minor amounts of sphalerite and pyrite and very little marcasite occur.

Three samples of soft material were also studied by XRD and found to be always more or less mixed with sulfides. The soft material from both Holes 649B (Fig. 15) and 649G (Fig. 16) is talc. Talc is also known to occur in the hydrothermal chimneys of the Guaymas Basin (Lonsdale et al., 1980). The soft material from Hole 649F is most likely chlorite although, being extremely soft and grayish, it does not look like chlorite in the hand specimen. Its XRD diagram is typical of chlorites because it does not expand during glycolation (Fig. 17). No smectites were found.

Some of the XRD diagrams also display unidentified peaks. Additional mineral species (sulfates?) may therefore also occur;

Table 4. Minerals identified by X-ray diffraction.

		Minerals identified							No.
Core/section/sample	Type	ch	sp	py	mc	pyrr	tc	chl	u.p.
Survey camera frame	Coarse sand	tr	4	4	tr	3			1
109-649B-1D-1, 35-36 cm	Scoop sample	4	3	2	1				2
109-649B-1D-1, 114-115 cm	Scoop sample	4	3	2	1				2
109-649B-1D-2, 75-76 cm	Scoop sample	4	3	2	1				2
109-649B-1D-3, 14-15 cm	Scoop sample	4	3	2	1				2
109-649B-1D-3, 109-110 cm	Scoop sample	4	3	2	1				2
109-649B-1D-4, 19-20 cm	Scoop sample	4	3	2	1				2
109-649B-1D-4, 104-105 cm	Scoop sample	4	3	2	1				3
109-649B-1D-5, 19-20 cm	Scoop sample	4	3	2	1				2
109-649B-1D-5, 104-105 cm	Scoop sample	4	3	2	1				2
109-649B-1D-6, 19-20 cm	Scoop sample	4	3	2	1				2
109-649B-1D-6, 104-105 cm	Scoop sample	4	3	2	1				2
109-649B-1D-7, 19-20 cm	Scoop sample	4	3	2	1				2
109-649B-1D-7, 104-105 cm	Scoop sample	4	3	2	1				2
109-649B-1D-8	Soft + sulfide mix.	4	2	2	1		3		5
CC	Fine-grained sand	4	3	2	1				2
Filter	Magn. separate	3	3		tr	4			2
Filter	Magn. separate + 2N HCl	3	3		tr	4			2
109-649F CC	Soft							4	
109-649F CC	Sand	4	2	2				1	
109-649G-1D-1	Sand	4	3	2	1				
109-649G-1D-1	Soft	4					3		3
109-649G-1D-1, 26-27 cm	Massive sulfide	4	2	2					
109-649H-1D-1	Sulfide fragment	1	4			2			
109-649H-1D-1	Sand	4	2	2	1	4			3

Note: ch = chalcopyrite; sp = sphalerite; py = pyrite; mc = marcasite; pyrr = pyrrhotite; tc = talc; chl = chlorite. No. u.p. = number of unidentified peaks. 4 to 1 = decreasing relative intensity of the peaks; tr = trace.

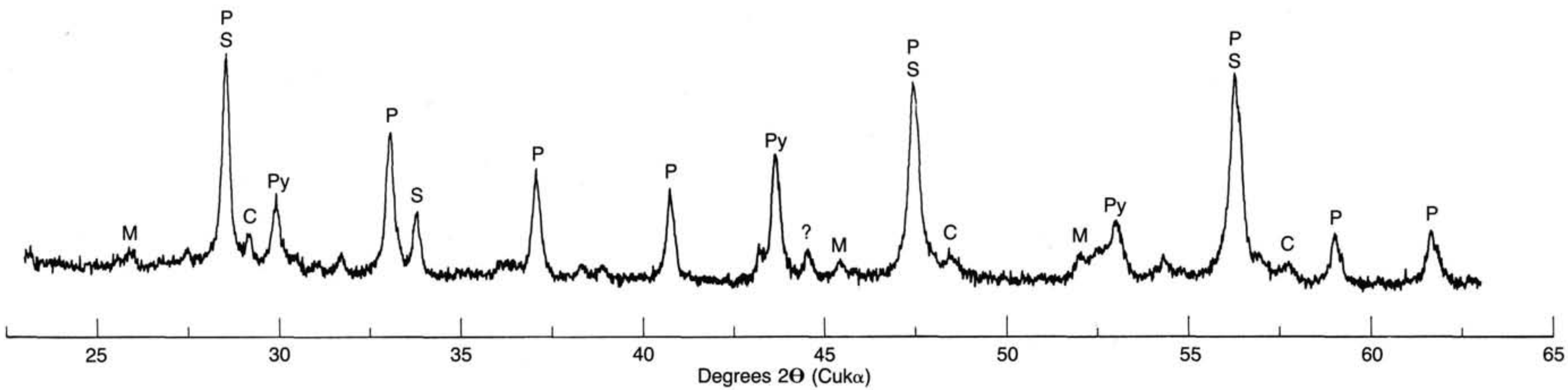


Figure 9. X-ray-diffraction pattern of the active vent sample (captured in camera frame). C = chalcopyrite; S = sphalerite; P = pyrite; Py = pyrrhotite; M = marcasite; ? = unidentified peak.

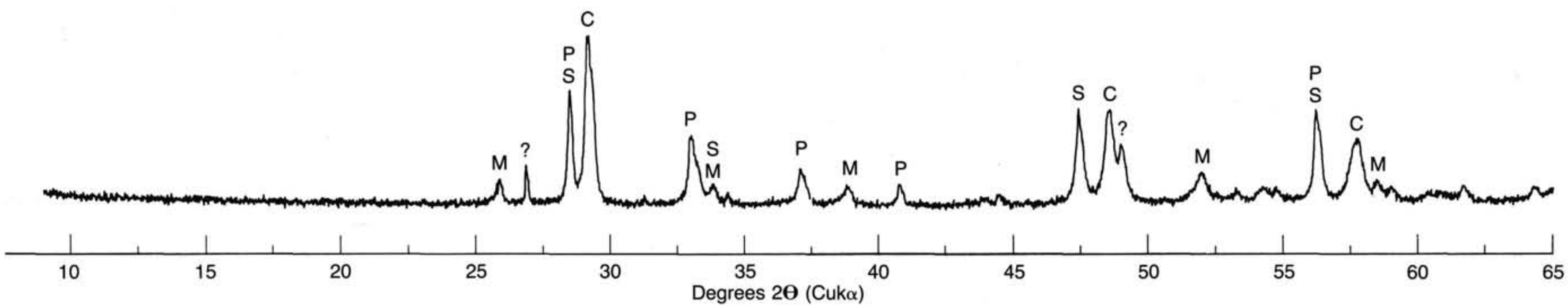


Figure 10. X-ray-diffraction pattern of a sample of hydrothermal deposit scooped from Hole 649B (Sample 106-649B-1D-4, 105–106 cm). C = chalcopyrite; S = sphalerite; P = pyrite; M = marcasite; ? = unidentified peak.

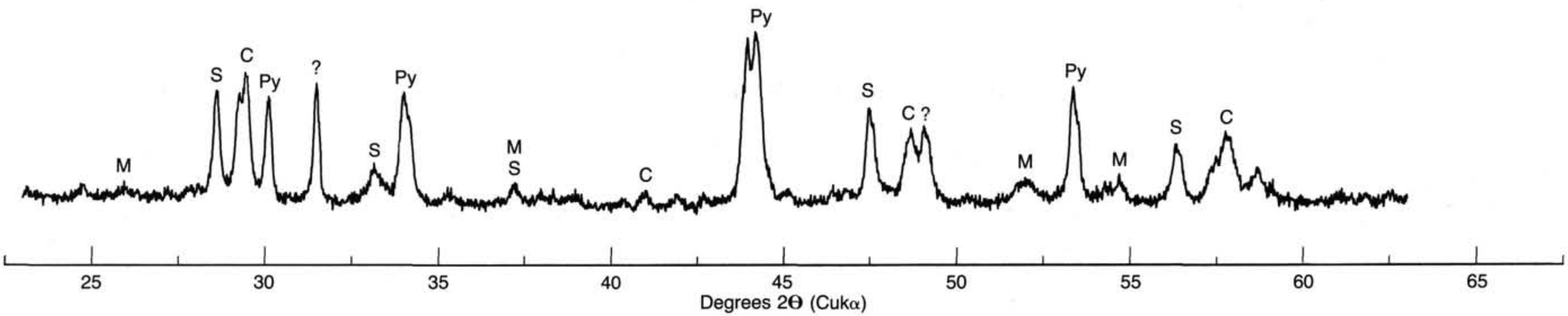


Figure 11. X-ray-diffraction pattern of a magnetically separated sample from Hole 649B (see Appendix, this chapter), treated for 5 min with 2N HCL. C = chalcopyrite; S = sphalerite; Py = pyrrhotite; M = marcasite; ? = unidentified peak.

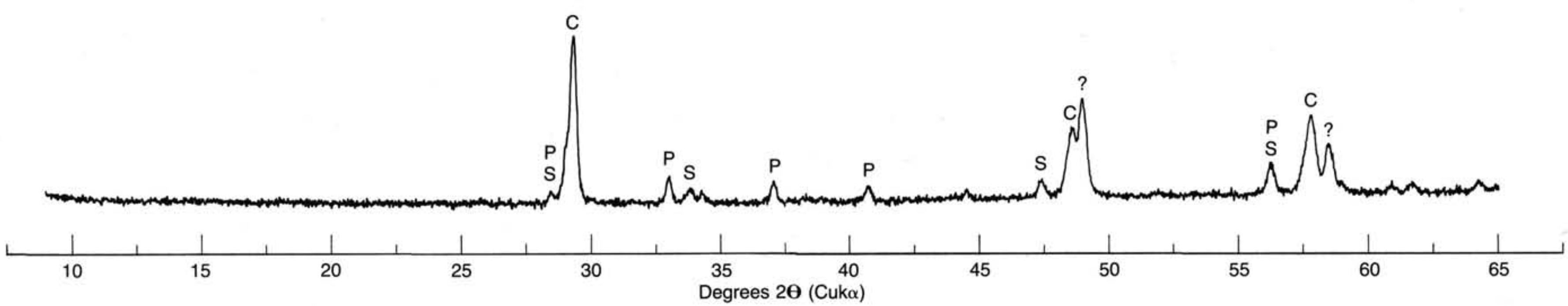


Figure 12. X-ray-diffraction pattern of the massive sulfide from Hole 649G (Sample 106-649G-1D-1, 26–28 cm). C = chalcopyrite; P = pyrite; S = sphalerite; ? = unidentified peak.

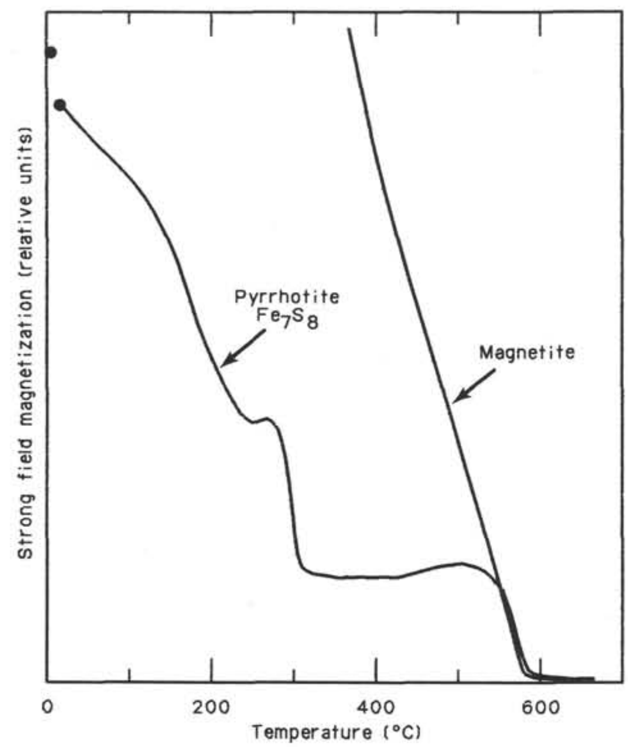


Figure 13. Thermomagnetic curve of Sample 106-649G-1D-1. Applied magnetic field H = 1.750 Oe. Measurement was carried out in air.

however, we checked that quartz, anhydrite, magnetite, bornite, galena, and so forth, were not present.

Crystal Morphology

The sulfide grains from the sands are always euhedral and display beautiful crystallizations. Different morphologies were observed with an SEM.

The magnetic separates show essentially two different shapes: (1) platelets with hexagonal outlines, identified as pyrrhotite (Figs. 18 and 19) and (2) cuboctahedra, identified as sphalerite (Fig. 18). Small balls of opal may occur between the sulfide grains (Fig. 18).

Conclusions

The Snake Pit hydrothermal deposit is essentially made up of copper, zinc, and iron sulfides. As a whole, on the basis of peak intensity, the chalcopyrite (and ISS) phase seems to be the most abundant phase; sphalerite, pyrite, marcasite, and pyrrhotite are less abundant. The associated silicates are opal, talc, and chlorite. Pyrrhotite is abundant only in the sample from the active chimney and in Hole 649H. The nature of the major sulfide phases is the same as in the high-temperature East Pacific Rise sulfide deposits, except in galena, sulfosalts, and wurtzite phases (described as being in some of the East Pacific Rise chimneys), the presence of which cannot be established (or ruled out). This deposit differs from the Mid-Atlantic Ridge disseminated deposit (described by Bonatti et al., 1976), where only chalcopyrite, pyrite, and pyrrhotite are present, but no ISS or sphalerite were identified. Haymon and Kastner (1981) suggested that rapid precipitation at the vents leads to metastable formation of pyrrhotite (and wurtzite) in "black-smoker" deposits at 21°N at the East Pacific Rise. Pyrrhotite would subsequently be replaced by pyrite at lower temperatures. Pyrrhotite does not exist in older deposits, such as the stockworklike sulfide mineralization occurring in Hole 504B, either because it has been completely replaced or because excessively high sulfur fugacity prevented its formation (Honnorez et al., 1984). The fact that pyrrhotite is replaced by pyrite at lower temperatures could explain why it is more abundant in the active chimney (sample on the camera frame); pyrrhotite could be subsequently replaced in the deposit forming the debris apron at the foot of the chimney. The presence of talc and chlorite rather than smectites indicates relatively high temperatures (above 250° C).

SUMMARY AND CONCLUSIONS

Site 649 is in the Mid-Atlantic Ridge rift valley about 25 km south of the Kane Fracture Zone on the crest of a northeast-trending ridge in the northern part of the rift valley. Beacon 3 was deployed in this area in May 1985 during the precruise SeaMARC I site survey. Photographs of the bottom taken during the site survey reveal the presence of greenish-white, mottled hydrothermal-looking sediment, crustaceans, and wormlike benthic organisms characteristic of hydrothermal vents. This discovery was the first convincing evidence of an active hydrothermal area on the slow-spreading Mid-Atlantic Ridge. Because of the amount of time available, the objectives at Site 649 were limited to (1) surveying the area to locate active vents and (2) drilling several unsupported, "bare-rock" holes using the Navidrill coring motors to sample a cross section of the hydrothermal deposits in the area and the underlying basement rocks.

On arriving at Site 649, we made a 36-hr survey of the area east and south of the beacon, using the television-sonar system and the high-resolution Mesotech color-imaging sonar to construct a geological map of the hydrothermal area. The combination of both these instruments with the drill ship's dynamic-positioning system gave us an invaluable and versatile tool for real-time observation of the hydrothermal activity, for drill site selection, and for monitoring seafloor drilling operations. We are completely convinced that this novel technique will add an unprecedented dimension to deep-sea drilling.

A major active hydrothermal field, called the Snake Pit hydrothemal area, was discovered about 140 m southeast of beacon site 3 near 23°22.08′N and 44°57.00′W. The vent field is on the western half of a small terrace near the crest of the median valley ridge. It is bordered on the east by a large northeast-trending fissure and on the west by two narrow ridges that form the summit of the ridge. The vent field covers at least 40,000 m^2 and consists of numerous, apparently inactive, decorated chimneys, one large "black-smoker" vent and two other large chimneys, which are probably active. The chimneys are as high as 11 m and are several meters in diameter. A thick apron of chimney debris generally surrounds their base, and similar debris is strewn over large areas of the field. When observed with the television camera, these hydrothermal deposits could easily be mistaken for lightly sedimented basaltic rubble. This is only the second time that "black smokers" have been reported from the Mid-Atlantic Ridge (they were found in the Trans-Atlantic Geotraverse area in the summer of 1985), and the first time that an Atlantic vent area has been surveyed in detail and monitored in real time.

The vent field is associated with a diversified biological community that is surprisingly different from that observed in the Pacific. No clams, mussels, or large sessile tube worms were observed near the vents. The most common forms of life are large swimming crustaceans, small shrimplike organisms (*Rimicaris oxoculata* and *R. chacri*), and long (about 30–60 cm) flat snakelike swimmers (possibly eels or worms) that give the area its name, the Snake Pit. The small shrimp appear to congregate on rock surfaces near the vent orifices, whereas sea anemones litter the seafloor around the vents. In general, the community appears to consist of smaller, more mobile organisms than those

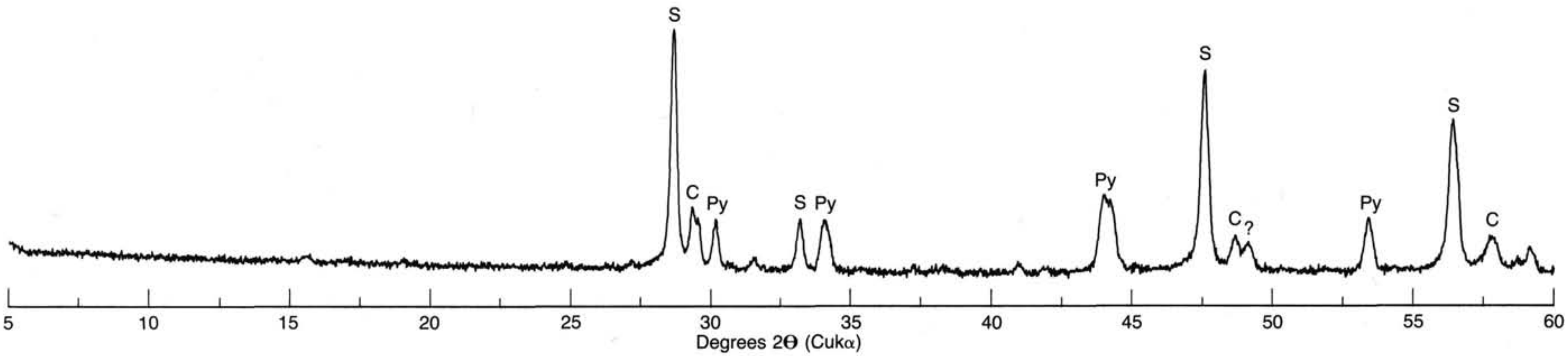


Figure 14. X-ray-diffraction pattern of a chunk of sulfide from Holes 649H, 649I, and 649J. C = chalcopyrite; Py = pyrrhotite; S = sphalerite; ? = unidentified peak.

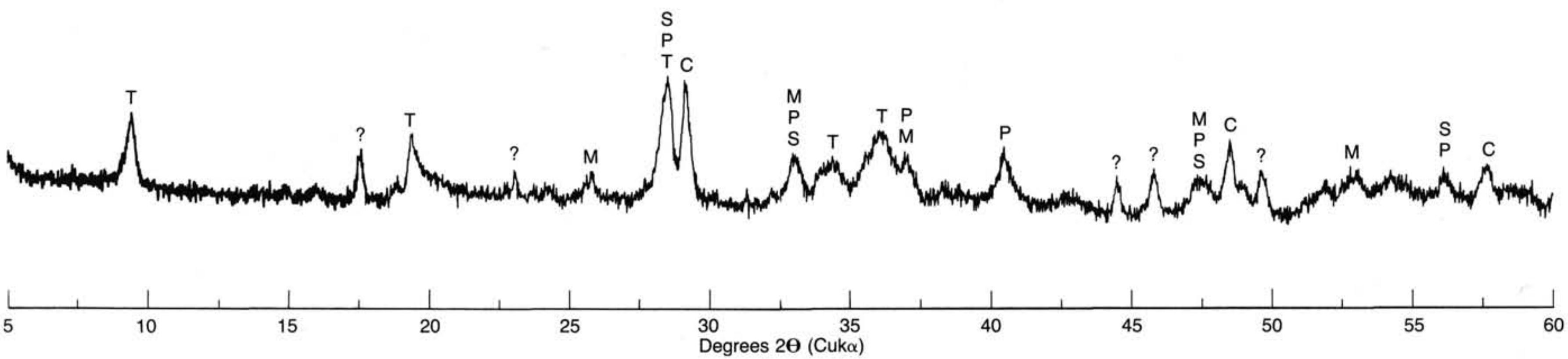


Figure 15. X-ray-diffraction pattern of a soft grayish material and sulfide mixture from Hole 649B (Section 106-649B-1D-8). T = talc; M = marcasite; P = pyrite; C = chalcopyrite; S = sphalerite; ? = unidentified peak.

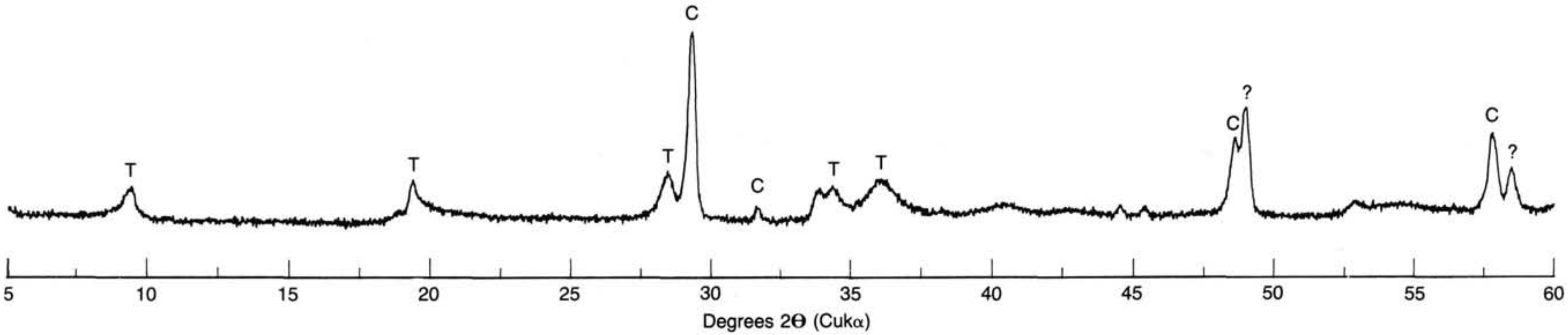


Figure 16. X-ray-diffraction pattern of a soft grayish material and sulfide mixture from Hole 649G (Section 106-649G-1D-1). T = talc; C = chalcopyrite; ? = unidentified peak.

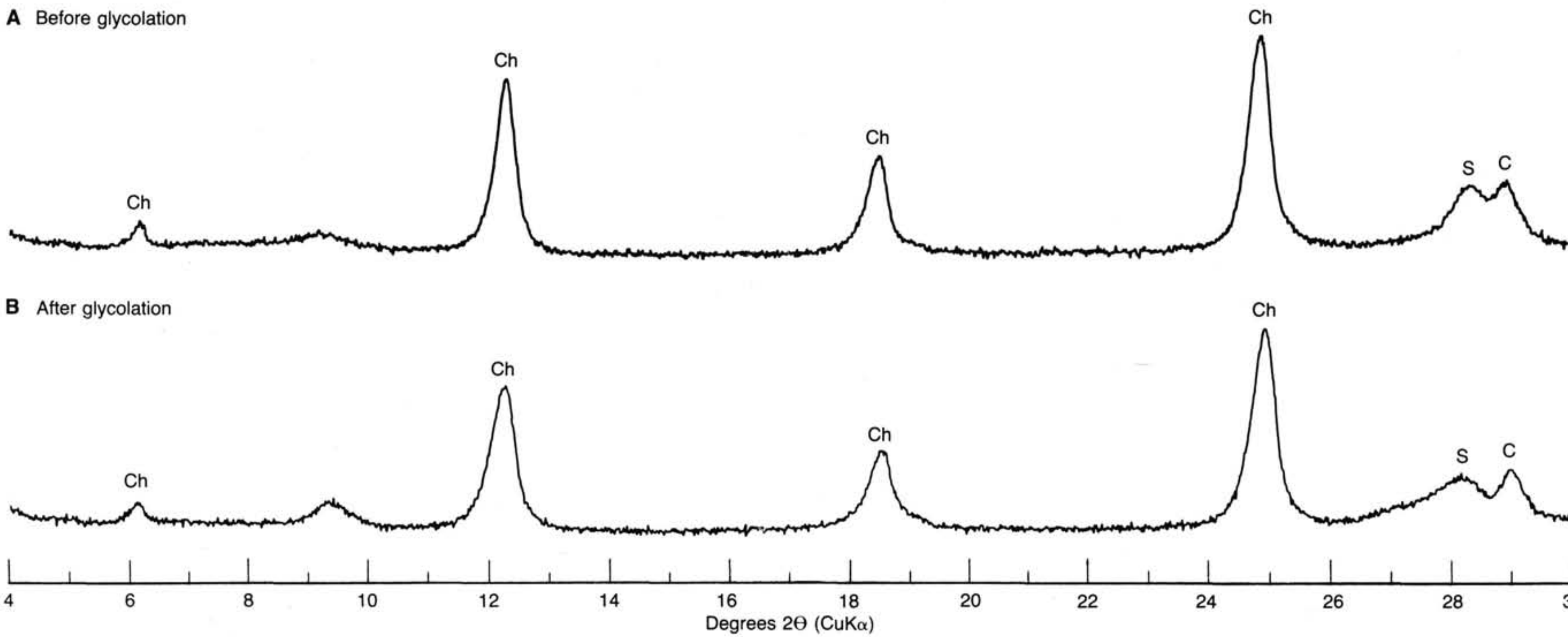


Figure 17. X-ray-diffraction pattern of a soft grayish material from Hole 649H. A. No glycol. B. After glycolation. Ch = chlorite; S = sphalerite; C = chalcopyrite.

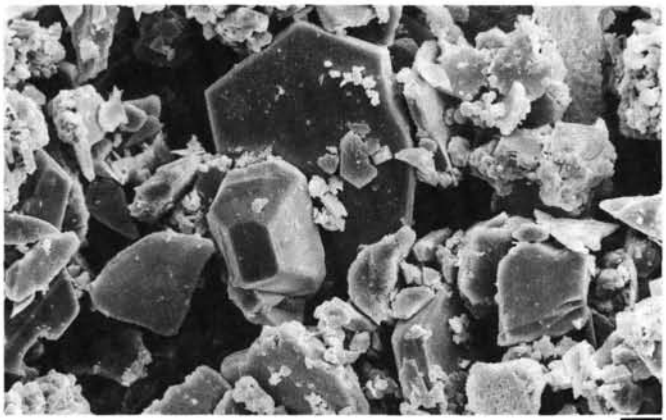


Figure 18. Scanning electron microscope photographs of the magnetic separate from Hole 649B. Pyrrhotite, sphalerite (center), and small balls of opal between the sulfide grains. (Photograph by H. Vali, Lehrstuhl für Mineralogie, Technical University, Munich.)

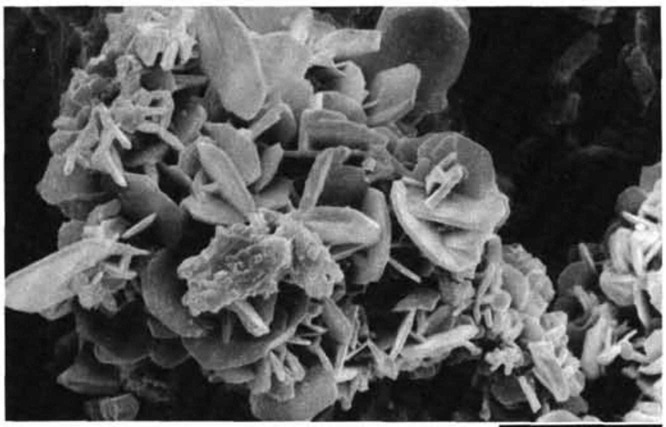


Figure 19. Scanning electron microscope photograph of the magnetic separate from Hole 649B. Pyrrhotite platelets.

previously found at submarine hydrothermal vents in the Pacific.

Ten shallow holes were drilled in the vent area at Site 649 to sample the hydrothermal sediments and the underlying basement rocks. These are the first holes ever drilled in an active submarine hydrothermal area. Holes 649F, 649G, 649D, 649A, and 649B were drilled at increasing distances away from the large active "black smoker." Hole 649F is at the foot of the active vent, whereas Holes 649G and 649D, Holes 649A and 649B, and Hole 649C are 3, 10, and 17 m, respectively, east of it. Hole 649C is located close to a small inactive chimney. Hole 649E was drilled 20 m south of the "black smoker," and Holes 649H, 649I, and 649J were spudded about 65-80 m west of this vent. The thickness of the hydrothermal deposits appear to rapidly decrease with distance from the active chimney: they thicken to at least 13 m at the base of the chimney (no hard formation was encountered in Hole 649F), and thin to 3-6 m or less about 17 m away. Subaerial equivalents of these deposits are known for their variability in thickness and mineralogy. As a rule, the uppermost part of the Snake Pit hydrothermal deposit consists of a layer a few meters thick, which is soft and was unsampled because the drill string always washed through this interval. The rest of the section is made up of alternating soft and firmer formations composed of various proportions of fine-grained iron, copper, and zinc sulfides (pyrite, pyrrhotite, marcasite, chalcopyrite, ISS, and sphalerite) associated with a clayey (talc or chlorite and possibly sulfate) matrix having lenses of massive sulfides (pyrite, pyrrhotite, ISS, and chalcopyrite). Opal was the last phase to crystallize.

All the basaltic lava and glass samples recovered from Site 649 are essentially fresh, indicating that the hydrothermal solutions did not affect the basement rocks beneath the sulfide deposit. The basalt is aphyric with some olivine or plagioclase phenocrysts, and typically contains 1%-5% vesicules, even though one sample exhibited a 20% vesicularity. The presence of glassy margins and shards indicates that the samples were recovered from pillow lavas. Site 649 basalts are different from those of Site 648 in that they have many fewer phenocrysts, contain more olivine, and are more primitive (higher MgO content). This observation is consistent with the occurrence in a nearby dredged area of unfractionated basalts containing 9%-10% MgO, similar to aphyric basalts recovered from DSDP Site 396.

APPENDIX

Magnetic Minerals Separation Procedure

Brownish mud, the fine-grained fraction of the unconsolidated hydrothermal deposit recovered from Hole 649B, was investigated for the presence of magnetic minerals. For this purpose, the magnetic fraction was separated with a permanent magnet.

First, the mud was diluted with distilled water and brought into suspension. Extraction was then conducted with a strong permanent magnet that was shaped in a way to produce a high magnetic field gradient combined with relatively low field intensity. This configuration attracted predominantly ferrimagnetic minerals and left behind any paramagnetic components.

The extraction system consists of a disk of samarium cobalt permanent magnet attached to a soft iron cone. Its fingerlike elongation is covered with a teflon tube, which can be slid off for harvesting of the magnetic separate. The magnetic field at the fingertip is about 1 kOe, the field gradient being about 200 Oe/mm.

The extracted material was divided into two parts. One was treated no further; the other was treated with 2N HCl for 5 min.

REFERENCES

Anderson, R. N., Langseth, M. G., and Sclater, J. G., 1977. The mechanisms of heat transfer through the floor of the Indian Ocean. *J. Geophys. Res.*, 82:3391-3409.

Bonatti, E., and Joensuu, O., 1966. Deep sea iron deposits from the South Pacific. *Science*, 154:643-645.

Bonatti, E., Honnorez, J., Kirst, P., and Radicati, F., 1975. Metagabbros from the Mid-Atlantic Ridge at 6°N: contact-hydrothermal-dynamic metamorphism beneath the axial valley. *Mar. Geol.*, 83:61-78.

Bonatti, E., Honnorez, J., Honnorez-Guerstein, B-M., and Stern, C., 1976a. Hydrothermal pyrite concretions from the Romanche Trench (equatorial Atlantic): metallogenesis in oceanic fracture zones. *Earth Planet. Sci. Lett.*, 32:1-10.

Bonatti, E., Honnorez-Guerstein, B-M., and Honnorez, J., 1976b. Copper-iron sulfide mineralizations from the equatorial Mid-Atlantic Ridge. *Econ. Geol.*, 71:1515-1525.

Bonatti E., Honnorez, B-M., and Honnorez, J., 1976. Copper iron sulfide mineralizations from the Equatorial Mid-Atlantic Ridge. *Econ. Geol.*, 71:1515-1525.

Bostrom, K., and Peterson, M.N.A., 1966. Precipitates from hydrothermal exhalations on the East Pacific Rise. *Econ. Geol.*, 61:1258-1265.

Bryan, W. B., Thompson, G., and Ludden, J. N., 1981. Compositional variation in normal MORB from 22°-25°N: Mid-Atlantic Ridge and Kane Fracture Zone. *J. Geophys. Res.*, 86:11815-11836.

Cann, J. R., 1969. Spilites from the Carlsberg Ridge, Indian Ocean. *J. Petrol.*, 10:1–19.

Corliss, J. B., Dymond, J., Gordon, L. I., Edmond, J. M., Von Herzen, R. P., Ballard, R. D., Green, K., Williams, D., Bainbridge, A., Crane, K., and van Andel, T. H., 1979. Submarine thermal springs on the Galapagos Rift. *Science*, 203:1073–1083.

Detrick, R. S., Ryan, W.B.F., Mayer, L., Fox, P. J., Kong, L., Manchester, K., Kastens, K., Karson, J., and Pockalny, R., 1985. Mid-Atlantic Ridge/Kane Fracture Zone final site survey report. Prepared for *Joint Oceanographic Institutions*.

Dungan, M. A., Rhodes, J. M., Long, P. E., Blanchard, D. P., Brannon, J. C., and Rodgers, K. V., 1978. The petrology and geochemistry of basalts from Site 396, Legs 45 and 46 of the Deep Sea Drilling Project. *In* Dmitriev, L., Heirtzler, J., et al., *Init. Repts. DSDP*, 46: Washington (U.S. Govt. Printing Office), 89–113.

Elder, J. W., 1965. Physical processes in geothermal areas. In *Terrestrial Heat Flow*. Am. Geophys. Union Monogr., 8:211–239.

Fehn, U., Siegel, M. D., Robinson, G. R., Holland, H. D., Williams, D. L., Erickson, A. J., and Green, K. E., 1977. Deep-water temperatures in the FAMOUS area. *Geol. Soc. Am. Bull.*, 88:488–494.

Finkel, R. C., MacDougall, J. D., and Chung, Y. C., 1980. Sulfide precipitates at 21°N on the East Pacific Rise: ^{226}Ra, ^{210}Pb, and ^{210}Po. *Geophys. Res. Lett.*, 7:685–688.

Francheteau, J., and Ballard, R. D., 1983. The East Pacific Rise near 20°N, 13°N, and 20°S: inferences for along-strike variability of axial processes of the mid-ocean ridge. *Earth Planet. Sci Lett.*, 64:93–116.

Haymon, R., and Kastner, M., 1981. Hot springs deposits on the East Pacific Rise at 21°N: preliminary description and genesis. *Earth Planet. Sci. Lett.*, 53:363–381.

Hoffert, M., Perseil, A., Hepinian, R., Choukroune, P., Needham, H. D., Francheteau, J., and Le Pichon, X., 1978. Hydrothermal deposits sampled by diving saucer in Transform fault "A" near 37°N on the Mid-Atlantic Ridge, FAMOUS area. *Oceanol. Acta*, 1:73–86.

Honnorez, J., Alt, J. C., Honnorez-Guerstein, B-M., Laverne, C., Muehlenbachs, K., Ruiz, J., and Saltzman, E., 1984. Stockwork-like sulfide mineralization in young oceanic crust: DSDP Hole 504B. *In* Anderson, R. N., Honnorez, J., Becker, K., et al., *Init. Repts. DSDP*, 83: Washington (U.S. Govt. Printing Office), 263–282.

Humphris, S. E., and Thompson, G., 1978. Hydrothermal alteration of oceanic basalts by seawater. *Geochim. Cosmochim. Acta*, 42:107–126.

Jannasch, H., and Wirsen, C. O., 1979. Chemosynthetic primary production of East Pacific sea floor spreading centers. *Bioscience*, 29: 592–598.

Kong, L., Ryan, W.B.F., Mayer, L., Detrick, R., Fox, P. J., and Manchester, K., 1985. Bare-rock drill sites, ODP Legs 106 and 109: evidence for hydrothermal activity at 23°N in the Mid-Atlantic Ridge. *Eos*, 66:936.

Lister, C.R.B., 1972. On the thermal balance of a mid-ocean ridge. *Geophys. J. R. Astr. Soc.*, 26:515–535.

Lonsdale, P., 1977. Clustering of suspension-feeding macrobenthos near abyssal hydrothermal vents at oceanic spreading centers. *Deep Sea Res.*, 24:852–863.

Lonsdale, P., Bischoff, J. L., Burns, V. M., Kastner, M., and Sweeney, B. E., 1980. A high-temperature hydrothermal deposit on the seabed at a Gulf of California spreading center. *Earth Planet. Sci. Lett.*, 49: 8–20.

Malahoff, A., 1982. Massive enriched polymetallic sulfides of the ocean floor - a new commercial source of strategic minerals? *Proc. Off. Technol. Conf.*, Paper 4293.

Melson, W. G., and van Andel, Tj. H., 1966. Metamorphism in the Mid-Atlantic Ridge, 22°N latitude. *Mar. Geol.*, 4:165–186.

Normark, W. R., Morton, J. L., and Delaney, J. R., 1982. Geologic setting of massive sulfide deposits and hydrothermal vents along the southern Juan de Fuca Ridge. *U.S. Geol. Surv. Open-File Report* 82-200A.

Rona, P. A., 1980. TAG hydrothermal field: Mid-Atlantic Ridge Crest at latitude 26°N. *J. Geol. Soc. London*, 137:385–402.

———, 1985. Black smokers and massive sulfides at the TAG hydrothermal field, Mid-Atlantic Ridge, 26°N. *Eos*, 66:936.

Rona, P. A., Klinkhammer, G., Nelsen, T. A., Trefry, J. H., and Elderfield, H., 1986. Black smokers, massive sulfides, and vent biota at the Mid-Atlantic Ridge. *Nature*, 321:33–37.

Simoneit, B.R.T., and Lonsdale, P. F., 1982. Hydrothermal petroleum on mineralized mounds at the seabed of Guaymas Basin. *Nature*, 295:198–202.

Skornyakova, I. S., 1964. Dispersed iron and manganese in Pacific Ocean sediments. *Internat. Geol. Rev.*, 7:2167–2174.

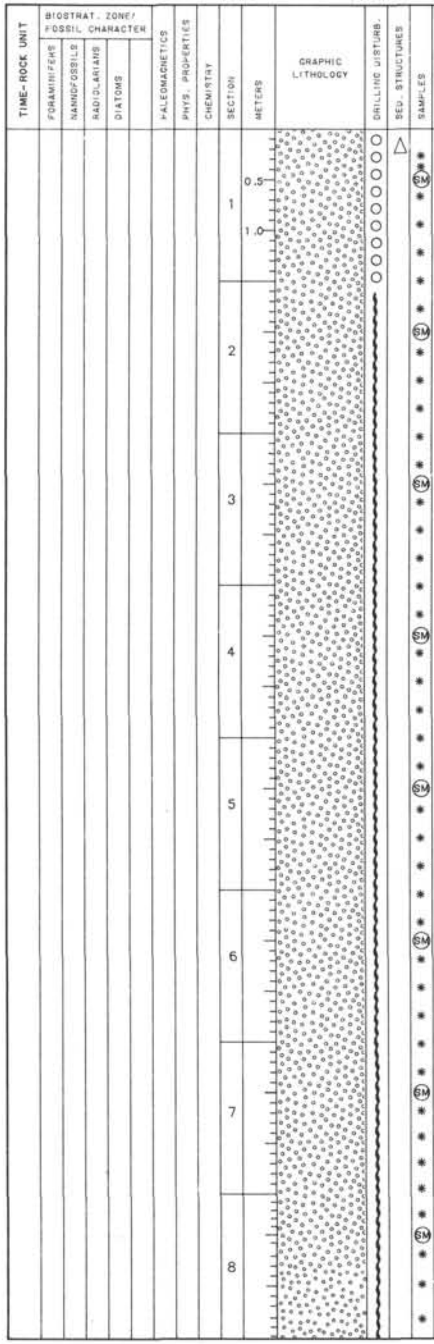
Spiess, F. N., Macdonald, K. C., Atwater, T., Ballard, R., Carranza, A., Cordoba, D., Cox, C., Diaz Garcia, V. M., Francheteau, J., Guerrero, J., Hawkins, J., Haymon, R., Hessler, R., Juteau, T., Kastner, M., Larson, R., Luyendyk, B., MacDougall, J. D., Miller, S., Normark, W., Orcutt, J., and Rangin, C., 1980. East Pacific Rise: hot springs and geophysical experiments. *Science*, 207:1421–1433.

Thompson, G., Mottl, M. J., and Rona, P. A., 1985. Morphology, mineralogy and chemistry of hydrothermal deposits from the TAG area, 26°N Mid-Atlantic Ridge. *Chem. Geol.*, 49:243–257.

Williams, D., and Von Herzen, R. P., 1974. Heat loss from the earth: new estimate. *Geology*, 2:327–328.

Williams, A. B., and Rona, P. A., 1986. Two new caridean shrimps (Bresiliidae) from a hydrothermal field on the Mid-Atlantic Ridge. *J. Crustacean Biol.*, 6:446–462.

SITE 649 HOLE B CORE 1 CORED INTERVAL 3528-3534.5 mbsl; 0-6.5 mbsf



LITHOLOGIC DESCRIPTION

HYDROTHERMAL DEPOSITS

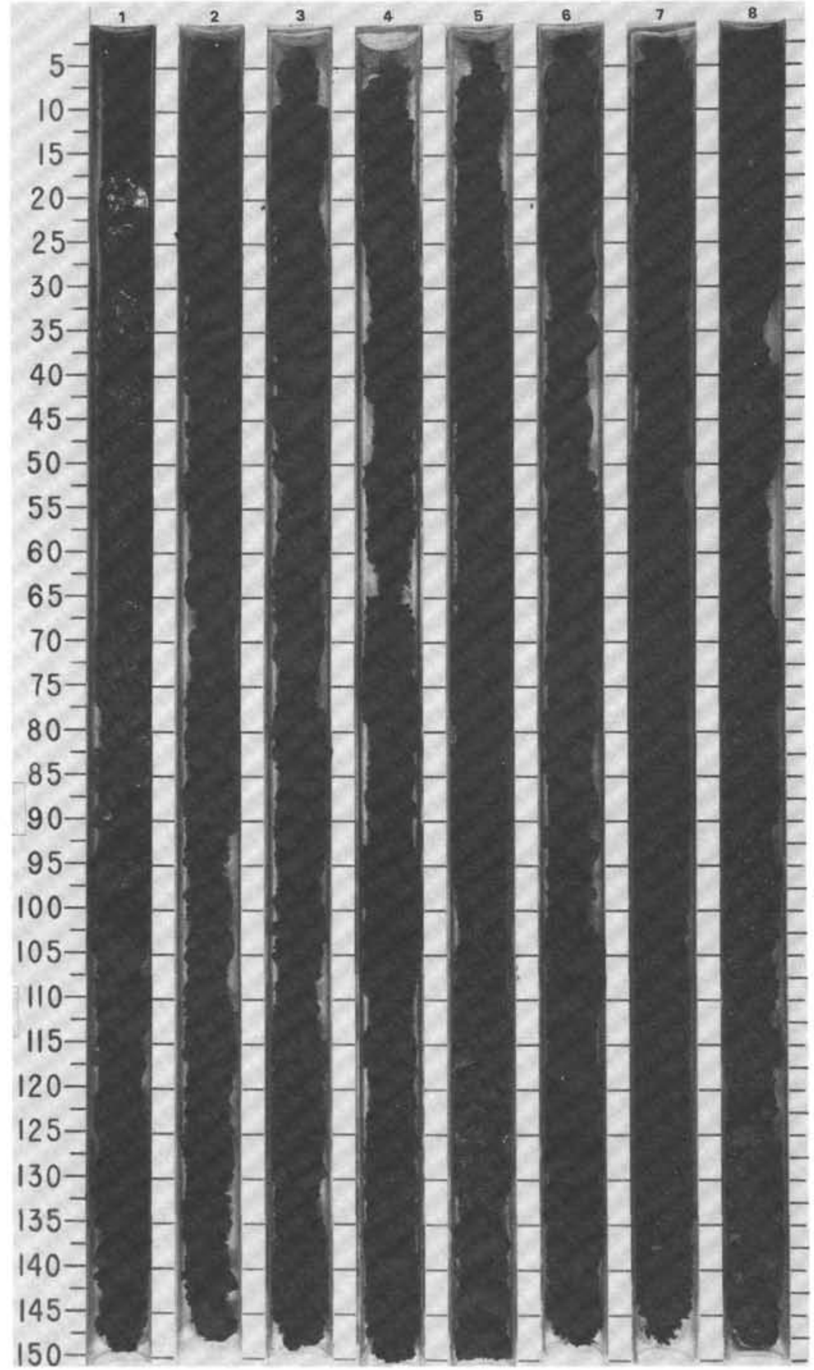
General description: Black hydrothermal deposits with abundant pyrite visible.
Components:

- Iron and manganese oxides
- Pyrite
- Pyrrhotite
- Sphalerite
- Chalcopyrite
- Possibly other sulfides
- ~1% clay, bluish gray
- <1% reddish brown oxides
- Tr organic material
- Tr basaltic glass

Grain size analysis: Grain size increases toward bottom of core.
Section 1: medium–coarse silt.
Section 2: very fine–very coarse sand.
Section 3: very fine–very coarse sand.
Section 4: very fine–very coarse sand.
Section 5: coarse sand–granular.
Section 6: coarse sand–granular.
Section 7: coarse sand–granular.
Section 8: very coarse sand–pebbles.

Note: pyrite increases in size toward the bottom of core.

Sampling: representative sample taken, 5 m smear slide taken for grain size analysis.



SITE 649 HOLE E CORE 1 CORED INTERVAL 3530.5-3539.4 mbsl; 0-8.9 mbsf

TIME-ROCK UNIT	BIOSTRAT. ZONE/ FOSSIL CHARACTER: FORAMINIFERS	NANNOFOSSILS	RADIOLARIANS	DIATOMS	PALEOMAGNETICS	PHYS. PROPERTIES	CHEMISTRY	SECTION	METERS	GRAPHIC LITHOLOGY	DRILLING DISTURB.	SED. STRUCTURES	SAMPLES	LITHOLOGIC DESCRIPTION
								1	0.5 1.0				SM	HYDROTHERMAL DEPOSITS
								2						
								3						

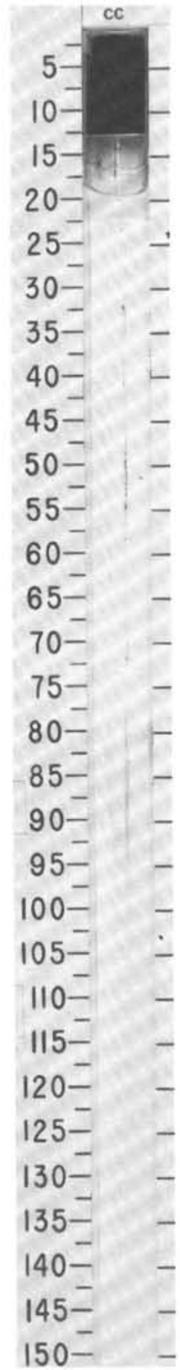
HYDROTHERMAL DEPOSITS

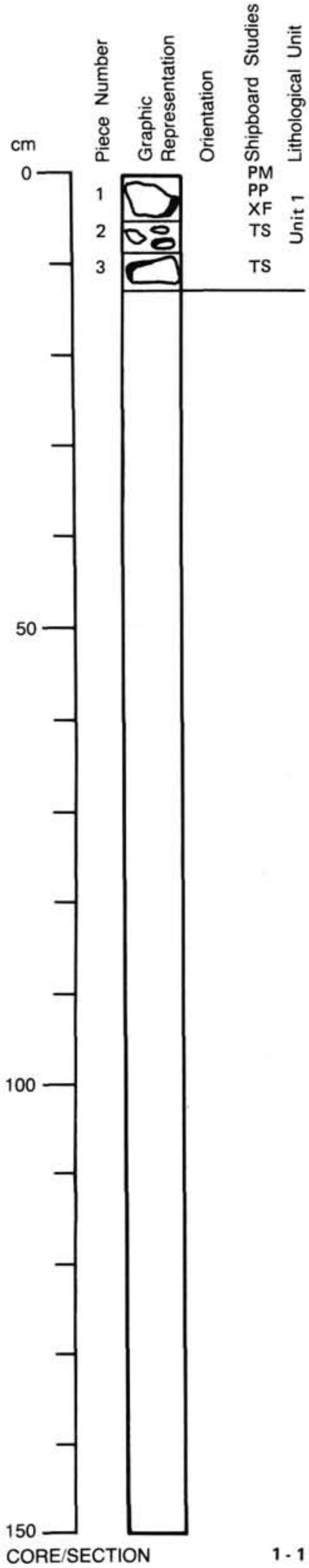
General description: Black hydrothermal deposits with abundant pyrite and sphalerite visible.

Components:
- Pyrite
- Sphalerite (reddish brown, oxidized surface)
- Pyrrhotite
- Chalcopyrite
- Sulfate(?)
- 1% clay
- 1% basaltic glass
- Tr organic material

Grain size analysis:
Section 1: fine-grained to granule-sized gravel.

Sampling: 5 m smear slide taken for grain size analysis.





106–649C–1D–1

UNIT 1: ASSORTED RUBBLE

Pieces 1–3

PIECE 1: APHYRIC BASALT

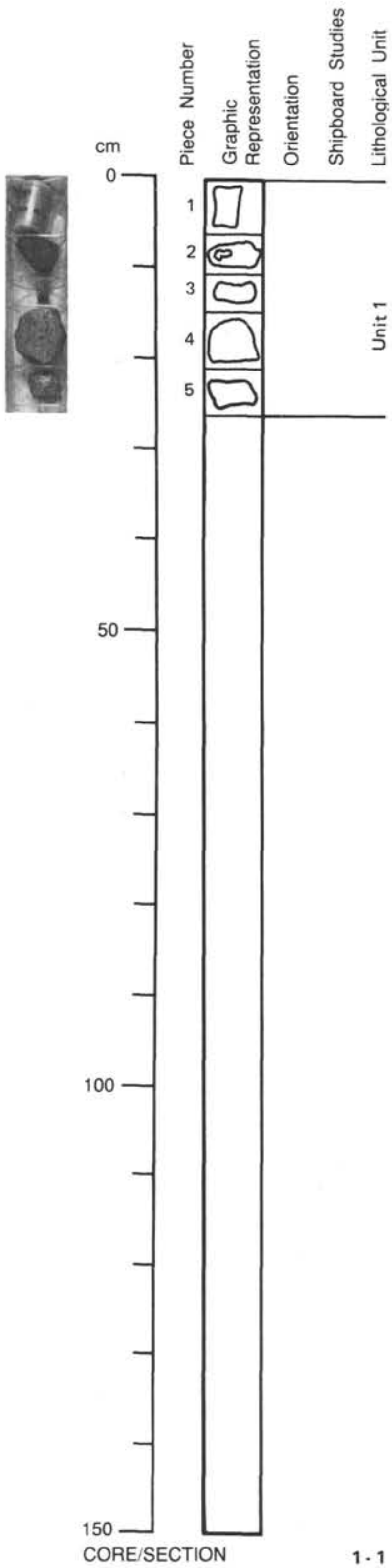
GLASS: glassy margin, fresh, no contacts.
PHENOCRYSTS: irregular distribution, plagioclase, 3 phenocrysts on outer surface, 2 mm, euhedral, fresh.
GROUNDMASS: glassy to very fine grained.
COLOR: gray.
VESICLES: 3%, <1 mm, some round, some elongate, mostly empty, but some lined with orange clay, even distribution.
ALTERATION: fresh, yellow green clay on outer surface, rare sulfides with clay.
VEINS/FRACTURES: one empty crack.

PIECE 2: APHYRIC BASALT

GLASS: glassy margin on one of three pieces, fresh, no contacts.
PHENOCRYSTS: absent.
GROUNDMASS: glassy to fine grained.
COLOR: gray.
VESICLES: 3%, <1 mm, round, some empty, some filled by green clay, even distribution.
ALTERATION: fresh, yellow green clay on outer surface, some orange brown.
VEINS/FRACTURES: none.

PIECE 3: APHYRIC BASALT

GLASS: glassy margin, fresh, no contacts.
PHENOCRYSTS: plagioclase, single euhedral phenocryst.
GROUNDMASS: glassy to very fine grained.
COLOR: gray.
VESICLES: 3%, <1 mm, round, some filled by orange brown clay, even distribution.
ALTERATION: fresh, orange brown coating on outer surface.
VEINS/FRACTURES: one fracture filled with single crystal of pyrite.



106–649G–1D–1

UNIT 1: MASSIVE HYDROTHERMAL SULFIDE DEPOSIT

Pieces 1–5

PIECE 1: WASHINGS FROM CORE BARREL

COMPOSITION: mainly sulfides and black material, grain size approximately 0.5 mm (stored in plastic vial).

PIECE 2: MASSIVE SULFIDES

COMPOSITION: massive, well-crystallized sulfides with light gray clay; approximately 90% sulfides and 10% clay; forms massive sulfide deposit.

VUGS: approximately 2%, <1 cm, coated by sulfide crystals; possibly filled with clay during cutting.

PIECE 3: MASSIVE SULFIDES

COMPOSITION: massive sulfide deposit with well-crystallized pyrite in vugs and surface depressions, minor amounts of light gray clay, black mineral on one outer surface.

VUGS: approximately 5%, <0.8 mm, lined with sulfides.

PIECE 4: MASSIVE SULFIDES

COMPOSITION: massive sulfide deposit with well-crystallized pyrite in vugs and surface depressions, minor amounts of light gray clay.

VUGS: approximately 5%, <0.8 mm, lined with sulfides.

PIECE 5: CLAY-RICH DEPOSIT

COMPOSITION: deposit of mixed gray clay and pyrite; on one side, white botryoidal mineral (sulfates?) with upper surface oxidized to orange brown mineral.

THIN SECTION DESCRIPTION

106-649C-1D-1 (Piece 1, 2-4 cm)

ROCK NAME: Aphyric basalt
WHERE SAMPLED: Unit 1
TEXTURE: Variolitic
GRAIN SIZE: Cryptocrystalline-microcrystalline

PRIMARY MINERALOGY	PERCENT PRESENT	PERCENT ORIGINAL	SIZE RANGE (mm)	APPROX. COMPO-SITION	MORPHOLOGY	COMMENTS
GROUNDMASS						
Olivine	5	5	≤0.12		Acicular, equant, euhedral	Some hopper crystals.
Plagioclase	20	20	≤1.50		Acicular	Radiate.
Clinopyroxene	10	10			Acicular	Radiate with plag.
Mesostasis	65	65				Cryptocrystalline. Brown-black.

VESICLES/ CAVITIES	PERCENT	LOCATION	SIZE RANGE (mm)	FILLING	SHAPE
Vesicles	1		0.15-0.60	None	Round

COMMENTS: Finer grained than 106-649C-1R-1 (Piece 3, 9-11 cm).

THIN SECTION DESCRIPTION

106-649C-1D-1 (Piece 3, 9-11 cm)

ROCK NAME: Aphyric basalt
WHERE SAMPLED: Unit 1
TEXTURE: Variolitic
GRAIN SIZE: Microcrystalline

PRIMARY MINERALOGY	PERCENT PRESENT	PERCENT ORIGINAL	SIZE RANGE (mm)	APPROX. COMPO-SITION	MORPHOLOGY	COMMENTS
GROUNDMASS						
Olivine	1	1	0.03-0.12		Acicular	Also lantern shapes, chains. Some larger crystals are euhedral-subhedral.
Plagioclase	45	45	0.03-0.30		Acicular	In radiating sheaths.
Clinopyroxene	40	40	0.03-0.30		Acicular, plumose	Radiate.
Opaques	2	2				
Mesostasis	12	12				Cryptocrystalline. Black.

SECONDARY MINERALOGY	PERCENT	REPLACING/ FILLING	COMMENTS
Clays	Tr	Mesostasis	Reddish brown bands in the groundmass and in small fractures.

VESICLES/ CAVITIES	PERCENT	LOCATION	SIZE RANGE (mm)	FILLING	SHAPE
Vesicles	1		0.1-0.5	None	Round

COMMENTS: Completely or partially filled segregation vesicles, 0.1-0.5 mm round, <1% of the section. Most are completely filled.