Davis, E. E., Mottl, M. J., Fisher, A. T., et al., 1992 Proceedings of the Ocean Drilling Program, Initial Reports, Vol. 139

# 6. SITE 8561

## Shipboard Scientific Party<sup>2</sup>

# HOLE 856A

Date occupied: 18 July 1991 Date departed: 19 July 1991

Time on hole: 1 day, 1 hr

Position: 48°26.201'N, 128°40.838'W

Bottom felt (drill-pipe measurement from rig floor, m): 2405.8

Distance between rig floor and sea level (m): 10.70

Water depth (drill-pipe measurement from sea level, m): 2395.1

Total depth (rig floor, m): 2521.50

Penetration (m): 115.70

Number of cores (including cores with no recovery): 14

Total length of cored section (m): 115.70

Total core recovered (m): 102.04

## Core recovery (%): 88

Oldest sediment cored:

Depth below seafloor (m): 107.34 Nature: silty clay Earliest age: Pleistocene (at 6H-CC, 50.7 mbsf) Measured velocity (km/s): 1.69

#### Hard rock:

Depth below seafloor (m): 115.70 Nature: basalt Measured velocity (km/s): 5.84

#### **Basement:**

Depth below seafloor (m): 115.70 Nature: basalt Measured velocity (km/s): 5.84

#### HOLE 856B

Date occupied: 19 July 1991

Date departed: 21 July 1991

Time on hole: 1 day, 1 hr, 45 min

Position: 48°26.102'N, 128°40.811'W

Bottom felt (drill-pipe measurement from rig floor, m): 2430.7

Distance between rig floor and sea level (m): 10.70

Water depth (drill-pipe measurement from sea level, m): 2420.0

Total depth (rig floor, m): 2552.40

Penetration (m): 121.70

Number of cores (including cores with no recovery): 16 Total length of cored section (m): 121.70

<sup>2</sup> Shipboard Scientific Party is as given in the list of participants preceding the contents.

Total core recovered (m): 108.33

Core recovery (%): 89

Oldest sediment cored: Depth below seafloor (m): 120.8 Nature: siltstone and basalt clasts Earliest age: Pleistocene (at 3H-CC, 20.8 mbsf) Measured velocity (km/s): 3.36

Hard rock: Depth below seafloor (m): 121.70 Nature: basalt fragments

Basement: Depth below seafloor (m): 120.38 Nature: basalt

Comments: Basalt sill at 8H-CC (recovered 0.11 cm) and 9X-1 (recovered 0.26 cm); basement at 16X-CC?

# HOLE 856C

## Date occupied: 21 July 1991

Date departed: 21 July 1991

Time on hole: 2 hr

Position: 48°26.042'N, 128°40.856'W (No GPS reception; position computed from beacon offset.)

Bottom felt (rig floor, m; drill-pipe measurement from rig floor, m): 2448.0

Distance between rig floor and sea level (m): 10.70

Water depth (drill-pipe measurement from sea level, m): 2437.3

Total depth (rig floor, m): 2450.00

Penetration (m): 2.00

Number of cores (including cores with no recovery): 1

Total length of cored section (m): 2.00

Total core recovered (m): 7.06

Core recovery (%): 353

Oldest sediment cored: Depth below seafloor (m): 7.06 Nature: silt and massive sulfide Earliest age: Pleistocene

Comments: Cored 2.0 m, recovered 7.06 m.

## HOLE 856D

Date occupied: 21 July 1991 Date departed: 21 July 1991

Time on hole: 45 min

Position: 48°26.026'N, 128°40.856'W (No GPS reception; position computed from beacon offset.)

Bottom felt (drill-pipe measurement from rig floor, m): 2449.0

Distance between rig floor and sea level (m): 10.70

<sup>&</sup>lt;sup>1</sup> Davis, E. E., Mottl, M. J., Fisher, A. T., et al., 1992. Proc. ODP, Init. Repts., 139: College Station, TX (Ocean Drilling Program).

Water depth (drill-pipe measurement from sea level, m): 2438.3

Total depth (rig floor, m): 2454.00

Penetration (m): 5.00

Number of cores (including cores with no recovery): 1

Total length of cored section (m): 5.00

Total core recovered (m): 8.30

Core recovery (%): 166

Oldest sediment cored: Depth below seafloor (m): 8.30 Nature: amorphous silica and sulfide sand

## HOLE 856E

Date occupied: 21 July 1991

Date departed: 21 July 1991

Time on hole: 45 min

Position: 48°26.009'N, 128°40.856'W (No GPS reception; position computed from beacon offset.)

Bottom felt (drill-pipe measurement from rig floor, m): 2447.1

Distance between rig floor and sea level (m): 10.70

Water depth (drill-pipe measurement from sea level, m): 2436.4

Total depth (rig floor, m): 2449.50

Penetration (m): 2.40

Number of cores (including cores with no recovery): 1

Total length of cored section (m): 2.40

Total core recovered (m): 2.43

Core recovery (%): 101

Oldest sediment cored: Depth below seafloor (m): 2.43 Nature: sulfide breccia Earliest age: Holocene at top

Comments: Cored 2.4 m, recovered 2.43 m.

# HOLE 856F

Date occupied: 21 July 1991 Date departed: 21 July 1991 Time on hole: 13 hr, 45 min Position: 48°26.018'N, 128°40.863'W Bottom felt (drill-pipe measurement from rig floor, m): 2434.0 Distance between rig floor and sea level (m): 10.70 Water depth (drill-pipe measurement from sea level, m): 2423.3 Total depth (rig floor, m): 2457.60 Penetration (m): 23.60 Number of cores (including cores with no recovery): 3 Total length of cored section (m): 23.60 Total core recovered (m): 0.56 Core recovery (%): 2

Oldest sediment cored: Depth below seafloor (m): 23.60 Nature: massive sulfide breccia HOLE 856G

Date occupied: 21 July 1991

Date departed: 23 July 1991

Time on hole: 1 day, 14 hr

Position: 48°26.016'N, 128°40.861'W

Bottom felt (drill-pipe measurement from rig floor, m): 2433.5

Distance between rig floor and sea level (m): 10.70

Water depth (drill-pipe measurement from sea level, m): 2422.8

Total depth (rig floor, m): 2498.90

Penetration (m): 65.40 Number of cores (including cores with no recovery): 7

Total length of cored section (m): 65.40

Total core recovered (m): 21.69

Core recovery (%): 33

Oldest sediment cored: Depth below seafloor (m): 17.60 Nature: sulfide sand and gravel

Hard rock: Depth below seafloor (m): 65.40 Nature: massive sulfide Measured velocity (km/s): 5.97 (at 7R-4)

Comments: Camera survey was done to find a good hole location.

# HOLE 856H

Date occupied: 23 July 1991

Date departed: 27 July 1991

Time on hole: 3 days, 17 hr, 15 min

Position: 48°26.020'N (includes offset between ship and bit determined from camera survey), 128°40.859'W

Bottom felt (rig floor, m; drill-pipe measurement from rig floor, m): 2434.5

Distance between rig floor and sea level (m): 10.70

Water depth (drill-pipe measurement from sea level, m): 2423.8

Total depth (rig floor, m): 2528.30

Penetration (m): 93.80

Number of cores (including cores with no recovery): 17

Total length of cored section (m): 93.80

Total core recovered (m): 18.86

Core recovery (%): 20

Oldest sediment cored: Depth below seafloor (m): 13.50 Nature: Sulfide sand

#### Hard rock:

Depth below seafloor (m): 93.80 Nature: massive sulfide

**Principal results:** Site 856 is situated over a small hill in the eastern part of Middle Valley, the sedimented rift valley of the northern Juan de Fuca ridge. The structure of this hill is characteristic of others in Middle Valley and other sedimented rifts. It is roughly circular, about 500 m in diameter, and stands about 60 m above the floor of the valley. Previous studies in this and other areas have indicated that the hills form by uplift of the sediment section above sub- or intrasedimentary igneous intrusions, and

Table 1. Summary of hole depths and locations, Site 856.

Hole	Depth <sup>a</sup> (mbrf)	Offset from beacon (m)	GPS location
856A	2405.8	191 N, 110 W	48°26.201'N, 128°40.838'W
856B	2430.7	3 N, 75 W	48°26.102'N, 128°40.811'W
856C	2448.0	102 S, 135 W	<sup>b</sup> 48°26.042'N, 128°40.856'W
856D	2449.0	132 S, 135 W	<sup>b</sup> 48°26.026'N, 128°40.856'W
856E	2447.1	162 S, 135 W	<sup>b</sup> 48°26.009'N, 128°40.856'W
856F	2434.0	147 S, 135 W	48°26.018'N, 128°40.863'W
856G	2433.5	157 S. 135 W	48°26.016'N, 128°40.861'W
856H	2434.5	122 S, 135 W	48°26.029'N, 128°40.859'W
<sup>c</sup> 856H	2434.5	139 S, 135 W	48°26.020'N, 128°40.859'W
<sup>d</sup> Calcula	ited beacon	position	48°26.097'N, 128°40.746'W

<sup>a</sup>Depths given in meters below rig floor. Depths below sea level can be calculated by subtracting height of rig floor above water line at this site (10.7 m).

<sup>b</sup>No GPS reception; positions computed from beacon offsets.

Includes offset between ship and bit determined from camera survey.

dSee "Explanatory Notes" chapter (this volume).

that hydrothermal massive-sulfide mineralization is often associated with these structures. Drilling at Site 856 addressed the origin of these structures, the extent and nature of associated hydrothermal alteration and mineralization, and the difficulties of drilling massive sulfide with existing Ocean Drilling Program drilling technology.

Operations began with a north-south transect of advanced piston corer/extended core barrel (APC/XCB) holes (see Table 1 for summary of hole locations). Holes 856A and 856B were located at the center and southern edge of the top of the hill. Coring in the two holes recovered intrusive basaltic rock at depths of 112 and 120 mbsf, respectively (see Table 2 for coring summary). The overlying sediment is an undisturbed section of semi-indurated turbidites, about 20% less porous throughout than the section sampled at Site 855. Heat flow was found to be 0.65 W/m<sup>2</sup> in Hole 856A and 1.73 W/m<sup>2</sup> in Hole 856B. Although high, these values probably do not reflect conditions that existed when the hill was formed and was hydrothermally active. Temperatures at the top of the sill are only 60°C in Hole 856A; they are projected to be about 160°C at the top of the sill in Hole 856B. Pore-water compositions suggest that currently there is no flow vertically through the sediment section, although the absence of a Pleistocene chlorinity anomaly suggests that seawater has flushed through the sediment at some time during the past 10,000 yr. Coarse clastic layers of massive sulfide interbedded with fine sand to silt turbidites were encountered at about 20 mbsf in Hole 856B. Semi-indurated sediment near the bottom of Hole 856B was weakly altered hydrothermally, and mineralized by disseminated barite, pyrrhotite, chalcopyrite, and sphalerite.

The Site 856 transect continued with APC/XCB Holes 856C through 856E, distributed over a distance of 60 m north to south across the southern flank of the hill. Massive sulfide, sulfide sand, and sulfide clay were encountered at or immediately beneath the seafloor in all of these holes. This material was difficult to penetrate or recover with either the APC or XCB systems; a final attempt (Hole 856F) resulted in no recovery and a bent APC barrel. Having thus defined the minimum extent of this massive sulfide outcrop, it was decided to continue operations at this site with a standard rotary core barrel (RCB) bit, to test this technology in massive sulfide, and to explore the nature and extent of this hydrothermal deposit at depth. RCB drilling was very successful, and the hydrothermal deposit proved to be much thicker than expected. Hole 856G penetrated 65 m of massive sulfide with 33% recovery before the bit became inextricably jammed by falling rubble. Hole 856H was then started using a section of drill-in casing connected to a free-fall reentry cone. This hole was drilled to 95 mbsf, again with apparently continuous massive sulfide throughout the section, before hole fill prevented further penetration. Core recovery from this hole was 21%.

The massive sulfide recovered from Holes 856G and 856H is composed predominantly of pyrite and pyrrhotite with subordinate amounts of chalcopyrite (CuFeS<sub>2</sub>) and sphalerite (Zn, FeS). Late-stage alteration has locally formed magnetite and hematite in some samples and apparently resulted in removal of some sphalerite from the upper part of the deposit. Magnetite and hematite alteration decreases downhole, resulting in increasing amounts of primary mineralization with higher zinc and copper contents. Only rare fragments of altered sediment are contained in the massive sulfide, suggesting that most or all of the massive sulfide was deposited above the seafloor. The lack of minerals rich in elements such as Pb, As, and Sb, which typically are enriched in sediment-hosted sulfide deposits, suggests that the major source of metals is the basaltic basement.

In terms of normal logging operations, Hole 856H was not very deep, but because of its unique character, a limited suite of logs was completed. This included several temperature runs, a gamma spectrometry log, a sonic velocity log, and an induction electrical resistivity log. Results indicate clearly that no sedimentary or volcanic material had been drilled but not recovered by coring. As expected, the geochemical log indicates high iron and sulfur, and low calcium and silicon contents. Electrical resistivities are low, ranging between 0.1 and 0.2 ohm-m. The upper 70 m of the hole remained very cool, less than 2.5°C warmer than bottom water at all times during the logging program, indicating downhole flow of water into the formation. Temperatures below 70 mbsf increased with depth to about 25°C at 80 mbsf. The temperature gradient defined between this point and the seafloor, combined with the typical value of thermal conductivity measured on the sulfide core material of over 5 W/(m·K), yields a heat flow that is similar to that measured at the seafloor and in Hole 856B, indicating that the thermal regime before drilling was probably conductive.

The total penetration in massive sulfide at both Holes 856G and 856H (up to 95 mbsf) extends to 70 m below the local level of the sedimented valley floor. This suggests either that the hydrothermal deposit fully replaced the sediment in which it lies, or that it was constructed by sulfide precipitation at or near the seafloor while turbidite and hemipelagic sedimentation continued. The massive texture of the sulfide suggests the latter. A large volume of fluid has clearly been involved in producing the deposit. The conditions that produced this massive sulfide deposit presumably are common in sedimented rift environments, in which an inherently low-permeability, nearly continuous sediment cover blankets the igneous crust that contains the heat source. This provides a favorable physical and chemical environment for efficient, high-temperature water-rock interaction and causes discharge to be highly focused and long-lived.

## **BACKGROUND AND OBJECTIVES**

Site 856 is located in the eastern part of Middle Valley roughly 3 km west (inside) of the normal fault scarp that forms the eastern topographic boundary of the valley, and about 4 km east (outside) of the primary structural boundary of the current rift axis. The site is situated over one of a number of small hills that occur in this part of the rift. The hills are typically a few hundred meters in diameter and stand a few tens of meters above the otherwise smooth, sedimented rift valley floor. They appear to be of syn- or post-sedimentary volcanic origin, and consist of sections of uplifted sediment typically about 100 m thick, overlying bright seismic reflectors that are believed to be sills, or laccolithic plug-like intrusions. Massive sulfide deposits are associated with these hills (Davis et al., 1987). Structures similar to these hills have been observed in other sedimented rifts, including Guaymas Basin (Lawver and Williams, 1979; Lonsdale and Becker, 1985) and Escanaba Trough (Morton et al., 1987; Davis and Becker, 1992; Dellinger and Holmes, 1992; Zierenberg et al., 1992); these examples also have associated hydrothermal mineralization. None of the hills in Middle Valley is currently hydrothermally active, although there is a small vent field roughly 300 m south of the southern flank of the hill where Site 856 is located; there the heat flow through the seafloor exceeds 4 W/m<sup>2</sup>, and 264°C fluid currently is discharging.

An array of shallow holes was completed on and near this hill at Site 856 with the following objectives: (1) to investigate the subsurface structure of this representative feature; (2) to determine the extent and geometry of hydrothermal alteration within the sediment section at various positions and levels beneath the hill; (3) to characterize the composition and distribution of the mineralization beneath, within, and/or above the sediment section; and (4) to establish the genetic

## Table 2. Site 856 coring summary.

Core	Date (July 1991)	Time (UTC)	Depth interval (mbsf)	Cored (m)	Recovered (m)	Recovery (%)
139-856A-						
114	10	0540	00.27	27	2.52	02.7
2H	19	0615	27-122	95	9.96	105.0
3H	19	0730	12.2-21.7	95	10.13	106.6
4H	19	0815	21.7-31.2	9.5	10.21	107.5
SH	19	0930	31.2-40.7	9.5	10.65	112.1
6H	19	1015	40.7-50.2	9.5	10.00	105.2
7H	19	1135	50.2-59.7	9.5	10.24	107.8
8H	19	1210	59.7-69.2	9.5	10.04	107.8
9H	19	1330	69.2-78.7	9.5	10.25	107.9
10X	19	1430	78.7-86.2	7.5	3.25	43.3
11X	19	1530	86.2-95.7	9.5	2.69	28.3
12X	19	1800	95.7-105.3	9.6	2.42	25.2
13X	19	2030	105.3-114.5	9.2	8.25	89.7
14X	19	2300	114.5-115.7	1.2	1.42	118.0
			Coring totals	115.7	102.24	88.4
139-856B-						
1H	20	0240	0.0-1.8	1.8	1.71	95.0
2H	20	0310	1.8-11.3	9.5	10.07	106.0
3H	20	0400	11.3-20.8	9.5	10.12	106.5
4H	20	0440	20.8-30.3	9.5	9.70	102.0
SH	20	0/25	30.3-39.8	9.5	10.10	106.3
6H	20	0810	39.8-49.3	9.5	9.97	105.0
/H	20	0920	49.3-58.8	9.5	10.06	105.9
SH	20	1005	58.8-62.3	3.5	4.97	142.0
9X	20	1205	62.3-70.8	8.5	3.40	40.0
TOH	20	1515	70.8-73.3	2.5	2.45	98.0
11A	20	1030	/3.3-81.0	8.3	7.16	86.2
12X	20	1/45	81.6-91.1	9.5	7.91	83.2
13A	20	1915	91.1-100.8	9.7	6.33	65.2
14A	20	2020	100.8-110.4	9.6	5.76	60.0
15X 16X	20	0030	120.1-121.7	9.7	0.68	81.8 42.5
			Coring totals	121.7	108.33	89.0
139-856C-1H	21	0320	0.0-2.0	2.0	7.06	353.0
			Coring totals	2.0	7.06	353.0
139-856D-1H	21	0430	0.0-5.0	5.0	8.30	166.0
			Coring totals	5.0	8.30	166.0
139-856E-1H	21	0455	0.0-2.4	2.4	2.43	101.0
			Coring totals	2.4	2.43	101.0
139-856F-						
1X	21	0630	0.0-11.7	11.7	0.05	0.4
2X	21	0820	11.7-17.2	5.5	0.34	6.2
3X	21	1155	17.2-23.6	6.4	0.17	2.7
120 0540			Coring totals	23.6	0.56	2.4
139-0300-						
IR	22	0445	0.0-8.6	8.6	5.25	61.0
2R	22	0640	8.6-17.6	9.0	6.73	74.8
3R	22	0905	17.6-27.0	9.4	1.05	11.2
4R	22	1410	27.0-36.7	9.7	1.07	11.0
5R	22	1645	36.7-46.3	9.6	0.81	8.4
6R	22	1940	46.3-55.8	9.5	3.03	31.9
/R	22	2245	55.8-65.4	9.6	3.75	39.0
			Coring totals	65.4	21.69	33.2

Tab	le 2	(con	tinued	).

Core	Date (July 1991)	Time (UTC)	Depth interval (mbsf)	Cored (m)	Recovered (m)	Recovery (%)
139-856H-						
1R	24	0325	0.0-13.5	13.5	4.04	29.9
2R	24	0600	13.5-22.1	8.6	0.39	4.5
3R	24	0915	22.1-26.6	4.5	3.32	73.8
4R	24	1215	26.6-32.4	5.8	2.58	44.5
5R	24	1415	32.4-37.4	5.0	0.44	8.8
6R	24	1600	37.4-43.1	5.7	0.55	9.7
7R	24	1715	43.1-48.0	4.9	0.70	14.3
8R	24	1930	48.0-52.5	4.5	1.02	22.6
9R	24	2100	52.5-57.0	4.5	0.73	16.2
10R	24	2245	57.0-61.3	4.3	0.50	11.6
11R	25	0030	61.3-66.3	5.0	0.93	18.6
12R	25	0200	66.3-70.9	4.6	0.05	1.1
13R	25	0400	70.9-75.7	4.8	0.50	10.4
14R	25	0535	75.7-80.5	4.8	1.03	21.4
15R	25	0720	80.5-85.2	4.7	1.18	25.1
16R	25	0920	85.2-90.1	4.9	0.57	11.6
17R	25	1310	90.1-93.8	3.7	0.33	8.9
			Coring totals	93.8	18.86	20.1

relationship between the mineralization and the local volcanic, tectonic, hydrologic, and thermal regime.

# SITE GEOPHYSICS AND GEOLOGY

The regional context of Site 856 is seen in Figures 1 to 3 and in the maps and profiles included in the back pocket of this volume. The site is located about 3 km inside the eastern valley-bounding fault (along which Site 855 is located) on crust that could be as old as 320,000 yr, based on its distance from the eastern Brunhes magnetic chron (Davis and Villinger, this volume). The holes at this site are situated over a hill 500 m in diameter and 60 m higher than the surrounding sedimented seafloor (Figs. 4 and 5). Based on 3.5-kHz and seismic profiles, surficial cores (Davis et. al., 1987; Figs. 5 and 6) and on studies of similar structures in Guaymas Basin (Lonsdale and Becker, 1985) and Escanaba Trough (Morton et al., 1987; Davis and Becker, 1992; Dellinger and Holmes, 1992), the hill appears to consist of sediment that has been uplifted above the original turbidite plain.

The seismic structure of the hill is typical of others in the area; bright isolated seismic reflectors lie directly beneath the hills, typically 100 to 150 milliseconds (ms) beneath their summits. The reflector beneath the hill at Site 856 lies at a local sub-bottom traveltime of about 170 ms; the reflected wave is about twice the amplitude of that from the seafloor surrounding the hill, and is reversed in polarity relative to the seafloor reflection (Fig. 7). The reflection amplitude can be accounted for by the expected acoustic impedance (density × velocity) contrast that would exist between basalt and sediment at this depth; the polarity is somewhat puzzling, as it requires an interface where the material above the interface has an acoustic impedance higher than the material below. The reflection may be from the bottom of a sill associated with the hill, although it would seem that the top of the sill should be highly reflective as well.

Depths to acoustic basement in the surrounding region are considerably greater, typically 400 to 500 ms, or roughly 350 to 450 m (Fig. 6). Other bright reflectors that are very flat and extensive, probably also from sills or buried flows, are seen commonly in the vicinity of the hills; two examples are visible about 30 ms (25 m) beneath the seafloor near the two hills located a few kilometers south of Site 856 (Davis and Villinger, this volume).



Figure 1. Multichannel seismic profile 89-14, crossing Middle Valley and Site 856 (from Rohr et al., 1992). The location of Site 857 is shown for reference.

The seafloor morphology of the hill at Site 856 is relatively simple. The top of the hill is fairly flat and smooth; the perimeter is incised by what appear to be erosional rills, which expose slightly indurated sediment in outcrop. The western flank is steep, linear, and possibly fault-controlled (Fig. 4). On the southern flank of the hill is a small promontory, the western face of which is nearly colinear with the western face of the main part of the hill.

Massive sulfide deposits have been observed in outcrop on this promontory, both in photographs and by direct observation from a submersible (R. Zierenberg and W. Goodfellow, pers. comm., 1991; Fig. 8). Deep-towed magnetic profiles show that a strong magnetic anomaly is centered here as well (M. Tivey, pers. comm., 1990). The deposit is believed to have been precipitated from hydrothermal solutions, the discharge of which has been focused by the permeability structure of the hills. The solutions may have been heated either locally by volcanic activity beneath the hill, or in a more regional high-temperature "reservoir" of fluid in the upper igneous crust, where they have been confined by the generally continuous sediment fill in the valley but able to escape wherever permeable pathways are available.

The background heat flow in this part of Middle Valley is relatively constant, with values ranging typically from about 0.4 to 0.6 W/m<sup>2</sup> (Fig. 9). Several significant anomalies are present, however, with values ranging locally up to 6 W/m<sup>2</sup>. None of these anomalies is associated with any of the larger hills, however, suggesting that the hills are all relic features (Davis and Villinger, this volume). This is true of the hill at Site 856, although there is a significant anomaly centered only 600 m south of the center of the hill, and 300 m south of its southern flank. The heat flow increases from background values of between 0.5 to 0.6 W/m<sup>2</sup>, typical of this part of Middle Valley, to 5 W/m<sup>2</sup> or more at the center of the anomaly, over a distance of only 800 m (see Davis and Villinger, this volume). The anomaly is centered over or near a small seafloor edifice and an area of strong acoustic backscatter, about 300 m south of the perimeter of the hill at Site 856. At this location, a hydrothermal vent with a temperature of 264°C has been observed and sampled (Fig. 8). The few heat flow measurements made over the hill at Site 856 are not precisely located at the scale of the maps shown in Figures 4 and 8 (estimated navigational uncertainty = 100 m). Values indicate, however, that the presence of the hill and its underlying structure do not significantly effect the present thermal field, which is dominated instead by the recent hydrothermal activity to the south.

Additional information relevant to the drilling at this site comes from controlled-source magnetometric electrical-resistivity soundings (Nobes et al., in press). Modeling of these results indicates that electrical resistivity is very low at shallow depths beneath the southern flank of the hill at Site 856, about 0.1 ohm-m, and anisotropy is high, suggesting that the formation is horizontally well connected. Results from soundings in the region away from the hill are well matched by a two-dimensional layered model consisting of seawater (0.3 ohm-m), overlying a 500-m layer of sediment (0.7 ohm-m), overlying a semiinfinite layer of basalt (2.3 ohm-m). This result is in good agreement with the local seismic structure (Fig. 6).

## **OPERATIONS**

The drillship got under way from Site 855 on 18 July at 1300 hr UTC and conducted a 3.5- and 12-kHz echo-sounding survey westward to a point just south of proposed Site 858. A short north-south line was surveyed across Site 858 to verify the position of the acoustic target before the ship turned and dropped a recallable acoustic beacon on the site. We then proceeded southeastward to Site 856, dropped a second beacon on that site, turned, took station on the beacon, and began site operations at 1530 hr.

#### Hole 856A

The coring program at Site 856 called for a series of APC/XCB holes in turbiditic, altered, and sulfide-enriched sediments, with no significant basement penetration. An APC/XCB outer barrel and bottom-hole assembly (BHA) were assembled and run to spud depth. The initial APC core found the seafloor at 2405.8 m, in agreement with the depth determined by the 12-kHz echo-sounder within a meter.

APC cores were collected continuously to refusal (105,000 lb pullout force) at 79 mbsf, with full recovery. The new Adara APC temperature shoe was used on Cores 139-856A-3H, -5H, -7H, and



Figure 2. Bathymetry (in meters) in the part of Middle Valley occupied during Leg 139, based on continuous SeaBeam swath soundings. Depths are computed using a sonic velocity of 1500 m/s and contoured at 10-m intervals. The area included in Figure 4 is outlined.

-9H and performed flawlessly, measuring a linear temperature gradient (see "Heat Flow" section, this chapter). Two XCB cores were then taken to 96 mbsf with 35% core recovery. After a successful watersampler temperature probe (WSTP) run, two additional XCB cores (57% recovery) took the bit to basalt, which was determined by the reduced rate of penetration to be at 112 mbsf. The hard drilling quickly wore down the conventional XCB shoe. About 30 cm of basalt was recovered in the core catcher of Core 139-856A-13X.

Initial interpretation of seismic profiles suggested that basement (a bright reflector) could be considerably deeper, so an additional core was attempted to see whether the basalt was very thin or discontinuous. A new-style tungsten carbide hard-formation XCB shoe was used. After 75 min, only about 1-1/4 m had been penetrated and the core barrel was recovered due to the low rate of penetration. The barrel contained 1.4 m of high-quality basalt core and the shoe was undamaged. Because of the slow progress, site priorities, and limited quantities of hard-rock XCB components, however, no more basalt cores were attempted and the location was abandoned with objectives declared fulfilled.

# Hole 856B

With the bit pulled above the seafloor, the vessel was offset in dynamic positioning mode 190 m to the south for the second planned hole of this site. The echo-sounder indicated a depth of 2408 m, but the reflection had become diffuse as the move progressed. Two "water cores" were pulled with the APC before the seafloor finally was cored at 2430.7 m, apparently just off the crest of the hill.

APC cores then were taken to 62 mbsf, with the APC temperature shoe used on Cores 139-856B-3H, -5H, and -7H before it was discontinued due to the hardness of the formation. The WSTP was run after Cores 139-856B-4H and -9H. A thin basalt intrusion halted APC penetration at Core 139-856B-8H (62 mbsf), but a small amount of basalt was recovered in the core catcher. After one XCB core failed to encounter additional hard material, another APC core was attempted in an effort to improve recovery. The sediment had become too firm, however, and only about 2 m of core were recovered following an incomplete stroke. XCB coring then continued to basement at 120 mbsf. An attempt to recover a basalt core using a hard-formation XCB shoe was partially successful, with 40%



Figure 3. SeaMARC II acoustic imagery in the part of Middle Valley occupied by Leg 139 (same area as in Figs. 2 and 9A). Several structures similar to the one drilled at Site 856 can be seen in the image, as can the position of the site relative to the fault scarp that bounds Middle Valley in the east.

recovery of a 1.7-m core in altered basalt and a rate of penetration of about 1 m/hr. Scientific objectives for the hole then were declared fulfilled, and the bit was pulled above the seafloor.

Estimated bottom-hole temperature was 150°C, but no temperaturerelated problems with core liners or other equipment were experienced. Heat-sensitive indicators installed in the sinker bar assembly showed that the temperature inside the pipe remained below 43°C as a result of the circulation of cold water.

# Holes 856C, 856D, and 856E

The drillship was offset 120 m south-southwest to the next proposed location, where massive sulfide deposits were known to occur in outcrop at the seafloor. Because the next drilling target was located on top of a small ridge a few tens of meters high, a series of APC mudline cores was used both to define the bathymetry and to sample the seafloor material. The drill string was lowered to "tag" bottom with the bit before each core attempt. The initial core (139-856C-1H) was shot from 2448 m, 1 m above tag depth. The stroke was incomplete but the core barrel contained over 7 m of clay and sulfide material. Most of the contents apparently had flowed in by "syringe" action as the barrel had been picked up by the piston rod. Penetration was estimated at 2 m.

After a further offset 30 m southward, the seafloor was tagged at 2436 m, indicating that the ridge had been found. An APC core from 2435 m again failed to stroke completely. Core 139-856D-1H contained 8.3 m of sulfide sediment. As more of the material appeared to be "real" core, penetration was estimated at 5 m.

The identical procedure was then repeated after another 30-m offset to the south. The weight indicator registered seafloor at 2441 m, so the APC was shot from 2440 m. This time a full stroke (pressure bleedoff) was indicated. Core 139-856E-1H contained 2.4 m of oxidized sulfide sediments with evidence of the seafloor interface at the top. It was inferred that the bit had swung over slightly deeper water between the times of tagging and spudding and that the seafloor had been cored from 2447.1 to 2449.5 m.

#### Hole 856F

The increase in water depth in Hole 856E was interpreted to mean that the ridge had been crossed. As the main sulfide accumulation was the primary target at this site, a 15-m northward offset was made to a



Figure 4. SeaMARC I side-scan acoustic image of the hill where Site 856 is located (from Johnson et al., in press) with individual hole locations shown.



Figure 5. The 3.5-kHz profile across the hill at the location of Site 856.

position midway between Holes 856D and 856E. An XCB barrel was pumped to the bit and the hole was spudded at a depth of 2434 m at 2245 hr on 20 July. The operation was done with great care because of the considerable seafloor relief and the firmness of the sediments. After several meters of penetration, drilling parameters indicated that a hole had been started and that the bit was not sliding down a slope.

Coring results were not satisfactory, however, with recovery limited to a few centimeters of friable massive sulfide material mixed with clay in each of three successive cores. The material had become quite hard after about 5 m, and the rate of penetration had dropped sharply. As scientific interest in a fairly deep penetration at that location was high, we decided to replace the XCB system with the RCB, which is better suited to coring hard material.

The desire for a seafloor APC core at the Hole 856F location had been expressed, so the APC corer was lowered for a single core attempt as soon as the bit cleared the seafloor. The bit was positioned at 2432.2 m and the APC was "fired." The stroke was incomplete, and the core barrel would not retract through the bit when pulled with the coring line, indicating a bent barrel. Considerable difficulty was encountered in shearing the pin to release the GS pulling tool (normally a simple operation), but the coring line was released and recovered after about one-half hour of effort. The APC was recovered with the drill string. When it reached the drill floor, the lower portion of the barrel was found to be broken off completely, probably as it was pulled through the upper guide horn. Thus any core that had been collected was lost.

### Hole 856G

A standard RCB BHA was made up except that a mechanical bit release (MBR) assembly with special seals and a ceramic lower support bearing was used and the drilling jars were omitted—all concessions to the abnormally high hole temperatures expected.

To ensure that a favorable spud location was found and to protect the BHA from loss or damage from an "angular spud," the vibrationisolated television frame was deployed with the TV and scanning sonar systems. The sonar was used to check bathymetry and local seafloor morphology and showed that a tentative move northward took the pipe away from the crest of the ridge. The offset was reversed and a fairly level area high on the ridge was found 10 m south of Hole 856F. The bit and TV frame were lowered together until the bit could be observed to tag sediment at 2433.5 m in an area that also was occupied by two boulders, a hole (856F?), and (temporarily) a rattail fish. The motion compensator was actuated and the bit was set down at 1845 hr on 21 July. Pump circulation was used to jet the bit about 2 m to firm resistance. The bit remained in contact with the seafloor and the drill string was compensated while the TV frame was recovered to the moonpool area.



Figure 6. Detail of seismic reflection profile 89-14 crossing Site 856. Shotpoints are spaced 50 m apart.

With the TV frame removed, the drill string could be rotated, and RCB coring began. Again hard material was encountered after about 6 m. The reason for the initial soft drilling soon became evident, as each of the first two core barrels contained several meters of loose, coarse sand composed of sulfide minerals. The dense sand continued to flow into the hole and cause hole-cleaning problems as coring progressed, although massive sulfide rock was recovered subsequently. The rate of penetration remained low, in the range of 5-6 m/hr, in the sulfide. As more drill collars were supported, attempts were made to increase the rate by adding weight, but the increased weight on the bit seemed only to slow the drilling rate. Recovery improved to about 3 m per core, but attempts to keep the hole clean were in vain. Considerable amounts of hole fill were present on each return to the bottom of the hole after tripping cores and making pipe connections, despite frequent mud flushes and high circulation rates. The problem was undoubtedly exacerbated by the high density of the material to be removed (specific gravity exceeding 4).

Following the connection after Core 139-856G-7R, which had reached 65.1 mbsf, circulation became plugged off and the drill string stuck, both vertically and rotationally. Circulation was quickly regained at high pressure, and the pressure gradually decreased to near normal, indicating that the loose material in the hole around the BHA had been removed by circulation. Nevertheless, the string remained firmly stuck and could be moved no farther than a few meters up the hole, to 47.5 mbsf. Because only a BHA of flush outside diameter was in the hole, it seemed reasonable that the drill string was stuck at the bit.

When the string had not been freed after 2 hr of working, the next logical step was to release the bit, in an effort to save the BHA. This was done, and the BHA came free with only moderate drag.

Before the drill string was pulled clear of the seafloor, a marker was fabricated of a glass flotation ball, a tether cable, and a piece of casing. The casing was stripped onto the drill string and dropped so that it would remain just inside Hole 856G after the BHA was pulled clear. The drill string then was recovered for installation of a new bit and MBR.

## Hole 856H

Though the actual cause of sticking in Hole 856G appeared to have been a "ratchet rock" at the bit, the flowing sand and sulfide debris from the uppermost few meters had posed a serious threat to successful deepening of the hole. That the massive sulfide deposit was more than 65 m thick was a major scientific find, and a premium was placed on deeper penetration at or near Hole 856G. The situation called for a short length of drill-in casing (DIC) with a small reentry funnel attached to the top to allow future reentries. The hardware was on board for one such installation, and preparations quickly were made to deploy it.

The new BHA was spaced out and equipped with special DIC subs. An MBR was included to allow logging of the hole without a round trip, and drilling jars were included in case the BHA again became stuck. A single 12-m joint of 11-3/4-in. casing was equipped with a



Figure 7. Near-trace display of multichannel seismic reflection line 89-13 over Site 856. Individual traces are spaced 12.5 m apart.

special 20-in. drilling shoe and attached to the lower BHA with the 9-7/8-in. bit and MBR protruding 1.25 m beyond the casing shoe. When the DIC/BHA had been assembled, the reentry funnel was attached in the moonpool area just before lowering the drill string.

The TV frame again was deployed to pinpoint a spud location near Hole 856G. The underwater television proved to be useless for this purpose because light reflected from the reentry funnel caused the iris of the camera lens to restrict and nothing could be seen beyond the funnel. The Mesotech sonar was invaluable, however, as the drill string did not reach the seafloor in the immediate vicinity of the previous drill hole. The sonar showed a hill nearby, which by trial and error was found to be to the north. A tentative spud found the seafloor about 20 m too deep, so the sonar was used to guide us to higher ground still farther to the north. Eventually the sulfide outcrop was crested at an offset 35 m north of that used for Hole 856G, and Hole 856H was spudded at 2434.5 m, only 1 m deeper than Hole 856G.

Pump circulation jetted the bit to about 2.5 mbsf. Motion compensation and circulation were maintained while the TV frame was recovered and until rotation could begin. We drilled in with a good rate of penetration. This seemed favorable at first, because there was concern that the hard sulfide below 5–6 mbsf would be penetrated with great difficulty by the 20-in. casing bit, particularly considering the extremely limited BHA weight available. When the high rate of penetration continued until the casing shoe reached the release point of 12 mbsf (bit at 13.5 m), the concern shifted to whether enough casing had been run to isolate all the loose sulfide debris. It took only 75 min to drill to the release point with very low bit weight and rpm); the casing was then released without incident. A second wireline trip was then made to recover Core 139-856H-1R, which contained about 4 m of pyrite sand.

Core 139-856H-2R encountered an additional 5 m of easy drilling before the rate of penetration finally decreased in harder material. The core recovered about 40 cm of massive sulfide, and about 4 m of fill accumulated in the hole during the wireline trip and drill-pipe connection. Hole-cleaning problems were reduced over the next few cores, as high-viscosity mud sweeps and high circulation rates were used to remove the heavy debris, and perhaps as the section of hole below the casing stabilized. Drilling rate again increased below about 50 mbsf and hole problems returned—apparently as a second unstable zone was penetrated. Inability to keep the hole clean increased with depth despite all measures, including the use of both mud pumps producing up to 1000 gallon/min and sweeps of up to 50 bbl ultrahigh-viscosity mud.

During the retrieval of Core 139-856H-17R from 93.8 mbsf, the pipe became stuck vertically, though rotation and circulation were maintained. Two hours were required to work the drill string free, and efforts to deepen the hole farther were abandoned.

A logging run with the JAPEX pressure/temperature/flow (PTF) logging tool then was requested. Because the tool was small in diameter, it did not require release of the core bit. A modified inner core barrel assembly was rigged to help the very light logging tool down the drill string and to hold the float valve open at the bit so the tool could be retrieved back into the pipe. Results of the PTF log showed that seawater was flowing down the hole and into the upper part of the formation. Because of the uniqueness of the formation, additional (full-diameter) logs were then requested. That added requirements for release of the bit and a reentry.

The core bit was then pulled clear of the reentry funnel, the rig was offset 20 m, and a wireline trip was made to release the bit. During the release operation, the camera frame was started down the exterior of the drill string. When the releasing tool had been recovered, preparations began for Schlumberger logging. The camera arrived at seafloor depth before assembly of the logging tools began, so a seafloor sonar/TV survey was conducted at no cost in operating time. This was carried out with an acoustic beacon mounted on the camera frame, which allowed the position of the bottom of the drill string to be monitored during the maneuvers. It was found that the horizontal offset between the bit and the ship was typically less than 10 m. The position of Hole 856H was found to be 17 m to the south of the ship's position during drilling operations, however. This greater displacement



Figure 8. Geological map of the Site 856 area based on side-scan imagery (Fig. 4), bottom photographs, and submersible observations (W. Goodfellow and R. Zierenberg, pers. comm., 1991). Individual hole locations are shown. Cross section A–B appears in Figures 56 and 57.

may have been caused by interaction of bottom currents with the reentry cone at the time the cone was set. This offset is accounted for in the position given in Table 1. Unfortunately, the marker dropped at Hole 856G was never seen during the survey.

The funnel was reentered while the first logging tool was being lowered down the drill string. The initial log (induction/sonic) came to rest at 70 mbsf. Following a successful run, a geochemistry log was recorded, also with good results, followed by a formation microscanner run. This last run went to 90 mbsf, indicating that the reason that other runs had ended at shallower depths was that the tools had landed on ledges, not in hole fill; cuttings and debris may have been only 5 m thick. The logging sheaves then were rigged down for the pipe trip, and operations at Site 856 ended.

# LITHOSTRATIGRAPHY AND SEDIMENTOLOGY

The eight holes of Site 856 are located along a transect from the top of a small, sediment-covered abyssal hill, southward to the eroded southern flank of the hill and farther southward to a low ridge of a massive sulfide deposit that is exposed at the seafloor. The northernmost hole, Hole 856A, was drilled at the shallowest water depth, 2395 m, on top of the hill. Water depths at the other holes range from 2420 to 2438 m.

The two most complete sedimentary sequences at Site 856 are Holes 856A and 856B. In general, Hole 856A contains a "background" record of hemipelagic and turbiditic sedimentation weakly affected by the hydrothermal activity which altered the sediments in Hole 856B. The sediments recovered at Site 856 are divided into six lithostratigraphic units (Table 3 and Fig. 10).

# **Lithologic Units**

## Lithologic Unit I

Sections 139-856A-1H-1, 0 cm, to -1H-2, 82 cm (0 to 2.32 mbsf); Holocene.

Lithologic Unit I is present only in Hole 856A. It is massive greenish gray (5GY 5/1) to gray (5Y 5/1) silty clay of Holocene age. The unit is 2.32 m thick and includes three silty laminations (<1 cm thick), probably distal deposits of turbidity currents. Foraminifers, radiolarians, and diatoms are common biogenic components. The unit is interpreted to be largely a hemipelagic sequence, probably deposited during the last sea level high stand.

## Lithologic Unit II

Lithologic Unit II is characterized by alternating hemipelagic and turbiditic sediments and is subdivided into four subunits based on hydrothermal alteration assemblages. Subunit IIA is weakly altered; Subunit IIC is moderately indurated and altered; Subunit IID is moderately to well indurated and contains abundant sulfide minerals. A fourth subunit, Subunit IIB, is recognized as an important slump deposit incorporating clastic sulfide.

#### Subunit IIA

Sections 139-856A-1H-CC, 0 cm, to -10X-CC, 34 cm (2.32 to 86.20 mbsf); Sections 139-856B-1H-1, 0 cm, to -3H-1, 70 cm (0 to 12.00 mbsf); Sections 139-856B-4H-6, 0 cm, to -5H-CC, 42 cm

Unit	Description (age)	Interval	Top (mbsf)	Bottom (mbsf)	Thickness (m)
I	Hemipelagic sediments (Holocene)	139-856A-1H-1, 0 cm, to -1H-2, 82 cm	0.00	2.32	2.32
IIA	Interbedded hemipelagic and	139-856A-1H-CC, 0 cm, to -10X-CC, 34 cm	2.32	86.10	83.88
	turbiditic sediments, weakly	139-856B-1H-1, 0 cm, to -3H-1, 70 cm	0.00	12.00	12.00
	altered (late Pleistocene-Pleistocene?)	139-856B-4H-6, 0 cm, to -5H-CC, 42 cm	28.30	39.80	11.50
		139-856C-1H-1, 52 cm, to 1H-5, 101 cm	0.52	7.01	6.49
ΠВ	Slumped (?) hemipelagic, turbiditic, and clastic sulfidic sediments (Pleistocene-Pleistocene?)	139-856B-3H-1, 70 cm, to -4H-5, 150 cm	12.00	28.30	16.30
IIC	Moderately altered, indurated	139-856A-11X-1, 0 cm, to -13X-CC, 5 cm	86.20	113.22	27.02
	hemipelagic and turbiditic	139-856B-6H-1, 0 cm, to -8H-4, 48 cm	39.80	62.30	22.50
	sediments with crystal molds and brecciation (Pleistocene?)	139-856B-9X-1, 26 cm, to -9X-CC, 22 cm	62.56	65.44	2.88
IID	Moderately to well-indurated hemipelagic and turbiditic sediments with downward increasing sulfide mineralization (Pleistocene?)	139-856B-10H-1, 0 cm, to -16X-CC, 13 cm	70.80	120.51	49.71
ш	Metalliferous, oxidized sediments (Holocene-?)	139-856E-1H-1, 0 cm, to -1H-1, 100 cm	0.00	1.00	1.00
IV	Clastic sulfide (Holocene-	139-856D-1H-1, 0 cm, to -1H-CC, 6 cm	0.00	5.00	5.00
	Pleistocene?)	139-856E-1H-1, 100 cm, to -1H-CC, 6 cm	1.00	1.43	0.43
		139-856F-1X-CC, 0 cm, to -3X-CC, 17 cm	0.00	17.37	17.37
		139-856G-1R-1, 0 cm, to -2R-CC, 6 cm	0.00	15.33	15.33
		139-856H-1R-1, 0 cm, to -1R-CC, 11 cm	0.00	4.04	4.04
v	Massive sulfide (Pleistocene-?)	139-856C-1H-1, 0 cm, to -1H-1, 52 cm	0.00	0.52	0.52
		139-856G-3R-1, 0 cm, to -7R-4, 78 cm	17.60	59.55	41.95
		139-856H-2R-1, 0 cm, to -17R-1, 43 cm	13.50	90.53	77.03
VI	Mafic intrusive rock (?)	139-856A-13X-CC, 5 cm, to -14X-CC, 76 cm	113.22	115.70	1.20
	850	139-856B-8H-CC, 0 cm, to -9X-1, 26 cm	62.30	62.56	0.26
		139-856B-16X-CC, 13 cm, to -16X-CC, 40 cm	120.51	120.78	0.27

#### Table 3. Lithostratigraphic units for Site 856.



Figure 9. A. Heat flow in the part of Middle Valley occupied during Leg 139. The area of Site 856 (shown in Figs. 4 and 9B is outlined). The quality of navigational control is variable; uncertainty of most measurement positions is about 100-200 m. B. Heat flow (in mW/m<sup>2</sup>) in the immediate vicinity of Site 856 superimposed on the acoustic image shown in Figure 4.

(28.30 to 39.80 mbsf); Sections 139-856C-1H-1, 52 cm, to -1H-5, 101 cm (0.52 to 7.01 mbsf); late Pleistocene–Pleistocene(?).

Sediment from Subunit IIA was recovered from Holes 856A, 856B, and 856C. It consists of interbedded greenish gray (5GY 4/1, 5/1, 6/1) to gray (5Y 5/1) silty clay and dark gray (N4) quartz and feldspar silt, silty sand, and sand. This subunit is similar to Unit I at Site 855. Commonly, the subunit comprises stacked Tb-e or Tc-e turbiditic sequences with sharp to scoured basal contacts overlain by sand or silt, that fine upward into hemipelagic clay.

This subunit contains an average of three turbidites per meter of recovered core. There is no systematic variation in the number of turbidites with depth in either Hole 856A or 856B. The coarse-grained (sand or silt) portion of individual turbidites is typically 5 to 10 cm thick.

Calcareous biogenic components include foraminifers, nannofossils, and spicules of unidentified origin. As discussed more thoroughly in the "Biostratigraphy" section (this chapter), the preservation of calcareous microfossils decreases with increasing burial depth and temperature. Calcareous components may have been leached by hydrothermal fluids. This latter mechanism seems particularly likely to have occurred in the lower part of Hole 856B where the concentration of inorganic carbon in the bulk sediment is very low (see "Organic Geochemistry" section, this chapter). Foraminifers persist only from Cores 139-856A-1H through -7H and 139-856B-1H through -3H. Nannofossils are found only in Cores 139-856A-1H through -4H, and 139-856B-1H. Some of this biogenic calcite may have been transferred to diagenetic carbonate nodules. Carbonate concretions, probably calcitic, occur in Cores 139-856A-3H through -10X, but were not observed in Hole 856B.

Siliceous biota, specifically diatoms, radiolarians, silicoflagellates, and sponge spicules, are found only in Cores 139-856A-1H through -3H and in Core 139-856B-1H. Siliceous microfossils are normally abundant in the hemipelagic sediment. They also commonly occur in nearly pure, white, millimeter-scale pockets that may be burrow infillings. Biogenic silica, like its calcareous counterpart, is lost with increasing burial depth and temperature at this site.

Sediments of Subunit IIA become progressively more compacted with increasing burial, but remain unconsolidated to weakly indurated. No positive identification of cementation has been made in this subunit.



Figure 9 (continued).



Figure 10. Hole-to-hole correlation of lithostratigraphic units, Site 856.

### Subunit IIB

Sections 139-856B-3H-1, 70 cm, to -4H-5, 150 cm (12.00 to 28.30 mbsf); Pleistocene-Pleistocene(?).

Subunit IIB consists of an upper interval of interbedded hemipelagic and turbiditic sediment, a middle interval interpreted as interbedded turbidites and gravity flows which consist of normally graded, clastic sulfidic sediments (Sections 139-856B-3H-5, 109 cm, to -4H-3, 37 cm; 18.39 to 24.17 mbsf), and a lower interval of interbedded hemipelagic and turbiditic sediment. Section 139-856B-4H-6 is composed of hemipelagic gray clay but contains laminations of pyrite less than 1 mm thick at depths of 11, 30, 78, 93, 107, and 148 cm. This pyrite appears to have formed authigenically.

In the lower interval, a sequence of strata with dipping contacts begins at the base of Section 139-856B-4H-5 and continues upward to -4H-4, 58 cm. The dipping contacts occur at the bases of fining-upward sequences, are typically between gray clay and silt to fine sand with minor pyrite, and dip from 20° to 30° (relative to horizontal across the cut surface of the core liner). Above this sequence of dipping strata, a sequence of homogeneous gray clay (similar to the sequence that forms the base of this interval) with dark gray laminations that trend horizontally across the cut surface of the core continues upward to Section 139-856B-4H-3, 105 cm. Another sequence of

dipping strata tops the interval. This uppermost sequence contains beds that dip an average of  $30^{\circ}$ .

The direction of dip, relative to the cut surface of the core, changes four times along the length of Core 139-856B-4H. This dip change is a result of rotation of the dip vector about the axis of the core, such that when the dip of bedding is either into or out of the plane of the cut surface of the core, the intersection of the cut surface of the core and the bedding plane appears to be horizontal. These observations and the consistent upward-facing direction of all fining-upward sequences eliminates overturned folding as an explanation for the apparent reversal of dip within this interval. There is no clear consensus, however, among the shipboard sedimentologists about whether this rotation was an artifact produced by rotation of the APC core barrel during penetration or core removal, or whether it represents an internal rotational deformation of these units during slumping.

In the middle interval of Subunit IIB, a 6-cm-thick bed, graded upward from coarse pyrite sand to pyritic silty clay, is present at Section 139-856B-4H-3, 31–37 cm. This bed is the lowermost of a series of fining-upward sequences of clastic sulfide interbedded with turbiditic silts and sands and hemipelagic silty clays. A minimum of 10 similar fining-upward sequences occurs within the 5.8-m-thick, clastic sulfide-containing middle interval. Beds of clastic sulfide are typically 3 to 10 cm thick, ranging up to 20 cm thick. The beds are typically graded from medium or coarse sulfide sand to sulfidic mud. Clasts of massive sulfide occasionally range up to 2.5 cm in diameter. The clasts and larger sand grains are predominantly composed of pyrite that is often accompanied by interstitial botryoidal masses of white amorphous silica. Coarser beds generally have the brassy greenish yellow color of pyrite, but finer beds are generally black. Some beds, especially those near the top of the sulfide-rich interval in Section 139-856B-3H-6, are colored brick red by disseminated hematite, sometimes accompanied by orange to brown iron oxyhydroxides interpreted to have formed by weathering of massive sulfide during exposure to seawater. The restriction of the hematite coloring to discrete beds, and the occurrence of hematite throughout these beds rather than only on their upper surfaces, suggests that the hematite formed by weathering of the sulfide in the source area, rather than at the site of clastic deposition.

The turbiditic silt, sand, and hemipelagic clay interbedded with the clastic sulfide beds in the middle interval of Subunit IIB show the same range of thickness, grain size, and sedimentary structures as the sediment above and below the sulfide-rich interval. However, these turbidites differ in that they are more highly indurated and contain anomalously high concentrations of pyrite. The pyrite is preferentially concentrated in the coarse basal portions of the turbidites, but the upper clay-rich portions of the turbidites and the overlying hemipelagic clay are also generally semi-indurated and anomalously pyritic and semi-indurated. Clay-rich intervals are also locally very sulfidic and contain beds of fine-grained sulfide mud.

The sediments of this entire subunit are interpreted to be either a slump deposit, possibly derived from the sulfide mound (Holes 856C to 856H), or an in-situ rotated fault block. In either case their presence in Hole 856B proves that at the time of their redeposition, this site was deeper than a local source of sulfidic debris. Both alternatives also, most likely, require faulting, either to uplift the sulfide mound region to promote slumping or to uplift the margin of the abyssal hill (Hole 856A) to cause block rotation. The clastic sulfidic sediments within the subunit were probably derived from the nearby sulfide mound. It is possible that they were formed by the collapse of chimney structures and local redeposition of minor clastic sulfide turbidites interbedded with the background turbiditic and hemipelagic sediment. It is important to note that the slumped(?) interval does not repeat this section. This observation supports the notion that the original sediments were simply rotated in situ. If in-situ rotation did not occur, the clastic sulfide turbidites would have had to feather out very close to the mound and never have been originally deposited as far away from the mound as Hole 856B.

## Subunit IIC

Sections 139-856A-11X-1, 0 cm, to -13X-CC, 5 cm (86.20 to 113.22 mbsf); Sections 139-856B-6H-1, 0 cm, to -8H-4, 48 cm (39.80 to 62.30 mbsf); Sections 139-856B-9X-1, 26 cm, to -9X-CC, 22 cm (62.56 to 65.44 mbsf); Pleistocene(?).

Subunit IIC was recovered from Holes 856A and 856B. It is characterized by fining-upward turbiditic sequences similar to those of Subunit IIA. In this subunit, however, the emplacement of mafic intrusions may have caused increased induration, hydrothermal alteration, and brecciation and fracturing. These effects extend about 20 to 25 m above the intrusive rock at the base of Hole 856A, about 25 m above the mafic intrusion in the middle of Hole 856B, but less than 10 m below the same intrusion in Hole 856B. Because of the pervasive alteration throughout the interval, it is difficult to assess the extent of the impact of the basal intrusion in Hole 856B on alteration of the overlying sediment.

Another apparent consequence of hydrothermal alteration in this subunit is the common occurrence of lath-shaped crystal molds in the finer grained portions of Cores 139-856A-11X through -13X and Cores 139-856B-6H through -9X (Fig. 11). These molds may be the result of retrograde dissolution of anhydrite(?) that was originally precipitated from hot pore fluids.

Brittle fracturing and brecciation occur throughout much of the finer-grained portions of Cores 139-856B-6H, -7H, and -8H (Fig. 12). Millimeter- to centimeter-size angular clasts of gray (N4) silty clay are separated by a matrix of paler gray (N5) clay. Structures vary from fracturing without any differential displacement of original sedimentary layering, to total brecciation and possible flow of clasts along fractures.

The deformational behavior in the coarser grained, turbiditic sand and silt of the same cores is very different from that in the hemipelagic intervals (Fig. 13). These sediments apparently deformed plastically, resulting in convolute laminations.

One possible scenario (also see "Sediment Alteration and Geochemistry," section, this chapter) summarizes these alteration and deformation processes is as follows: (1) the fine sediments become mildly indurated as clay minerals recrystallize due to initial heating during igneous rock emplacement; (2) anhydrite grows in fine sediments due to continued heating; (3) pore fluid expands due to heating, causing increased pore pressure which fractures the fine sediments either hydraulically or mechanically; (4) at the same time, unlithified and fluidized coarser lithologies deform plastically; (5) pyrite precipitates hydrothermally along fractures.

#### Subunit IID

Sections 139-856B-10H-1, 0 cm, to -16X-CC, 13 cm (70.80 to 120.51 mbsf); Pleistocene(?).

Subunit IID occurs only beneath the mafic intrusion in Hole 856B. As in Subunits IIA and IIC, the primary sediments of Subunit IID are interbedded turbidites and hemipelagic sediments, but in this case they are characteristically moderately to well indurated. They contain increasing amounts of sulfide downcore and become hydrothermally altered downcore. Thus, Core 139-856B-11X contains local pyrite accumulations; Core 139-856B-12X contains pyrite in small quantities throughout its length as well as scattered pyrite nodules; Core 139-856B-13X contains both disseminated pyrite and discrete layers of pyrite; Core 139-856B-14X contains marcasite and disseminated sphalerite; Core 139-856B-15X contains pyrite, sphalerite, chalcopyrite, and pyrrhotite as fracture fills, laminations, burrow fills, and disseminated crystals. Core 139-856B-15X also contains silicified claystone, siltstone, and sandstone, disseminated barite crystals, barite vein fillings, and clay-replacing barite, and abundant authigenic chlorite (Fig. 14). Core 139-856B-16X contains drilling fragments of silicified siltstone with aggregates of chalcopyrite and euhedral pyrite.

# Lithologic Unit III

Sections 139-856E-1H-1, 0 cm, to 139-856E-1H-1, 100 cm (0.00 to 1.00 mbsf); Holocene-(?).

Unit III consists of surficial, oxidized sediments overlying a breccia of massive sulfide. The unit is variably colored: dark yellowish brown (10YR 4/4), light olive brown (2.5Y 5/4), very dark gray (N3), olive yellow (5GY 6/1), and pale gray (2.5Y 6/1). It is believed that most of the sediment in this unit formed *in situ* by the oxidation of underlying sulfide to iron oxyhydroxides and by the precipitation of authigenic clay minerals. Common biogenic components include diatoms and well-preserved foraminifers. No nannofossils are present. The top of this unit is Holocene.

## Lithologic Unit IV

Sections 139-856D-1H-1, 0 cm, to -1H-CC, 6 cm (0.00 to 5.00 mbsf); Sections 139-856E-1H-1, 100 cm, to -1H-CC, 6 cm (1.00 to 1.43 mbsf); Sections 139-856F-1X-CC, 0 cm, to -3X-CC, 17 cm



Figure 11. Close-up photo of interval 139-856B-7H-6, 1–17 cm. Crystal molds of anhydrite(?) in fine, hemipelagic sediment of Subunit IIC.



Figure 12. Close-up photo of interval 139-856B-6H-2, 100-130 cm. Brittle fracture and brecciation of silty clay in Subunit IIC.



Figure 13. Close-up photo of interval 139-856B-6H-2, 56-71 cm. Plastic deformation of turbidite sand and brittle deformation of silty clay in Subunit IIC.

(0.00 to 17.37 mbsf); Sections 139-856G-1R-1, 0 cm, to -2R-CC, 6 cm (0.00 to 15.33 mbsf); Sections 139-856H-1R-1, 0 cm, to -1R-CC, 11 cm (0.00 to 4.04 mbsf); Holocene–Pleistocene.

Unit IV consists of sulfide sand recovered at the tops of Holes 856D, 856F, 856G, 856H, and near the top of 856E. These sediments probably formed either by chimney collapse and sulfide resedimentation or by surficial weathering of underlying massive sulfide. These materials were subsequently thoroughly disaggregated by coring or drilling. These sediments are discussed in the "Sulfide Petrology" section (this chapter).

# Lithologic Unit V

Sections 139-856C-1H-1, 0 cm, to -1H-1, 52 cm (0.00 to 0.52 mbsf); Sections 139-856G-3R-1, 0 cm, to -7R-4, 78 cm (17.60 to 59.55 mbsf); Sections 139-856H-2R-1, 0 cm, to -17R-1, 43 cm (13.50 to 90.53 mbsf); Pleistocene–(?).



Unit V consists of massive sulfide recovered throughout most of the lower parts of Holes 856C, 856G, and 856H. These are discussed in the "Sulfide Petrology" section (this chapter).

#### Lithologic Unit VI

Sections 139-856A-13X-CC, 5 cm, to -14X-CC, 76 cm (113.22 to 115.70 mbsf); Sections 139-856B-8H-CC, 0 cm, to -9X-1, 26 cm (62.30 to 62.56 mbsf); Sections 139-856B-16X-CC, 13 cm, to -16X-CC, 40 cm (120.51 to 120.78 mbsf); (?).

Unit VI consists of mafic intrusive rocks recovered at the base of Hole 856A, at the base of 856B, and in a short interval in the middle of Hole 856B. These rocks are discussed in the "Igneous Petrology" section (this chapter).

## Lithostratigraphic Interpretation of Magnetic Susceptibility Records

The magnetic susceptibility (MS) records for Holes 856A and 856B are presented in the "Paleomagnetism" and "Physical Properties" sections (this chapter). These data have at least two important implications for lithostratigraphy as discussed below.

Identification of an interval of extremely low MS in the upper parts of Holes 856A, 856B, and 857A may permit correlation between these holes. This low-MS interval occurs between 34.9 and 39.1 mbsf in Hole 856A (4.2 m thick), 14.8 and 18.4 mbsf in Hole 856B (4.6 m thick), and about 16.0 and 21.0 mbsf in Hole 857A (about 5.0 m thick). This interval lies within Subunit IIA in both Holes 856A and 856B. If correlatable, the difference in the sub-bottom depth of the top of the interval in Holes 856A and 856B implies that approximately 20 m of sediment was eroded from the top of Hole 856B either by slow mass wasting or by slumping.

Detailed smear slide observations (Section 3, this volume) comparing sediment from adjacent low-MS and high-MS intervals failed to reveal any obvious differences in magnetic mineral composition or abundance between the intervals. Furthermore, no systematic decrease in thickness, frequency, or grain size of turbidites has been observed between intervals. The only observed difference is that the low-MS sediment contains much more siliceous or calcareous microfossil remains than surrounding high-MS sediments. This difference implies that the low-MS interval was deposited during a time of higher biological productivity, possibly during an interglacial stage. Confirmation of this speculation awaits further biostratigraphic analysis.

One possible explanation for the lower MS signal during this interval is the alteration of detrital magnetite to pyrite, perhaps due to an increased deposition rate of organic carbon, which would have enhanced the rate of sulfate reduction. A second possibility is that the source sediments were different during the low-MS interval because of different rates of continental weathering or changes in sea level. These hypotheses also require further study.

A second interval of very low MS occurs in the lower part of Hole 856B (at all depths greater than 34.2 mbsf). This low-MS interval is believed to have been brought about by the destruction of detrital magnetite, possibly due to hydrothermal pyritization. Within this interval, disseminated pyrite is concentrated in the turbiditic silt and sand. Furthermore, the sand and silt in the lower part of Hole 856B are lighter colored than the clay, whereas in the upper part of Holes 856A and 856B the sand and silt are darker than the clay. This may point to the pyritization of mafic minerals in the coarser units in the lower part of Hole 856B.

# BIOSTRATIGRAPHY

Figure 14. Close-up photo of interval 139-856B-15X-CC, 0–24 cm. Cross-laminated, planar-laminated, and burrowed turbiditic sequence of silicified siltstone to silty claystone mineralized along laminations (3–5 cm and 20 cm) and crosscutting burrows (10–13 cm) in Subunit IID. Veins are filled by barite-chlalcopyrite with dark chloritic selvages developed in the sediment along the vein margins.

Site 856 is situated over a small uplifted hill that has been hydrothermally active in the past. The lithology at this site consists of turbidites, coarse clastic layers of massive sulfide interbedded with silt to fine sand turbidites, and massive sulfide. Foraminifers and nannofossils were originally rare in the coarse portion of these turbidites, and hydrothermal alteration has reduced their abundance even further. Foraminifers occur in 57% of the samples examined; calcareous nannofossils occur even less frequently, in only 18% of the samples examined. The age of sediments cored from the fossiliferous intervals of Holes 856A and 856B is late Pleistocene, as evidenced by the foraminifers and calcareous nannofossils (Table 4). Barren samples were questionably dated as late Pleistocene (Table 4). At the request of the geochemists, we did not prepare several core-catcher samples that appeared altered by hydrothermal fluids, and we did not prepare samples of massive sulfide.

# Table 4. Comparison of sequences zoned by calcareous nannofossils (Martini, 1971) and planktonic foraminifers.

Sample	Depth (msbf)	Age	Foraminifer zone	Nannofossil zone	
Hole 856A					Е.
1H-1, 0-1 cm	0.0	Holo.	CD1	h	<i>uxleyi</i> Acme
1H-CC 2H-CC 3H-CC 4H-CC	2.7 12.2 21.7 31.2	late Pleist.	CD2?	NN	21
SH-CC	40.7	Pleist.			
7H-CC 8H-CC 9H-CC 10X-CC	59.7 69.2 78.7 86.2	Pleist.		?	
11X-CC 12X-CC 13X-CC	95.7 105.3 114.5	?	2		
Hole 856B	0.0	late Pleist.		NN- 21	E. uxleyi Acme
1H-CC 2H-CC 3H-CC	1.8 11.3 20.8	Pleist.	CD2?		
4H-CC 5H-CC 6H-CC 7H-CC 8H-CC 9H-CC 10H-CC 11X-CC 12X-CC 13X-CC 13X-CC 15X-CC 16X-CC	30.3 39.8 49.3 58.8 62.3 70.8 73.3 81.6 91.1 100.8 110.4 120.1 121.7	Pleist- ocene?	?	?	
Holes 856C through 856G 856C-1H-1, 0-1 cm 856C-1H-CC	0.0 2.0	Pleist.	CD2	?	
856D-1H-1, 0-1 cm 856D-1H-CC	0.0 5.0	?	?	?	
856E-1H-1, 0-1 cm 856E-1H-CC	0.0 2.4	Holo.	CD1	?	
856C-1H-1, 0-1 cm	0.0	?	?	-	

#### Foraminifers

A total of 35 samples were examined from Site 856: six mulline core tops, 28 core-catcher samples, and one composite sample of foraminifers picked directly from split Sections 139-856H-1R-1, 139-856H-1R-2, and 139-856H-1R-3, a slumped gravel of massive sulfide. Preservation and abundance of foraminifers at the massive sulfide locality was, in general, quite poor. Of the 35 samples examined, 20 are barren, only six have abundant planktonic foraminifers, and only four have abundant benthic foraminifers (Table 5).

The planktonic foraminiferal fauna (Table 6) bears species typical of subarctic waters and includes *Globigerina bulloides* d'Orbigny, *Globigerinita glutinata* (Egger), *Globigerinita minuta* (Natland), *Globigerinita uvula* (Ehrenberg), sinistral and dextral *Neogloboquadrina pachyderma* (Ehrenberg), and *Turborotalita quinqueloba* (Natland). Transitional species include *Orbuline universa* d'Orbigny and *Globorotalia scitula* (Brady) and are few to rare in abundance. Subtropical species include *Globorotalia theyeri* (Fleischer) and *Pulleniatina obliquiloculata* (Parker and Jones), the latter of which is found only in the mudline core of Hole 856B.

Holocene-age sediment was observed at the surface in two of eight holes. In Hole 856A, the epoch was recognized using the relative frequency of dextral to sinistral Neogloboquadrina pachyderma (Bandy, 1960) (Table 6). Dextral coiling forms are more frequent than sinistral forms at this latitude in the North Pacific Ocean during interglacial climatic intervals. The dextral form occurs commonly relative to the sinistral form in Sample 139-856A-1H-1, 0-1 cm, whereas the dextral form is absent from all core-catcher samples in Hole 856A. One other sample from the top of a mudline core, Sample 139-856E-1H-1, 0-1 cm, contains planktonic foraminiferal species known from the Holocene and other interglacial times. The association consists of Globigerina bulloides, dextral Neogloboquadrina pachyderma, and Orbulina universa transitional and subarctic species that inhabit this region in abundance in the late spring, summer, and fall, respectively, in the present day (Sautter and Thunell, 1989). The two samples described above, 139-856A-1H-1, 0-1 cm, and 139-856E-1H-1, 0-1 cm, are assigned to the planktonic foraminiferal assemblage Zone CD1 of Lagoe and Thompson (1988). We place the Holocene-Pleistocene boundary within Core 139-856A-1H. The Holocene sediments in Hole 856E lie unconformably above massive sulfide deposits, and it is unlikely that the Holocene-Pleistocene boundary is present.

All other samples that bear planktonic foraminifers in Holes 856A, 856B, and 856C are tentatively assigned to Zone CD2. The topmost sediment from Holes 856B and 856C bear a glacial Pleistocene fauna, Hole 856D is barren of foraminifers, and Hole 856H is barren of planktonic foraminifers although rare agglutinated benthic foraminifers are present as detritus slumped from the surface into Cores 139-856H-1R through -3R during drilling. No material was examined from the massive sulfide deposits of Hole 856F.

The benthic assemblage consists of species from depth zones ranging from neritic to lower bathyal (Table 6). Lower and lower-middle bathyal species dominate most samples, consistent with the depth of Site 856. Prominent members of the in-situ fauna include Cibicides wuellerstorfi, Gyroidina altiformis, Gyroidina planulata, Hoeglundina elegans, Melonis pompilioides, Pullenia bulloides, Sphaeroidina bullides. Uvigerina dirupta, and Uvigerina senticosa. Species from neritic and upper bathyal depths in the Gulf of Alaska (Bergen and O'Neil, 1979) and Queen Charlotte Sound (R. Patterson, unpubl. data, 1991) persist in minor amounts throughout most of the foraminiferbearing samples. Upper bathyal species include Stainforthia complanata, Globobulimina affinis, Bulimina barbata, and Bolivina pacifica. Neritic taxa include Cribroelphidium foraminosum, Globobulimina pacifica, Nonion, Nonionella, Pullenia salisburyi, Elphidium, Buliminella elegantissima, and Rosalina. Neritic and upper bathyal species are most abundant in some turbiditic samples, suggesting a shelf source and a pathway down the slope. Foraminiferal abundance

Sample	Lithology	Nannofossil abundance	Benthic foraminifer abundance	Planktonic foraminifer abundance
139-856A-				
1H-1, 0-1 cm	Brown clay	С	С	С
1H-CC	Greenish gray clay	C	C	A
2H-CC	Graded sand	R	в	B
3H-CC	Silty clay	A	č	Ā
4H-CC	Disturbed sand and clay	R	A	A
5H-CC	Grav clav	в	A	A
6H-CC	Graded sand	B	C	C
7H-CC	Graded sand	В	в	B
8H-CC	Disturbed	В	в	B
9H-CC	Graded sand	в	B	B
10X-CC	Graded sand	B	В	В
139-856B-				
1H-1, 0-1 cm	Olive green clay		С	А
1H-CC	Dark gray clay	A	A	A
2H-CC	Clay above laminated zone	в	В	в
3H-CC	Sulfide and clay breccia	в	R	R
4H-CC	Clay	в	в	В
5H-CC	Clay	в	R	В
6H-CC	Hydrothermal breccia	В	в	в
7H-CC	Graded sand	в	в	в
8H-CC	Basalt sill	В	в	В
9X-CC	Altered silty claystone	в	в	В
10X-CC	Graded mudstone	в	в	в
11X-CC	Graded sand	в	в	В
12X-CC	Graded sand	в	в	в
13X-CC	Silty clay	в	в	В
14X-CC	Brecciated sandstone	в	в	в
15X-CC	Sulfide	в	в	в
16X-CC	Basalt and sandstone drilling breccia	В	В	В
139-856C-				
1H-1.0-1 cm	Clay	в	R	F
1H-CC	Disturbed	R	R	Ċ
139-856D-				
1H-1, 0-1 cm	Sulfide sand	в	В	В
1H-CC	Sulfide sand	В	в	в
139-856E-				
1H-1.0-1 cm	Gossin	в	A	F
1H-CC	Massive sulfide	В	В	В
139-856G-1R-1, 0-1 cm	Clay	-	R	В
139-856H-				
-1R, -2R, -3R	Drilling breccia	-	R	В

Table 5. Comparison of abundance of calcareous nannofossils, planktonic foraminifers, and benthic foraminifers with lithology of sample.

Note: A = abundant, C = common, F = few, R = rare, B = barren.

is low in well-sorted, fine sand units (for example, Samples 139-856A-2H-CC and 139-856A-7H-CC to 139-856A-10X-CC) due to hydraulic sorting during turbidite emplacement.

As at Site 855, the Holocene fauna of Site 856 differs from the Pleistocene fauna. *Hoeglundina elegans* occurs in the Holocene and is absent from the Pleistocene. Unlike Site 855, however, *Uvigerina dirupta* occurs in the Pleistocene fauna and *Melonis* occurs in the Holocene fauna of Site 856 (Table 6).

## **Calcareous Nannofossils**

Only six of 33 samples examined from Holes 856A and 856B contain calcareous nannofossils. The remaining 27 samples are completely barren of nannofossils due to the unfavorable preservational conditions in coarse turbidites, altered silt and mud, and sulfide (Table 5). The nannofossils from Pleistocene deposits are usually as small as 1.5 to 13  $\mu$ m and very light in weight. Their size varies from species to species and from taxa to taxa. For example, *Emiliania huxleyi* is usually 2 to 4  $\mu$ m, species of *Gephyrocapsa* from the upper Pleistocene are typically 3 to 4  $\mu$ m, and *Coccolithus pelagicus* is commonly larger than 5 and as large as 13  $\mu$ m. Winnowing and sorting during turbidite transportation and deposition, therefore, strongly affected the fossil abundance, species diversity, and preservation at Site 856. For example, those six samples in which nannofossils are common to abundant are composed of clay (for example, Sample 139-856A-3H-CC), and those in which nannofossils are rare are composed of sand and/or coarse turbidite materials (for example, Sample 139-856A-4H-CC) (Tables 5 and 7).

Hydrothermal alteration also affected the fossil abundance and preservation. For example, 20 of 27 barren samples are either sulfide or altered silt or mud. The fossil preservation at Site 856 is generally poor. For example, the central bridge of *Gephyrocapsa* is sometimes dissolved; *Coccolithus pelagicus* in Samples 139-856A-3R-CC and 139-856A-4R-CC exhibits calcite overgrowth in addition to dissolution.

The species diversity at this site is lower than at Site 855, perhaps because of more unfavorable preservational conditions. The nannofossil flora includes eight species: *Gephyrocapsa caribbeanica, Emiliania huxleyi, E. pujosae, Coccolithus pelagicus, Calcidiscus leptoporus, Braarudosphaera bigelowii, Pontosphaera japonica,* and *Syracosphaera pulchra.* 

The nannofossil assemblages from Cores 139-856A-1H to -4H and Sample 139-856B-1H-CC were assigned to Zone NN21 (Martini, 1971) on the basis of the occurrence of *Emiliania huxleyi* in samples from the interval (Table 7). *Emiliania huxleyi* is common in Samples 139-856A-1H-CC and -1H-CC; therefore, the Acme Zone of the species (Gartner, 1977) exists at both holes. The base of the Acme Zone, however, cannot be precisely pinned because investigations of nannofossils were limited to core-catcher samples. The base will be located during shore-based studies using both light and scanning electron microscopy.

#### Alteration

Foraminifers in Hole 856A show a zone of alteration beginning at Sample 139-856A-3H-CC and culminating in Sample 139-856A-6H-CC. Most of the abundant planktonic foraminifers in Sample 139-856A-3H-CC have calcite crystals protruding in a coarse stubble from their surfaces. Some of the benthic foraminifers appear chalky in color and/or sugary in texture when normally they are a transparent yellowish hue and smooth. Affected specimens include the species Uvigerina dirupta, Globobulimina ovula, some lagenids, and Cibicides kullenbergi. Coarse masses and crystals of calcite also occur in the sand-size fraction. In Samples 139-856A-4H-CC and 139-856A-5H-CC, all specimens look altered. Most have a sugary surface texture and some appear to have a polished, clear coating. Planktonic foraminifers are still abundant, as are benthic foraminifers. In Sample 139-856A-6H-CC, foraminifers are common in occurrence but they are poorly preserved. It is difficult to identify some specimens. Most tests have a sugary coating and are chalky in color. Foraminifers are absent from Sample 139-856A-7H-CC and all samples below are barren. The calcareous nannofossils show both dissolution and calcite overgrowth between Samples 139-856A-3H-CC and -4H-CC. All samples from Sample 139-856A-5H-CC to the base of the hole are barren of calcareous nannofossils. The absence of foraminifers and calcareous nannofossils in this interval may be caused by winnowing of tests from turbiditic sands during their emplacement (Table 5) as well as by chemical alteration.

Fossil preservation in Hole 856B is notably different from that in Hole 856A. Most notably, the foraminifers show no evidence of recrystallization in Hole 856B and poor preservation is due to simple dissolution of the tests. Foraminifers are abundant and moderately well preserved in the topmost core, as are the calcareous nannofossils, but carbonate fossils virtually disappear below this depth. Sample 139-856B-2H-CC is barren of both foraminifers and calcareous nannofossils, and the remaining sequence is barren of all calcareous nannofossils. Samples 139-856B-3H-CC and -5H-CC contain only agglutinated benthic foraminifers. The barren core-catcher samples below 139-856B-5H-CC are from units unlikely to preserve microfossils, such as turbidite sands, sulfide deposits, other hydrothermal deposits, and basalt sills.

The depth at which carbonate fossils become rare to absent in Hole 856B is 30 to 40 mbsf shallower than in Hole 856A, but the depth difference may not be related to style of alteration at the two holes. Several lines of evidence suggest that 20 to 30 m of sediment is missing from the top of Hole 856B (see "Physical Properties" and "Paleomagnetism" sections, this chapter). The Pleistocene age of the surficial sediments in Hole 856B compared with the Holocene age of surficial sediment in Hole 856A supports this interpretation.

#### PALEOMAGNETISM

Site 856 is located on and just south of a hill of uplifted sediment where massive sulfide deposits occur in outcrop. Holes 856A and 856B were drilled on the center and on the southern flank of the hill, respectively. Hole 856G was drilled into a low ridge of outcropping massive sulfide just south of the hill.

The first nine cores from Hole 856A and the first eight cores from Hole 856B were recovered with the APC system and were suitable for paleomagnetic investigations. Cores 139-856A-10X to -14X and 139-856B-9X to -16X were drilled using the extended core barrel (XCB) and showed minor to heavy core disturbance depending on the nature of the sediment recovered. Poor core recovery and disturbed sediment make it difficult to interpret paleomagnetic data from the latter intervals.

The archive halves of Holes 856A and 856B were measured with the pass-through cryogenic magnetometer to obtain their natural remanent magnetization (NRM). Each section of core was demagnetized at peak alternating fields (AF) of 5, 10, and 15 milliTesla (mT). The NRM intensities of the sediment cores for Hole 856A were high, between 10 and 1000 mA/m. Intensities of sediment from Hole 856B were generally lower, between 0.1 and 1000 mA/m.

Nineteen oriented, discrete samples were taken from the working half of sediment cores from Holes 856A and 856B and were progressively demagnetized to 5, 10, 20, 30, 40, 50, 65, 80, and 95 mT using the Schonstedt demagnetizer. Intensities were measured with the Molspin spinner magnetometer. One discrete sample cube of diabase from Hole 856A and five discrete cubes of sulfide from Hole 856G were also demagnetized and measured with the spinner magnetometer.

Magnetic susceptibility of all cores was measured using the multisensor track (MST) at 2-cm intervals before splitting. Downhole susceptibility profiles can be interpreted as reflecting fluctuations in the volume concentration of magnetic particles.

#### Results

#### **Magnetic Properties**

Holes 856A and 856B contain sequences of turbidite flows, whose magnetic susceptibility is quite high and variable  $(10^{-4} \text{ to } 10^{-2} \text{ SI})$ . Normally the susceptibility is used to correlate depth between different holes at a site, although at Site 856 no clear correlation is immediately evident (Fig. 15A, 15B).

In Hole 856A (Fig. 15A) the volume magnetic susceptibility lies between  $10^{-3}$  and  $10^{-2}$  SI at 0-32 mbsf; below that it decreases abruptly to  $3 \times 10^{-4}$  SI. This interval of extremely low volume magnetic susceptibility contains more siliceous or calcareous microfossils than the surrounding sediments with higher susceptibilities. This difference implies that the material was deposited during a time of higher biological productivity, possibly during isotopic stage 5 (see "Biostratigraphy" section, this chapter). Another possible explanation for the low volume magnetic susceptibility interval is the alteration of detrital magnetite to pyrite. Confirmation of these speculations awaits further studies.

At 40 mbsf the susceptibility increases again to a value similar to that in the upper part of the hole. At 46 mbsf the susceptibility decreases to  $10^{-3}$  SI and remains constant to 88 mbsf. By 100 mbsf it has decreased further to about  $3 \times 10^{-4}$  SI.

In Hole 856B (Fig. 15B) the susceptibility lies between  $2 \times 10^{-4}$  SI and  $10^{-1}$  SI for the first 36 mbsf. Below 36 mbsf the susceptibility fluctuates less and reaches a background value of  $2-3 \times 10^{-4}$  SI. This marked decrease in the magnetic susceptibility is probably caused by the hydrothermal alteration of magnetite. Only at a depth near 20 mbsf

Sample (cm)	Abundance of benthic foraminifers	Abundance of planktonic foraminifers	Preservation of foraminifers	Globigerina bulloides	Globigerinita glutinata	Globigerinita minuta	Globigerinita uvula	Globorotalia scitula	Globorotalia theyeri	Neogloboquadrina pachyderma (dex.)	Neogloboquadrina pachyderma (sin.)	Orbulina universa	Pulleniatina obliquiloculata	Turborotalita quinqueloba	Agglutinated taxa	Ammodiscus sp. A	Cribrostomoides sp. A	Eggerella bradyi	Hormosina sp. A	Hyperammina sp. A	Saccammina sp. A	Spirosigmoilinella (?)	Trochammina sp. A
139-856A-																							
1H-1, 0-1 1H-CC 2H-CC 3H-CC 4H-CC 5H-CC 6H-CC 7H-CC 8H-CC 9H-CC 10X-CC	C B C A C B B B B B	C A B A A C B B B B B B	M G M P P P 	C A A C ·			F R	R R F		C	F A			F C C	x · ·	<b>x</b>	x	x x ·	x 	<b>x</b>	<b>x</b>	x	
139-856B-									1														
1H-1, 0-1 1H-CC 2H-CC 3H-CC 5H-CC 6H-CC 8H-CC 9H-CC 10H-CC 11X-CC 12X-CC 13X-CC 14X-CC 15X-CC 15X-CC	C A B R B R B B B B B B B B B B B B B B B	A B B B B B B B B B B B B B B B B B B B	M M P 	A A	C F · · · ·	0	. <b>R</b>	F F · · · · · · · · · · · · · · · · · ·		(2) 水水水 医子子 医子宫 医子宫	A A		R 101 5 5 5 5 5 5 4 4 5 10 101 5 5 5	C . R .	· · · · <b>· · · · · · · · ·</b> · · · · · ·			x x · · · · · · · · · · · · · · · · · ·		다 1908년 번 번 번 번 번 번 것 같 않았던 번			计正式分子 化化化化化化化化化
139-856C-																							
C-01H-1, 0–1 C-01H, CC	R R	F F	P M	F C	R	R	R	R	a a	× ×	F C	a a		F	3	•	•	(*); (*);	ж а	e e	er K	38 18	•
139-856D-																							
1H-1, 0–1 1H-CC	B B	B B	<u>.</u>		•		•	•					•		• •		•	•	2	2.325			•
139-856E-			2																1				
1H-1, 0–1 1H-CC	A B	F B		F ,	34) (*)	•	•	(*) (*)		R	т. К	F	÷	*	x	x ,	x ,	x	*	÷	х	2 (*	х
139-856G-1H-1, -CC	R	В	G	R	040	×	98) (18)	(a):	3+		a))	39	ж	*		*	80	1.0		ж	ĸ		×
139-856H-1R-1, -2, -3	R	1.00	Р		1411	2	50		1 54		2	24	*		х	х		197	- 14	÷		54	*
139-856G-1H-1, -CC	- 20	4	2	12		ų.	2		- Q	÷	÷	71	5	20	25		ţ:	120	SF	¥2	×.	2	÷
139-856H-1R-1123	1 2		1.	10.2										1.15					1.5	22	12	12	

Table 6. Range chart of planktonic and benthic foraminifers, their abundance and preservation, and abundance of other major constituents of the sand-size fraction.

139-856H-1R-1, -1, -2, -3
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#### Table 6 (continued).

Sample (cm)	Miliolina spp.	Pyrgo murrhina	Triloculina	Bolivina pacifica	Bolivina spp.	Bulimina barbata	Buliminella elegantissima	Buliminella tenuata	Cassidulina cushmani	Cassidulina laevigata carinata	Chilostomella oolina	Cibicides kullenbergi	Cibicides mckannai	Cibicides wuellerstorfi	Cribroelphidium foraminosu	Dentalina frobisherensis	Elphidium spp.	Eponides turgida	Globobulimina affinis	Globobulimina ovula	Globobulimina pacifica	Globocassidulina spp.	Gyroidina altiformis
139-856A-																							
1H-1, 0-1 1H-CC 2H-CC 3H-CC 4H-CC 5H-CC 6H-CC 7H-CC 8H-CC 9H-CC 10X-CC		<b>x</b>	x	x x x x x x	×	: x : : :	· · · · ·		x		x x x x x	x x	x	x x		x	x	x x	X X	x	x		0000 J. D. A.
139-856B-																							
1H-1, 0–1 1H-CC 2H-CC 3H-CC 6H-CC 6H-CC 8H-CC 9H-CC 10H-CC 10H-CC 12X-CC 13X-CC 13X-CC 15X-CC				<b>X</b>	化化化化化化化化化化			· <b>X</b>	ស្តេតថ្ថា ជាក្បាស់ ស្តេតស្	X	x 	医脊髓炎 化硫酸钙医硫酸酸 医	x 	<b>X</b>	X			X	X		x 	x	
139-856C-							208		·				1.00						*.)				. 4
C-01H-1, 0–1 C-01H, CC 139-856D-	1993 - 1993 1993 - 1993		•		81 42 42	(*) (*)	1. 12	î.		27 22		5) 16		2	1997 - 13		5 <b>9</b> 2 •3	•	140.000		÷.		•
1H-1, 0–1 1H-CC	ж Э	e e	•	*	ii X	06 (4)	3	•	•	34 53		87 80	240 040	÷		()K) ()K)	12 13	×	•		:	•	0
139-856E- 1H-1, 0–1 1H-CC	x	2		•			•		1.1.1					1.00			2	-	1	64 55	-	21 22	
139-856G-1H-1, -CC	,	,		ः 	*			۰ ب	30 •0			72	2070 2010	30 34	•		50 54						
139-856H-1R-1, -2, -3		er je	5.4N		*					54									*5				
139-856G-1H-1, -CC		×	7.(*)		*	-						10	(94):	*								*:	
139-856H-1R-1, -1, -2, -3	*	×	2(6))	8	×		9		8	54."	a.	2	(a))	×		18	3¥		÷	-		÷	2413

do we observe high values of susceptibility, which are correlated with occurrences of interbedded massive sulfide (see "Sulfide Petrology" section, this chapter).

Many characteristics of NRM intensity profiles of Hole 856A and 856B are strikingly similar to those of the magnetic susceptibility profiles. An even better correlation is present when the intensity plots after 15-mT demagnetization are used (Fig. 16A, 16B). A vertical offset of 21 m was observed between the two holes in intensity values and in stable directions of the inclination after 15-mT demagnetization, suggesting that the sediment corresponding to the upper 21 m of sediment in Hole 856A may be missing in Hole 856B. This suggestion is supported by the absence of Holocene nannofossils and foraminifers in Hole 856B (see "Biostratigraphy" section, this chapter).

The NRM directions have very steep negative inclinations, which are probably produced by a consistently strong overprint induced by

#### Table 6 (continued).

Sample (cm)	Gyroidina planulata	Gyroidina quinqueloba	Gyroidina sp. A	Hoeglundina elegans	Lagenids	Melonis barleeanum	Melonis pompilioides	Nonion sp. A	Nonionella spp.	Oridorsalis tener	Pullenia bulloides	Pullenia quinqueloba	Pullenia salisburyi	Rosalina sp. A	Sphaeroidina bulloides	Stainforthia complanata	Uvigerina dirupta	Uvigerina senticosa	Valvulineria laevigata	Valvulineria sp. A	Valvulineria spp.	Others:	Clay lumps
139-856A-																							
1H-1, 0-1 1H-CC 2H-CC 3H-CC 5H-CC 5H-CC 6H-CC 7H-CC 8H-CC 9H-CC 10X-CC	x	x	X X · ·	X	x x · x · ·	x x	x		×x	x		x	x	网络黄金属黄金属	X	x x x x	x · ·	X X	x 	x			A
139-856B-																							
1H-1, 0–1 1H-CC 2H-CC 3H-CC 5H-CC 6H-CC 8H-CC 9H-CC 10H-CC 10H-CC 12X-CC 13X-CC 13X-CC 13X-CC 15X-CC 15X-CC	X X	* * * * * * * * * * * * * *	· x	化化合金 化化化合合物 化化化合合物	x	x	X X		计分析 计存在 计算机 化化合物	医子宫 化化化化化化化化化化化化	x x	<b>x</b> · · · · · · · · · · · · · · · · · · ·	<b>X</b>	·x		x	<b>X</b> • • • • • • • • • • • • • • • •	X X	<b>x</b>	x	计选择 化乙酰胺 化化化合物 化化合物 化		· · · · · · · · · · · · · · · · · · ·
139-856C-																							
C-01H-1, 0–1 C-01H, CC	12		2 2	2 2	Na	3 4	ж 4	13 121	04 14	ж Ф	22 27	a a	я q	2 2	а. А	2	2) 22	Ŕ	R	R	4 4		•
139-856D-																							
1H-1, 0–1 1H-CC	20 20		*	21 20		82 83	*	98) 98	2	* *	± €	2	2 3	8) 12	2393 2393	0 13	7. 22	755 326	2 2	2) 3	2		
139-856E-																							
1H-1, 0–1 1H-CC	81 10	90) 90	а 4	i. X	00) 141	34 34	9 2	18 2	а 3	*	80 80	91 54	э ж	× e		*		x	;	× ×	• •		*
139-856G-1H-1, -CC	1.2	94.	2	2	120	8	۹	10	ы	ų.	12	24	a.	2	(a)	2	×	- 24	5	×	£		×.
139-856H-1R-1, -2, -3	8	•	3			8		10	iž.	٠			3	÷.			÷	180	ų.	×.			
139-856G-1H-1, -CC	- 2	5		5	121	3	*		63		<b>5</b> 1	25				÷	7		Ģ.	÷	ŝ		
139-856H-1R-1, -1, -2, -3		12	. <u>.</u>		12.0	- 65		18.	38	8	52	22			3.9				38	*			

drilling (Fig. 16A). With increasing AF demagnetization, the inclination changes toward the direction that is expected from an axial dipole field at this site ( $I = 67^{\circ}$ ). Discrete samples from the central part of the working half of the core are not overprinted to the same degree. Nevertheless, discrete samples were demagnetized with alternating fields up to 95 mT and provided more accurate results. As a measure of remanence stability, we calculated the median destructive field

(MDF) for each discrete specimen (the MDF is the AF required to reduce the NRM to half its initial value). The direction of the primary remanent magnetization, the intensity of the NRM, and the median destructive field are listed in Table 8. The very low median destructive fields observed are believed to be caused by drilling. After removal of the drilling-induced component, most samples have an MDF of 15 to 30 mT (see Fig. 17), and a stable component of magnetization was

#### Table 6 (continued).

Sample (cm)	Diatoms	Mica	Mineral grains	Ostracodes	Pyrite	Radiolarians	Recrystallized foraminifers	Snail shells	Sponge spicules	Sulfides	Talc	Test fragments
139-856A-												
1H-1, 0–1 1H-CC 2H-CC 3H-CC 5H-CC 5H-CC 6H-CC 7H-CC 8H-CC 9H-CC 10X-CC	A C 	· · · · · · · · · · · · · · · · · · ·	· · · · · · · · · · · · · · · · · · ·	R	R C A A C A A A	A C 	· x x x x x					À
139-856B-												
1H-1, 0-1 1H-CC 2H-CC 3H-CC 5H-CC 6H-CC 8H-CC 9H-CC 10H-CC 11X-CC 12X-CC 13X-CC 13X-CC 15X-CC 15X-CC		A A · · · ·	· · · A A · · · A C A A A F ·		· X A A X · · · ·	<b>C</b>		• <b>X</b> • • • • • • • • • • • •	化化化化物 化化化合物 化化合金		Ă	A A 
139-856C-												
C-01H-1, 0–1 C-01H, CC				•	8	•	•	•		A A		•
139-856D-												
1H-1, 0–1 1H-CC	× ×	×	e K	14 24	×	KI Æ1	•	×	e e	A A	a a	*
139-856E-												
1H-1, 0–1 1H-CC	2	2	A A		9 - 10 0	C	•	2	C	A A	1	•
139-856G-1H-1, -CC	2		:	°.,		<b>t</b> 0	1.5		7	Α		
139-856H-1R-1, -2, -3	2	25	<b>1</b> 0	8		*	æ	æ		A	2	*
139-856G-1H-1, -CC	- 14 -		•1)	•				×		5.05	2	*
139-856H-1R-1, -1, -2, -3	- 5		£	3	- 3	2	30	×	×	$\infty$		

usually isolated. Projections of the remanence vectors onto horizontal and vertical planes show a linear decay to the origin for AF >10 mT.

# Magnetostratigraphy

Massive sulfide was recovered with the RCB and showed less overprint from drilling than did the APC cores of sediment. The intensities of NRM are very high, with values between  $1.5 \times 10^3$  and  $3.4 \times 10^5$  mA/m. The MDF values lie between 5 and 13 mT.

The characteristic magnetization observed in Holes 856A and 856B is dominantly positive (normal polarity). The excursions in the Brunhes normal polarity chron (Champion et al., 1988) were not clearly visible at this site, although there is evidence for a possible

# Table 7. Range chart of calcareous nannofossils and their abundance and preservation.

	1	-			-									
Sample	Depth (mbsf)	Age	Nannofossil zonation	Abundance	Preservation	Braarudpsphaera bigelowii	Calcidiscus leptoporus	Coccolithus pelagicus	Emiliania huxleyi	Emiliania pujosae	Gephyrocapsa caribbeanica	Gephyrocapsa oceanica	Pontosphaera japonica	Syrocosphaera pulchra
Hole 856A 1H-1 (top) 1H-CC 2H-CC 3H-CC 4H-CC Hole 856B	0.1 2.7 12.2 21.7 31.2	I. Pleistocene-Holocene	NN21	C C R A R	M P M P P	R	F	R C R	F F R R	R R R R	C C R R	R A R	R	R
IH-CC	1.8			A	М	*	20	a	R	R	R	А	1	R

Note: A = abundant, C = common, F = few, R = rare, B = barren, G = good preservation, M = moderately good preservation, P = poor preservation.

reversed subchron in Core 139-856A-4H at 29–31 mbsf. This possible excursion was confirmed also by progressive demagnetization of discrete specimens. Figure 18 shows the inclination plot, with enlarged scale over this depth range. The same figure also shows the NRM and the intensity after 15-mT demagnetization for the whole core and for discrete samples. The difference in intensity measured on the whole core and the discrete samples is caused by the difference in drilling influence between the outer part of the core and the central part, where the discrete samples were taken. Thus the data do seem to reflect a paleomagnetic event, although this observation must be considered with some caution, since this event is not seen in Hole 856B at the equivalent stratigraphic depth.

Although the declination is not stable, there is evidence for negative inclination in Core 139-856A-8H at 60–70 mbsf (Fig. 17C). Unfortunately the progressive demagnetization of discrete specimens from Core 139-856A-8H showed no stable direction. Further studies will address this problem after the cruise.

## Conclusions

The paleomagnetic results from Site 856 indicate that the sediments have a large magnetic content and that all sediments from Holes 856A and 856B were deposited during the Brunhes Chron. The high intensity and the stability of the magnetization may result from a high concentration of fine-grained magnetite in the turbidites. Moreover, the large variation in the magnetic intensity and volume magnetic susceptibility within the turbidites probably results from the variability in concentration of magnetite (or titanomagnetite) grains between fine and coarse-grained parts.

The general decrease of NRM intensity and volume magnetic susceptibility in Hole 856B with depth is believed to result from the destruction of detrital magnetite, possibly due to hydrothermal pyritization (see "Sediment Geochemistry and Alteration" section, this chapter).

# FLUID GEOCHEMISTRY

Interstitial waters collected at Site 856 include 17 samples from Hole 856A, 20 samples from Hole 856B, and a single sample from Hole 856D. Hole 856A is sited near the center of a small hill and Hole 856B is on its southern flank, 200 m to the south. The hill is 60 m high and 500 m across and is believed to have formed by uplift of sediment above a sub- or intrasedimentary igneous intrusion. Holes 856A and 856B both penetrated mainly semi-indurated turbidites and bottomed in basaltic sills at depths of 113 and 121 mbsf, respectively, where the projected temperatures are 60° and 157°C. Hole 856B also penetrated a second, thinner sill higher in the section, at 64 mbsf. Coincident with its higher thermal gradient, Hole 856B yielded sediment from the lower 50 m of the hole that is weakly hydrothermally altered and mineralized. Hole 856D is sited 140 m south of Hole 856B, on a small ridge where massive sulfide outcrops. It penetrated only 5 mbsf and recovered massive sulfide sand and gravel that consists mainly of pyrite and pyrrhotite.

All interstitial water samples from Site 856 were squeezed from whole-rounds of sediment core, except for one sample each from Holes 856A and 856B that was collected with the WSTP (see "Fluid Geochemistry" section, "Explanatory Notes" chapter, this volume). Two samples are believed to be contaminated, based on their anomalously low chlorinity relative to samples from similar depths: 139-856B-51-1, 74–97 cm (diluted by distilled water due to the small sample size), and 139-856B-10H-1, 140–150 cm (diluted by surface seawater because of core disturbance). Data for these samples have been corrected to the appropriate chlorinity in Figures 19 to 21, but not in Table 9, using a two-end-member mixing model.

## **Composition of Pore Waters**

The pH varies within a very narrow range and shows no trend with depth: all of the samples but two fall between 7.6 and 8.0 (Fig. 19), the normal range for pore water from marine sediment. The one anomalously low value is that from the sulfide sand in Hole 856D; the same sample has anomalously low alkalinity. The one anomalously high value is from 22 mbsf in Hole 856B. It correlates with a similarly high alkalinity and with the 6-m-thick middle interval of Subunit IIB, an interval of clastic sulfidic sediment (see "Lithostratigraphy and Sedimentology" section, this chapter). This interval also has the highest concentration of inorganic carbon measured in sediment from Hole 856B: 0.62 weight percent (wt%), compared with concentrations  $\leq 0.04$  wt% elsewhere in the hole (see "Organic Geochemistry" section, this chapter).

Alkalinity increases in the surficial sediment at both Holes 856A and 856B, from 2.3 meq/kg in bottom seawater to about 3.2 meq/kg, then decreases irregularly with depth, displaying several maxima and minima (Fig. 19). Except near the basalt at the bottom of the holes, the cooler Hole 856A has higher alkalinity at a given depth than does the warmer Hole 856B. Hole 856A also has a much higher inorganic carbon content (0.2 to 0.6 wt%) from 0 to 60 mbsf than does Hole 856B ( $\leq 0.04$  wt%). One sample from 39 mbsf in Hole 856A has exceptionally high alkalinity (Fig. 21).

Chlorinity in Hole 856A is similar to that in bottom seawater to 107 mbsf, below which it decreases with depth (Fig. 19). Chlorinity may also be constant in Hole 856B to 57 mbsf, or it may decrease slightly over this interval. Below 57 mbsf it clearly decreases. Near the bottom of both holes, chlorinity is about 1% less than that in bottom seawater.

Sulfate decreases slightly with depth in the upper part of both holes (Fig. 19). The concentration remains below that in bottom seawater to 67 mbsf in Hole 856A and to 17 mbsf in Hole 856B. Sulfate then increases in Hole 856B to a maximum of 31 mmol/kg at 46 to 57 mbsf,



Figure 15. Inclination and intensity of total NRM and volume magnetic susceptibility vs. depth of archive half of sediment cores from Holes 856A (A) and 856B (B). Volume magnetic susceptibility is not corrected for variation in core volume. The strong decrease in intensity and volume magnetic susceptibility with depth in Hole 856B probably correlates with increasing temperature and the increasing degree of alteration.





Volume magnetic

susceptibility (SI)

10-4

10-3

Intensity (mA/m)

90 10-1 100

 $10^1 \ 10^2 \ 10^3$ 



190

А

0

20

40

80

100

120

\$ ...

Depth (mbsf) 60 -90

Inclination (degrees)

1 4 %.

0

SITE 856

10-2

Core, section, interval (cm)	Depth (mbsf)	I (degrees)	$J_0$ (10 <sup>3</sup> mA/m)	MDF (mT)	Lithology
139-856A-					
2H-1, 95-97	3.60	66	0.103(0.110)	32(30)	Sediment
3H-1, 77-79	12.92	56	0.069(41)	19(29)	Sediment
4H-1, 110-112	22.70	52	0.040(54)	30(22)	Sediment
4H-6, 43-45	29.08	45	0.057	24	Sediment
4H-6, 111-113	29.71	-78	0.156(0.106)	14(23)	Sediment
4H-6, 126-128	29.85	-70	0.163(0.082)	5(22)	Sediment
4H-6, 131-133	29.90	-75	0.328(0.214)	12(25)	Sediment
4H-7, 45-47	30.49	-20(?)	0.185(0.074)	4(15)	Sediment
4H-7, 54-56	30.57	-79	0.320(0.192)	5(17)	Sediment
5H-2, 18-20	31.70	38	0.105(0.059)	5(20)	Sediment
6H-1, 105-107	41.70	56	0.091(0.027)	3(30)	Sediment
7H-3, 130-132	54.19	68	0.0048(0.0015)	3(27)	Sediment
8H-3, 50-52	62.94	Unstable	0.011(?)	2(?)	Sediment
8H-4, 36-38	64.21	Unstable	0.015(?)	3(?)	Sediment
8H-5, 58-60	65.90	Unstable	0.013(?)	3(?)	Sediment
8H-6, 57-59	67.19	Unstable	0.437(?)	3(?)	Sediment
9H-4, 122-124	74.50	76	0.006	?	Sediment
13X-CC, 19-21	114.19	75	3.5	84	Diabase
139-856B-					
3H-1, 139-141	12.60	60	0.0040(0.0028)	14(23)	Sediment
3H-1, 145-147	12.66	70	0.0030	25	Sediment
139-856G-					
3R-1, 38-40	17.98	-7	340	7	Massive sulfide
4R-1, 23-25	27.23	85	14(8.2)	5(13)	Massive sulfide
6R-1, 139-141	47.69	-85	4.5	13	Semimassive sulfide
6R-3, 126-128	50.56	72	337(14)	3(5)	Massive sulfide
7R-4, 40-42	60.50	38	1.5	8	Massive sulfide

Table 8. Paleomagnetic results of progressive demagnetization experiments on sediment and diabase from Holes 856A and 856B, and on sulfide from Hole 856G.

Notes: The characteristic inclinations (I) were determined from orthogonal vector projections.  $J_0 = NRM$ intensity, MDF = median destructive field, which is required to AF-demagnetize to half of the NRM. The values in parentheses are characteristic values after removal of the drilling-induced remanence, and are derived from intensity diagrams.

just above the thin sill at 64 mbsf. Calcium, ammonium, and silica also reach a maximum at these depths in this hole, although the shapes of these profiles are somewhat different. At depths greater than 70 mbsf sulfate increases again, to a similar concentration in both holes as the basal basalt is approached. This concentration is about 9% higher than that in bottom seawater. The single sample from Hole 856D has similarly high sulfate at a much shallower depth, only 4 mbsf. The elevated sulfate coupled with low pH and alkalinity suggests oxidation of the sulfide sand from which this sample was collected.

Magnesium varies by less than 5% from the concentration in bottom seawater in all of the samples (Fig. 20). The profiles from Holes 856A and 856B are quite similar to one another. The calcium profiles from the two holes also resemble each other, showing little change from seawater over the upper 20 to 30 mbsf and then increasing with depth below that. The only major difference is the abrupt increase and plateau in calcium above and below the thin sill at 64 mbsf in Hole 856B. The general increase in calcium with depth is not balanced by a decrease in magnesium, as is often observed in deep-sea sediment.

Sodium and potassium decrease more or less steadily in Holes 856A and 856B (Fig. 20), suggesting uptake by reaction with the underlying basalt. Potassium shows a minor minimum in Hole 856B immediately above the thin sill at 64 mbsf. The well known temperature-of-squeezing artifact for potassium is evident in the high concentration in the surficial sediment, which exceeds that in seawater by 13%–17%.

Silica reaches a discrete maximum at 10 mbsf in Hole 856A and at 1 mbsf in Hole 856B. Dissolved silica then decreases to about 20 to 30 mbsf in both holes before increasing again toward basalt at the maximum depth drilled. The concentration at this depth is much higher in the warmer Hole 856B, which also displays a plateau above and below the thin sill at 64 mbsf that is similar to those for sulfate, calcium, and ammonium.

Like silica, ammonium also shows a maximum within the upper 10 mbsf and a maximum or plateau at about 40 to 60 mbsf. The sample from immediately above the sill at 64 mbsf in Hole 856B is free of ammonium, but all the deeper samples from this hole have higher concentrations again (although the absolute concentrations are low, <70  $\mu$ mol/kg). These deeper samples from Hole 856B contrast with those from Hole 856A, which are ammonium-free.

The concentration of phosphate is at or above that in bottom seawater within the upper 10 mbsf in both Holes 856A and 856B. At greater depths phosphate is uniformly very low, except in the prime aliquot of the sample collected from Hole 856A with the WSTP.

#### Comparison of Pore Waters from Holes 856A and 856B

The pore waters from Holes 856A and 856B have several features in common:

1. The overall profiles for pH, magnesium, potassium, sodium, and sodium/chlorinity are similar in the two holes.

2. Between 0 and 20 mbsf, the variations in concentration resulting from diagenesis of organic matter are quite small. Alkalinity, silica,



Figure 17. Examples of Zijderveld plot (left), equal-area projection (top right), and intensity decay plot (bottom right) as a function of AF demagnetization (0 to 95 mT) of sediments from Hole 856A. **A.** Sample 139-856A-2H-1, 95–97 cm, scale = 20.00 mA/m per division. **B.** Sample 139-856A-4H-6, 131–133 cm, scale = 70.00 mA/m per division. **C.** Sample 139-856A-8H-4, 36–38 cm, scale = 2.00 mA/m per division. **D.** Sample 139-856A-13X-CC, 19–21 cm, scale = 500.00 mA/m per division. Open circles represent vector endpoints projected onto the vertical plane; solid circles represent endpoints projected onto the horizontal plane. A viscous component of magnetization is removed at 10 mT. Except for Sample 139-856A-8H-4, 36–38 cm, the straight line above 10 mT in the Zijderveld diagram represents a single component of the magnetization. The intensity decay curves are representative of a stable magnetization.

and phosphate increase more in Hole 856A than in 856B, but the increases are still small. The small ammonium increase is similar in both holes, as is the small decrease in sulfate.

3. Between 30 and 60 mbsf, both holes show a similar but small maximum in ammonium.

4. Near the basalt at the bottom of both holes, the pore waters have similar pH and chlorinity, and similar concentrations of sulfate, calcium, potassium, and phosphate.

Differences between the two holes are as follows:

1. Chlorinity is lower at 60 to 120 mbsf in Hole 856B than in 856A, although both holes have similar chlorinity near the basalt at the bottom of the holes.

2. Alkalinity is higher than in seawater in Hole 856A, except near the basalt at the bottom of the hole. It is lower than in seawater in Hole 856B, except near the seafloor.

3. Sulfate, calcium, and silica show a maximum or plateau at about 36 to 64 mbsf in Hole 856B that is lacking in Hole 856A.

4. Silica and ammonium are much higher near basalt at the bottom of Hole 856B than in Hole 856A.



Figure 18. Inclination, intensity, and volume magnetic susceptibility vs. depth for 29–32 mbsf of Hole 856A. Small open and solid circles represent whole-core measurements; open and solid squares represent discrete samples. See text for further explanations.

## **Interpretation of Pore-Water Compositions**

The constant chlorinity of the pore water from the upper part of Holes 856A and 856B contrasts with the chlorinity at Site 855, which displays a 2% maximum at about 30 mbsf. This is the typical chlorinity maximum associated with Pleistocene bottom water, which was about 4% saltier than that of today. In most marine sediments this maximum has diffused downward to about 30 mbsf, and has diminished to about 2% in the process (McDuff, 1985). We infer that the Pleistocene chlorinity maximum has been eradicated at Site 856 by recent flow of pore water vertically through the sediment column.

Below 1.5 mbsf, alkalinity generally decreases with depth in both holes, but especially in Hole 856B, while pH stays nearly constant; thus, carbon dioxide must also decrease. This implies removal of carbonate ion from the pore water with increasing depth and temperature, probably as calcium carbonate. Numerous carbonate nodules were found in Hole 856A, in the interval from about 12 to 86 mbsf, but none were found in Hole 856B. The surface of these nodules should be equilibrated with the pore water; this can be checked by electron-spin resonance spectroscopy of the nodule surfaces. The overall decrease in alkalinity is only about 1 meq/kg, so that precipitation of calcium carbonate should have little effect on the calcium profile.

The decrease in sulfate in the surficial sediments almost certainly results from bacterial degradation of organic matter utilizing sulfate as an oxidant. As expected, it is accompanied by increases in alkalinity, ammonium, and phosphate. The decrease reverses with depth in both holes such that the concentration of sulfate exceeds that in bottom seawater as basalt is approached, both at the bottom of the holes and at the intermediate-level sill at 64 mbsf in Hole 856B. These increases require a source of sulfate, either in sediment or in basalt. Molds of tabular crystals suspected to be anhydrite were observed at 86 to 115 mbsf in Hole 856A, just above the basalt at the bottom of the hole, and at 40 to 71 mbsf in Hole 856B, just above and below the intermediate-level sill (see "Lithostratigraphy and Sedimentology" section, this chapter). Anhydrite has been tentatively identified by X-ray diffraction (XRD) in sediment from both holes, above and only slightly overlapping with the intervals where the molds occur (see "Sediment Geochemistry and Alteration" section, this chapter). Sulfate correlates positively with calcium in those pore-water samples from both holes that have calcium concentrations exceeding that in seawater (Fig. 22). A best-fit regression line has a slope of 0.92, that is, over the depth interval where sulfate increases, the gain in calcium nearly equals the gain in sulfate. Thus, the gain in sulfate can readily be explained by dissolution of anhydrite from the sediment and basalt. The best-fit line passes through the seawater sulfate concentration at a calcium concentration of 12.6 mmol/kg. Relative to seawater, therefore, the most sulfate-rich samples have gained nearly twice as much calcium as sulfate. This implies that only about half of the overall calcium increase comes from calcium sulfate dissolution; the other half must be supplied by an additional source.

The maximum in dissolved sulfate and calcium at 36 to 64 mbsf in Hole 856B, therefore, is almost certainly caused by dissolution of calcium sulfate from the sediment. This maximum is undoubtedly related to the sill at 64 mbsf in Hole 856B; both sill and maximum are absent in



Figure 19. Composition of pore water from sediment at Site 856. Hole 856A = circles; Hole 856B = squares; Hole 856D = diamonds. Lettered tick marks on the depth axis indicate the tops of basaltic sills in Holes 856A and 856B. The plus sign inside a square at 0 mbsf denotes the composition of bottom seawater.

Hole 856A. Heat from the intrusion of this sill has indurated the sediment over a depth interval of about 25 m above and 10 m below the sill (see "Lithostratigraphy and Sedimentology" section, this chapter), corresponding almost exactly with the depth interval of the tabular crystal molds and the maximum in dissolved calcium and sulfate. Heating would cause gypsum or anhydrite to precipitate from the pore water; on later cooling, these minerals would redissolve, as is inferred to be happening at present.

The minimum in dissolved sulfate at 78 mbsf in Hole 856B, below the sill at 64 mbsf, requires either an active sink, lateral flow of low-sulfate water at that depth, or a non-steady-state condition in which calcium sulfate is presently dissolving less rapidly at that depth than above and below it. Lateral flow is difficult to prove or disprove and will not be discussed further here. The most likely active sink is sulfate reduction, but the lack of any substantial corresponding increase in alkalinity, ammonium, or phosphate weighs against it. A small minimum in dissolved calcium at the same depth as the minimum in dissolved sulfate suggests instead that calcium sulfate is dissolving more slowly at that depth, and that the profiles are not at steady state.

The importance of a second source of dissolved calcium can be seen in the steady increase in calcium with depth in both holes below 20 to 30 mbsf. At shallower depths calcium remains constant, probably because of a balance between supply from below by diffusion, and precipitation of calcium carbonate as a result of alkalinity production by organic matter degradation. Both foraminifers and calcareous nannofossils are overgrown with calcite in the upper 10 to 30 mbsf of Hole 856A, where the carbonate content exceeds 1.7 wt% CaCO<sub>3</sub>, but Hole 856B largely lacks both calcium carbonate (<0.8 wt%) and calcareous fossils. Below 20 to 30 mbsf the concentration of dissolved calcium increases along with sulfate, in response to calcium sulfate dissolution and the apparent supply of calcium from alteration of silicates. That silicates rather than carbonates are the source of this calcium is indicated by the absence of an increase in the alkalinity of the pore water and by the very low carbonate content of the sediment (<0.8 to 1.7 wt% CaCO<sub>3</sub>). The silicates that are supplying dissolved



Figure 20. Composition of pore water from sediment at Site 856; symbols and letters as in Figure 19.

calcium are probably mainly plagioclase feldspar present in both the sediment and the basalt.

That this plagioclase feldspar is being albitized is suggested by the steady decrease in dissolved sodium with depth in both holes. This decrease totals about 12 meq/kg and thus matches the overall increase in calcium. Potassium is also being taken up by secondary silicates, probably mixed-layer clay minerals or mica, whereas magnesium stays nearly constant with depth.

Both silica and ammonium show a shallow maximum, which is probably caused by dissolution of biogenic silica and degradation of organic matter, respectively. Both also show a deeper maximum or plateau above the sill at 64 mbsf in Hole 856B, that coincides with the maximum in dissolved calcium and sulfate. This deeper maximum probably reflects the thermal effect of sill intrusion on sediment diagenesis. Heating would enhance dissolution of biogenic silica and degradation of organic matter. The much higher concentrations of dissolved silica and ammonium near the bottom of Hole 856B than near the bottom of Hole 856A are probably also thermally produced; diagenesis should be more rapid in the much warmer Hole 856B. Given the difference of about 100°C projected for the bottom of the holes (60°C in Hole 856A vs. 157°C in Hole 856B), however, the differences in pore water composition are remarkably small. The silica profile in Figure 31 shows that the concentration in the deeper part of Hole 856A may be controlled by equilibrium with chalcedony, whereas that in Hole 856B may be controlled instead by equilibrium with quartz. This difference in controlling phases would account for the relatively small difference in silica concentration in the two holes vs. that in temperature; such a difference has been observed in hydrothermal systems in Iceland (Arnorsson, 1975). Specialized techniques for studying surfaces should tell whether chalcedony or quartz overgrowths are present on silica minerals in these holes.

Like alkalinity, silica, and ammonium, phosphate displays a shallow maximum resulting from diagenesis of organic matter. Its abrupt decrease to very low concentrations with depth probably results from adsorption on iron oxyhydroxide and sulfide minerals that are known to be present in the sediment.



Figure 21. Composition of pore water from sediment at Site 856; symbols and letters as in Figure 19. Saturation curves for chalcedony (C) and quartz (Q) are from Michard (1989) and are for *in-situ* temperatures in Holes 856A and 856B.

#### **Possible Timing of Sill Emplacement**

An unusual aspect of the ammonium profile is that, unlike for calcium, sulfate, and silica, the maximum at 36 to 60 mbsf in Hole 856B is matched by a nearly identical maximum in Hole 856A. One possible explanation is that the heat from intrusion of the intermediate-level sill in Hole 856B produced ammonium diagenetically at a greater distance laterally than it did dissolved silica, or calcium sulfate precipitation. The maximum for each of these species in Hole 856B occurs over the same depth interval, however, indicating that there was no differential effect with distance vertically. Another possibility is that the two holes, which are only 200 m apart, are connected by lateral convective flow over this depth interval. Lateral convection, however, should also carry higher concentrations of dissolved silica. Moreover, the seafloor at Hole 856B is about 20 m deeper than that at Hole 856A, so that a similar depth below the seafloor in the two holes is actually offset by 20 m relative to the horizontal. The ammonium profiles are thus difficult to explain. It seems more likely that the sharp maxima and intervening minima result from non-steady-state conditions associated with sill intrusion, rather than from multiple sources and sinks distributed vertically throughout the sediment column.

This is the same conclusion suggested above from the sulfate minimum at 78 mbsf in Hole 856B. If this conclusion is correct, then the sharpness of the vertical gradients, which have a scale length, x, of 20 to 25 m, implies that the peaks in ammonium and silica were produced at  $t = x^2/4D$ , where D is the diffusion coefficient for ammonium in the sediment pore water. For  $D = 10^{-9}$  m<sup>2</sup>/s,  $t = 4000 \pm 1000$  yr. If the sill at 64 mbsf in Hole 856B was, in fact, emplaced 4000 yr ago, then the resulting convection of pore water could well have erased the Pleistocene chlorinity maximum from the pore waters.

## Has Slumping Removed 20 m of the Section in Hole 856B?

Correlation of magnetic susceptibility records between Holes 856A and 856B suggests that the upper 20 m of the sediment column is missing in Hole 856B (see "Paleomagnetism" section, this chapter),




Figure 22. Concentration of calcium vs. sulfate in sediment pore water from Site 856. Symbols as in Figure 19. The plus sign inside a square denotes the composition of bottom seawater. The regression line is calculated for all samples with calcium greater than 10.5 mmol/kg and has a slope of 0.92.

presumably because of mass wasting from the flank of the hill where the hole was drilled, or from nondeposition. Holocene sediment is absent from Hole 856B, whereas it is present at the seafloor in Hole 856A (see "Biostratigraphy" and "Lithostratigraphy and Sedimentology" sections, this chapter). Offsetting the profiles of pore water composition from Hole 856B downward by 20 m relative to Hole 856A does improve the match between the two holes for some species, including chlorinity, alkalinity, sulfate (below 100 mbsf), magnesium, and sodium. It degrades the match for other species, however, including sulfate and calcium (between 0 and 20 mbsf), potassium, and ammonium. The good match between the two holes for sulfate, calcium, and ammonium between 0 and 20 mbsf suggests that if the upper 20 m of sediment in Hole 856B has eroded, it did so sufficiently long ago for reaction to reproduce the original profiles.

### ORGANIC GEOCHEMISTRY

The shipboard organic geochemical analyses of sediment samples from Holes 856A, 856B, 856C, 856D, and 856G included inorganic carbon; total carbon, hydrogen, nitrogen and sulfur; volatile hydrocarbon and nonhydrocarbon gases; organic matter fluorescence estimation; and total hexane-soluble lipid/bitumen analysis. Instrumentation, operating conditions, and procedures are summarized in the "Explanatory Notes" chapter (this volume).

#### Volatile Gases

Volatile gases (hydrocarbons, CO<sub>2</sub>, H<sub>2</sub>S, and N<sub>2</sub>) were continuously measured in the sediments at Site 856 as part of the shipboard safety and pollution monitoring program. Results are listed in Table 10. Methane concentrations in the headspace volumes range between 2 and 7 ppm (volume/volume), which are negligible compared with the laboratory background level of 2 ppm. No ethane or higher hydrocarbons, nor H<sub>2</sub>S were detected in the headspace samples. One vacutainer sample taken from a gas crack from the first core of Hole 856B (Sample 139-856B-1H, 105–110 cm) showed a small amount of ethane (0.64 ppm). As discussed previously for Site 855, the overall low methane contents in these sediments suggest that the environmental conditions were not favorable for methanogenesis. Carbon dioxide was present at concentrations of 0.1% to 0.7% (Fig. 23).

#### Fluorescence

The extract colors ranged from pale yellow in Core 1H of each hole to colorless at depths of 50 mbsf. Cores 139-856A-1H and 139-856C-1H had yellow fluorescence. Core 139-856B-1H had strong yellow-white fluorescence and Core 139-856B-6H (49.3 mbsf) had white fluorescence. The concentration levels of extractable organic matter are extremely low based on the color and fluorescence intensities. The yellow fluorescence is interpreted as thermal maturation of bitumen to the mature stage and white fluorescence is overmature bitumen enriched in polynuclear aromatic hydrocarbons (PAH) (Curray, Moore, et al., 1982).

### **Bitumen Analyses**

Aliquots of the hexane/isopropanol or methanol extracts of the samples from the fluorescence assessment or subsamples of freezedried sediments were concentrated under a stream of nitrogen to about 10-40 µL. These concentrates were analyzed by high-resolution gas chromatography and examples of traces are shown in Figure 24. The dominant compound series in the total extracts are hydrocarbons ranging from n-C15 to n-C35, with pristane (C19H40, Pr) and phytane (C20H42, Ph) as the major isoprenoid alkanes. The bitumen parameters for maturation and organic matter sources are listed in Table 11. The n-alkanes >C26 have a significant predominance of odd carbon numbers (carbon preference index, CPI, >1.0) and carbon number maximum (Cmax) at C27 or C29, typical for immature hydrocarbons with an origin from terrestrial higher plants (Fig. 24B-D; Simoneit, 1977, 1978). The *n*-alkane patterns  $< C_{24}$  with the unresolved complex mixture (UCM) of branched and cyclic compounds and the Cmax at C17 are typical for autochthonous marine bitumen derived from alteration of microbial lipids (Fig. 24A, 24B, Table 11; Simoneit, 1977, 1978)

The CPI (range C26-C35) for Hole 856A decreases to less than 1 below 20 mbsf, indicative of an unusual hydrocarbon source with an even alkane predominance (Fig. 25). This has also been reported for Holocene sediments from other geographic areas (Grimalt and Albaiges, 1987; Simoneit, 1977). Thermal maturation does not produce CPI values of less than 1, so that the decrease in CPI with depth in this hole must be at least partially source-related. Since maturation in these sediments commences with immature organic matter that has not completed diagenetic alteration, the n-alkanols from terrestrial plant waxes (Simoneit, 1978) may be the source of the even-chain alkanes >C24. This would require low-temperature alteration by dehydration and double bond reduction of the n-alkanols (probably <100°C) analogous to that described for the alteration of sedimentary organic matter in the Bransfield Strait by the intrusion of a volcanic plug (Brault and Simoneit, 1988). One anomalous higher CPI value of 3.63 occurs in Sample 139-856A-5H-CC at 40.7 mbsf within this even CPI trend, possibly diagnostic of turbidites or different organic matter sources in some sections of this hole below 20 mbsf. This CPI value is the highest observed in this hole, equivalent to those observed at 12 to 14 mbsf (Fig. 25). The slightly elevated Pr/n-C<sub>17</sub> and Pr/Ph values and a somewhat lower Ph/n-C18 values are also comparable between the 12.0 to 14.0 mbsf interval and the 40.7 mbsf sample.

CPI profiles for Holes 856B, 856C, 856D, and 856E are plotted in Figure 26. The surficial CPI value of 3.49 in Hole 856B at 1.8 mbsf is in the same range as the highest values in the top 20 mbsf of Hole 856A (Fig. 25). The CPI then rapidly decreases to values close to 1 in deeper sections of Hole 856B, suggesting maturation. One exception occurs in Sample 139-856A-5H-2, 63-65 cm, at 33.35 mbsf, where the CPI is 0.78, clearly less than 1 and diagnostic of a significant contribution from the even CPI source described above for Hole 856A.

#### Table 9. Composition of pore water from sediments at Site 856.

Sample <sup>a</sup>	Core, section, interval (cm)	Depth (mbsf)	Volume (mL)	Squeeze pressure (psi)	Salinity <sup>b</sup> (%)	pH	Alkalinity (meq/kg)	Chlorinity (mmol/kg)	Sulfate (mmol/kg)	Na (mmol/kg)	K (mmol/kg)
Surface se	awater (22 July 1991)							496.0			10.4
Bottom se	awater (calculated for 54	1 mmol/kg	chlorinity)				2.31	541.0	27.95	463.3	10.1
	139-856A-										
IW-1	1H-2, 06	1.53	50	10,000	35.0	7.66	3.077	540.6	28.01	467.2	11.8
IW-2	2H-1, 140-150	4.15	50	10,000	35.5	7.64	3.192	540.6	27.93	464.3	10.3
IW-3	2H-2, 140-150	5.65	24	14,000	35.5	7.76	3.206	542.6	27.62	467.8	9.0
IW-4	2H-5, 140-150	10.15	50	10,000	35.5	7.79	3.275	539.7	27.81		
IW-5	3H-1, 143-150	13.67	50	15,000	35.0	7.80	3.041	538.7	27.67	466.1	9.7
IW-6	3H-5, 143-150	19.67	50	15,000	35.5	7.81	2.824	540.6	27.56	468.0	9.0
IW-7	4H-1, 140-150	23.15	50	10,000	35.5	7.75	3.028	541.6	27.16	464.9	9.0
IW-8	5H-6, 140-150	39.03	50	10,000	35.5	7.71	4.873	538.7	27.48	462.0	9.2
IW-9	6H-5, 140-150	48.15	50	10,000	35.5	7.82	3.046	538.7	27.25	457.3	8.6
IW-10	7H-5, 140-150	57.65	50	13,000	35.5	7.76	2.781	541.6	27.31	457.8	8.5
IW-11	8H-5, 140-150	67.15	50	13,000	35.5	7.77	2.420	540.6	27.45	462.3	7.4
IW-12	9H-5, 140-150	76.65	50	13,000	35.5	7.83	2.992	543.6	27.90	463.0	8.0
IW-13	10X-1, 140-150	80.15	25	20,000	36.0	7.91	3.021	540.6	27.93	456.3	8.3
IW-14	11X-1, 140-150	87.65	50		35.0	7.88	3.137	538.7	28.21	460.8	8.3
BC-15	12I-1, 74-97	96.55	10		35.5	7.87	2.687	539.7	29.09	465.7	8.0
<sup>d</sup> BO-15	12I-1, 74-97	96.55				8.21	3.600	331.6	28.04	244.4	11.1
IW-16	13X-1, 140-150	106.75	21	20,000	35.5	7.77	1.998	538.7	30.81	454.7	6.6
IW-17	13X-5, 140-150	112.75	30	20,000	35.0	7.71	2.042	534.8	30.19	448.1	8.0
	Depth to basalt:	113.2									
	139-856B-								All constants	1012040113	140.000.0001
IW-1	1H-1, 144–150	1.47	52	6,000	36.0	7.76	3.153	538.7	28.01	463.5	11.4
IW-2	2H-1, 140-150	3.25	43	10,000	35.5	7.77	2.787	542.6	27.84	465.3	10.2
IW-3	2H-2, 140–150	4.75	32	14,000	35.0	7.84	2.814	538.7	27.53	461.1	9.5
IW-4	2H-5, 140-150	9.25	50	6,000	35.0	7.69	2.702	541.6	27.76	464.4	
IW-5	3H-4, 140–150	17.25	54	14,000	35.0	7.69	2.447	538.7	27.48	460.7	10.3
IW-6	3H-6, 140–150	20.25	45	14,000	34.5	8.17	3.203	540.6	28.07	463.9	9.9
IW-7	4H-4, 140–150	26.75	50	10,000	35.5	7.72	2.283	541.6	28.29	463.1	9.9
BC-8	51-1, 74-97	31.15	8		36.0	7.91	2.237	516.3	27.33	442.4	9.8
IW-9	5H-4, 140–150	36.25	48	16,000	35.5	7.68	2.092	537.7	29.93	456.8	9.2
IW-10	6H-4, 140–150	45.75	35	17,000	36.0	7.75	2.047	540.6	31.06	456.0	8.3
IW-11	7H-3, 140–150	53.75	50	13,000	36.0	7.60	1.979	539.7	31.06	459.3	8.7
IW-12	7H-5, 140–150	56.75	50	12,000	35.5	7.66	2.039	540.6	31.06	460.3	8.3
IW-13	8H-1, 140-150	60.25	50	16,000	36.0	7.71	2.098	536.8	30.02	454.8	8.1
IW-14	9X-1, 140–150	63.75	40	13,000	35.5	7.68	2.140	537.7	29.93	457.3	7.6
IW-15	10H-1, 140-150	72.25	50	8,000	34.0	7.66	2.103	517.3	27.59	438.3	8.6
IW-16	11X-3, 140–150	77.75	50	20,000	35.5	7.94	2.212	535.8	28.94	454.9	8.2
IW-17	12X-2, 140-150	84.55	25	20,000	35.0	7.88	2.179	534.8	30.07	452.1	8.5
IW-18	13X-2, 140–150	94.05	42	20,000	36.0	7.73	1.939	536.8	30.21	455.3	8.7
IW-19	14X-2, 140-150	103.75	19	20,000	35.5	7.72	2.112	534.8	30.21	454.1	8.6
IW-20	15X-4, 140-150	116.35	20	20,000	36.0	7.72	2.570	536.8	30.55	456.6	8.8
	Thin sill:	63.8									
	Depth to basalt:	120.7									
1400000	139-856D-							11 an Ferrar 100	2000/02191	10004410	100000
IW-1	1H-3, 140–150	4.45	50	4,000	35.5	7.41	2.255	536.8	30.21	462.4	10.2

<sup>a</sup> IW = squeezed interstitial water sample, BC = interstitial water sample taken *in situ* with the WSTP, BO = overflow aliquot from the WSTP (diluted with distilled water). <sup>b</sup> By refractive index.

<sup>c</sup> Ca and Mg have been corrected using the equations of Gieskes and Peretsman (1986).

<sup>d</sup> Concentrations in mmol/kg measured in overflow aliquots have been adjusted to the chlorinity of the prime aliquot.

Surficial CPI values for Holes 856C, 856D, and 856E are all close to one (Fig. 26), consistent with surficial sediments experiencing higher thermal stress as the currently active hydrothermal vent area is approached (see "Heat Flow" section, this chapter).

Maturation is also evident in the decreases of the isoprenoid to normal hydrocarbon ratios (Pr/n- $C_{17}$ ) from a maximum in the range of 0.75 to 1.5 in the surficial sections of Holes 856A, 856B, and 856C to a minimum 0.4 to 0.1 in deeper sections of Holes 856A (Fig. 25) and 856B (Fig. 26), as well as within the surficial sediments of Holes 856D and 856E (Fig. 26). These low Pr/n- $C_{17}$  values (<0.5) are characteristic of sediments which, at some time in their history, have been heated to temperatures greater than 50°C, at the beginning of the oil thermal window (Farrington et al., 1988; "Organic Geochemistry" section, "Site 855" chapter).

The Ph/n-C<sub>18</sub> ratios do not show any systematic changes with depth or increasing geothermal gradients in these holes (Figs. 26 and 27).

These results are consistent with those observed elsewhere (Farrington et al., 1988; Simoneit et al., 1981; J. Whelan, pers. comm., 1991) and suggest that the largest changes observed in this ratio are related predominantly to source, rather than to maturation.

Pr/Ph, which has been reported to be influenced both by source (e.g., Didyk et al., 1978) and by maturation (e.g., Simoneit et al., 1981), generally show lower and fluctuating values in the range of 0.5 to 1.5 in the 10 to 60 mbsf section of Hole 856A (Fig. 25), as well as in most sections of Holes 856B, 856C, 856D, and 856E (Fig. 26). Pr/Ph in some of the samples from less than 20 mbsf of Hole 856A are >1.5. It is possible that the general decrease here with increasing depth and thermal stress is indicative of maturation effects.

The changes in extractable hydrocarbons at Sites 855 and 856 have been discussed in terms of source and maturation changes. The parameters described above can be used to constrain source and degree of maturation in these sediments because, at this site, the

#### Table 9 (continued).

	Cora saction	Donth	Volume	Mas	Cec	0:	NH <sub>4</sub>	Phosphata
Sample <sup>a</sup>	interval (cm)	(mbsf)	(mL)	(mmol/kg)	(mmol/kg)	βi (µmol/kg)	(µmoi/kg)	(µmol/kg)
Surface se	awater (22 July 1991)			49.54	100000			
Bottom sea	awater (calculated for 541	mmol/kg cl	nlorinity)	52.71	10.17	183		
	139-856A-							
IW-1	1H-2, 0-6	1.53	50	50.53	9.85	516	0	4.5
IW-2	2H-1, 140-150	4.15	50	52.36	10.18	645	27	13.4
IW-3	2H-2, 140-150	5.65	24	51.80	10.30	592	34	
IW-4	2H-5, 140-150	10.15	50	50.90	10.24	675	17	3.2
IW-5	3H-1, 143-150	13.67	50	50.59	10.05	466	10	
IW-6	3H-5, 143-150	19.67	50	50.58	10.23	252	4	0.2
IW-7	4H-1, 140-150	23.15	50	51.77	10.77	152	4	0.0
IW-8	5H-6, 140-150	39.03	50	52.56	11.06	166	61	0.0
IW-9	6H-5, 140-150	48.15	50	53.11	12.01	171	68	0.7
<b>IW-10</b>	7H-5, 140-150	57.65	50	53.40	12.90	212	60	0.2
IW-11	8H-5, 140-150	67.15	50	52.60	11.55	288	8	0.0
IW-12	9H-5, 140-150	76.65	50	52.69	12.97	209	0	
<b>IW-13</b>	10X-1, 140-150	80.15	25	53 38	14.11	212	0	
<b>IW-14</b>	11X-1, 140-150	87.65	50	51.56	13.01	254	0	0.3
BC-15	121-1.74-97	96.55	10	50.43	12.97	455	0	3.0
dBO-15	121-1.74-97	96.55	10	55.67	12.20	321		0.6
IW-16	13X-1 140-150	106 75	21	53.72	16.81	323	0	0.1
IW-17	13X-5 140-150	112 75	30	55.13	15.45	312	0	0.5
	Depth to basalt:	113.2	50	55.15	15.45	512	U	0.5
	139-856B-							
TW-1	1H-1 144-150	1 47	52	51.48	10.01	402	0	24
IW-2	24.1 140-150	3.25	13	52.56	10.01	362	15	0.4
IW-3	2H-2 140-150	4 75	32	52.50	10.20	338	42	0.5
TW_4	2H-5 140-150	0.25	50	52.59	10.19	336	25	0.0
TW-5	34-4 140-150	17.25	54	52.30	10.18	210	20	0.0
TW-6	311-4, 140-150	20.25	45	52.40	10.07	106	20	0.0
TW.7	44-4 140-150	26.25	50	53.40	10.20	184	20	0.0
BC-8	51.1 74.07	21.15	50	50.79	0.25	69	20	0.3
IW.0	54 4 140 150	36.25	49	53.15	12.65	410	40	0.0
IW. 10	6H A 140 150	15 75	25	54.07	15.05	419	49	0.0
IW-10	711 3 140 150	43.13	50	52.21	13.25	421	21	0.0
IW-11	711-5, 140-150	55.15	50	53.51	14.50	267	51	0.0
TW-12	/H-5, 140-150	50.75	50	53.40	14.62	307	51	0.0
TW-15	0X 1 140-150	62.75	30	53.32	14.43	409	47	0.0
1W-14	9X-1, 140-150	03.75	40	52.97	14.47	405	0	0.0
IW-15	10H-1, 140-150	12.25	50	51.52	12.30	291	00	0.0
1W-10	11X-3, 140-150	11.15	50	52.39	13.99	369	47	0.1
IW-17	12X-2, 140-150	84.55	25	53.90	14.37	379	47	0.4
IW-18	13X-2, 140-150	94.05	42	53.37	14.18	519	42	0.0
1w-19	14X-2, 140-150	103.75	19	51.34	15.96	455	61	0.0
1W-20	15X-4, 140-150	116.35	20	52.88	14.63	970	58	0.0
	Thin sill:	63.8						
	Depth to basalt:	120,7						
	139-856D-							
IW-1	1H-3, 140–150	4.45	50	53.32	10.12	551	0	0.4

potential influences of other processes—including migration and bio-degradation—can be ruled out. Specifically, we do not feel that hydrocarbon compositions are influenced to any significant extent at this site by primary or secondary migration processes or by biodegradation for the reasons given below. The general processes that affect sedimentary organic matter are source, maturation, expulsion or primary migration, secondary and tertiary migration, and biodegradation. Primary oil migration, which is the rate limiting step in the petroleum generation process (Lewan, 1985), is the initial expulsion of oil from the fine-grained source rock where it is first formed into a more permeable carrier or reservoir bed, such as a silt or sand or porous limestone. Secondary and tertiary migration processes occur as the petroleum moves and fractionates further within the carrier or reservoir beds (Hunt, 1979).

The overall decreases in total organic carbon (TOC) in the top 20 mbsf of Holes 855A and 855C as well as 856A are consistent with microbiological degradation of sedimentary organic matter occurring in those intervals. In terms of the ratios discussed here, biodegradation tends to preferentially remove the shorter before the longer hydrocarbon chains (which would result in an enrichment of the  $C_{23}$ - $C_{35}$  hydrocarbons over  $C_{17}$ ) and the straight before the branched chains, which would cause an increase in Pr/n- $C_{17}$  and Ph/n- $C_{18}$ . Table 11 shows that  $C_{17}$  predominates over  $C_{29}$  in the majority of the sediments from all of the holes at Site 856, so that biodegradation does not appear to affect the carbon number maximum ( $C_{max}$ ) in any consistent way. Similarly, Pr/n- $C_{17}$  and Ph/n- $C_{18}$  either remain constant or decrease with increasing depth and maturation. Biodegradation would have just the opposite effect, causing a preferential increase in the branched isoprenoids (e.g., Pr and Ph) over n- $C_{17}$  and n- $C_{18}$ . Therefore, biodegradation cannot be altering the bitumen in these sediments to any significant degree.

We also think that petroleum migration processes, including both primary expulsion and migration of generated hydrocarbons from finegrained intervals and secondary migration of hydrocarbons within more permeable sand and silt layers, are unimportant in the sediments at either Sites 855 or 856. A great deal of research has been carried out in recent years on primary petroleum expulsion and migration (e.g., Durand, 1988; Leythaeuser et al., 1984; Carlson and Chamberlain,

Core, section, interval (cm)	Type <sup>a</sup>	Depth (mbsf)	Methane <sup>b</sup> (ppm)	Ethane (ppm)	CO <sub>2</sub> (ppm)
139-856A-					
1H-1, 145-150	HS	1.45	2.6	0.0	n.d.
2H-3, 0-5	HS	5.70	3.0	0.0	n.d.
3H-5, 0-5	HS	18.20	2.6	0.0	1790
4H-6, 0-5	HS	29.20	2.5	0.0	5960
5H-4, 15-17	V	35.85	70.0	0.0	700
5H-7, 0-5	HS	40.20	3.0	0.0	1220
6H-3, 0-5	HS	43.70	3.0	0.0	4230
7H-6, 0-5	HS	57.70	3.0	0.0	3760
8H-6, 0-5	HS	67.20	2.2	0.0	3950
9H-6, 1-4	HS	76.70	4.0	0.0	3080
10X-2, 0-5	HS	79.70	4.0	0.0	4790
11X-1, 4-5	HS	86.20	2.5	0.0	3760
12X-1, 145-150	HS	97.15	4.5	0.0	n.d.
13X-4, 147–150	HS	111.27	3.3	0.0	3080
39-856B-					
2H-3, 0-5	HS	4.80	3.0	0.0	4140
2H-6, 0-5	HS	9.30	2.0	0.0	5640
3H-3, 0-5	HS	14.30	2.0	0.0	3310
3H-4, 0-5	HS	15.80	2.0	0.0	3290
4H-5, 0-5	HS	26.80	2.0	0.0	n.d.
5H-5, 0-5	HS	36.30	2.0	0.0	n.d.
6H-5, 0-4	HS	45.80	5.0	0.0	4700
7H-6, 0-5	HS	56.80	6.6	0.0	5360
8H-1, 100-105	V	59.80	2.4	0.0	1320
8H-1, 105-110	V	59.85	7.2	0.6	5550
8H-1, 137-140	HS	60.17	5.4	0.0	4610
9X-2, 0–2	HS	63.80	4.3	0.0	3480
10X-2, 0-5	HS	72.30	3.2	0.0	2820
11X-3, 5-10	HS	76.35	4.1	0.0	3290
11X-5, 15-20	HS	79.45	5.5	0.0	6390
13X-2, 134-137	HS	84.44	3.4	0.0	3200
15X-4, 134–137	HS	116.20	5.5	0.0	6770
139-856C-					
1H-4, 0-5	HS	6.50	2.3	0.0	2730
139-856D-					
1H-5, 0-3	HS	6.00	2.5	0.0	6020
139-856G-					
1R-4, 0-1	HS	4.50	3.4	0.0	1370
2R-4, 0-1	HS	13.10	3.0	0.0	1470

Table 10. Composition of headspace gases for sediments from Holes 856A, 856B, 856C, 856D, and 856G.

Note: n.d. = not determined.

<sup>a</sup>HS = headspace, V = vacutainer

<sup>b</sup>Concentrations of gases are by volume.

1986; Lewan, 1987). The overall conclusion is that primary petroleum expulsion substantially lags oil generation and that the fine-grained source rock must be capable of generating sufficient oil to totally saturate the pore spaces before primary expulsion can occur. Because oil and water are largely immiscible at temperatures commonly found within the oil generating window (about 50° to 200°C; Hunt, 1979), any water remaining in the pore spaces of the source rock will inhibit this expulsion.

There is considerable controversy in the literature and among oil companies on the exact amount of sedimentary organic matter needed to accomplish the required oil saturation. Certainly, 0.5% of lipid-rich organic matter is an absolute lower limit upon which everyone would agree. However, most researchers feel that the amount of TOC required is considerably higher. For example, Lewan (1987) has shown in hydrous pyrolysis experiments that at least 1.5% of algal organic matter or a minimum of 2.5% of more woody organic matter is required in a sediment to produce saturation of sediment pore spaces with oil after heating. He concludes that these are the minimum sediment TOC values required to produce primary expulsion of oil.

If saturation of pore spaces with oil and oil expulsion do not occur during heating, then further thermal degradation of the unexpelled oil in the pore spaces of the sediment and in the kerogen ultimately leads to production of a black graphitic (carbonaceous) residue accompanied by dry gas  $(C_1-C_3)$ . Such a black carbonaceous residue is found in the sediments at depths >40.7 mbsf of Hole 857A and >11 mbsf of Hole 857B. This black carbonaceous residue is similar to that described in the hydrothermally altered sediments drilled in Guaymas Basin (Curray, Moore, et al., 1982), except that it occurs here in much lower concentrations.

We would argue that sediments at Sites 855 and 856 are not rich enough in the correct type of organic matter to undergo primary oil expulsion. Therefore, only alterations caused by source, maturation, and ultimately thermal degradation need to be considered in interpreting the solvent extract data. Even if the TOC is predominantly a hydrogen-rich, oil-prone algal type kerogen, the total amounts of TOC in the range of 0.2% to 0.8% for Site 855 (see "Organic Geochemistry" section, "Site 855" chapter) and 0.2% to 0.6% for Site 856 (Table 12) are either too low or, at best, very marginal for production of expelled oil. Furthermore, the solvent extract data suggest a significant contribution of higher plant or more oxygen-rich woody organic matter, which is not optimal for producing oil, and tends, instead, to be gas-prone. Therefore, we conclude that all of the C17+ hydrocarbons in sediments from these two sites (as well as any others encountered in future research in the region which do not show higher TOC values) reflect "in-situ" conditions diagnostic of source and maturation only. Complications arising from expulsion and migrational effects need not be considered, as has to be done for more organic-rich source rocks.

The overall hydrocarbon signatures of the surficial intervals of these sediments are quite similar to those reported for shallow gravity cores taken near the Middle Valley hydrothermal vents (Simoneit et al., 1992). In the deeper intervals, however, the hydrocarbons do not resemble the mature hydrothermal petroleum encountered in Escanaba Trough (Kvenvolden et al., 1986). Thus, these hydrocarbon mixtures indicate rapid maturation by accelerated diagenesis resulting from high regional heat flow, and not from hydrothermal alteration.

### Molecular Stratigraphy

Molecular stratigraphy utilizes specific organic compounds (biomarkers) with distinct biological origins to characterize sedimentary sequences. One class of such biomarkers which can be applied here is a group of long-chain ketones, the C37 and C38 alkenones. These compounds elute late in the gas chromatograms of the bitumen extracts without interference from other compounds and are resolved into two peak clusters (cf., Fig. 22 in "Organic Geochemistry" section, "Site 855" chapter). These alkenones are widespread in Quaternary marine sediments and preserve the record of past sea-surface temperature (Marlowe et al., 1984; Brassell et al., 1986). They are derived primarily from prymnesiophyte algae such as Emiliania huxleyi (Volkman, Eglinton, Corner, and Forsberg, 1980; Volkman, Eglinton, Corner, and Sargent, 1980), where the degree of ketone unsaturation (i.e., C37 alkatrienone to C37 alkadienone, Fig. 27) expressed as an index (U<sup>K</sup><sub>37</sub>) is linear vs. the growth temperature determined by laboratory culture experiments with Emiliania huxleyi (Marlowe, 1984; Prahl and Wakeham, 1987). We calculated this index for sediments from this site as:

$$U_{37}^{K} = [C_{37:2}]/([C_{37:2}] + [C_{37:3}])$$

The results are listed in Table 11 and plotted in Figure 28, showing warmer conditions ( $6^{\circ}-8^{\circ}C$ ) in the upper 10 mbsf than in deeper sections ( $4^{\circ}-5^{\circ}C$ ). Examples of this ratio with temperatures for surficial sediments from the more tropical Sites 658 on Walvis Ridge (Poynter et al., 1989) and 686 on the Peru Margin (Farrimond et al.,

Core, section, interval (cm)	Depth (mbsf)	Carbon maxima <sup>a</sup>	Relative yield (× 10 <sup>6</sup> )	CPI. 26-15)	Pr/Ph	Pr/n-C17	Ph/n-C18	U <sup>K</sup> <sub>37</sub>
139-856A-	AU. (1997)			(20-33)		11	10	
1H-1 0-1	1H-1, 0–1 0.00 20, 29 22.3		1.17	1.36	1.03	1.05	0 34	
1H-1, 69-72	0.00	17 20	18.0	3.07	1.30	0.52	0.85	0.54
111-1, 05-72	1.86	17,29	10.1	2.08	1.11	0.32	1.08	0.31
1H-CC	2.70	27 20	73	1.82	1.12	0.52	0.47	0.51
2H-1_61_64	3.32	27, 17	0.7	2.56	1.82	0.62	0.97	na
2H-2 62_64	4.83	17 20	13.0	0.04	1.17	0.02	1.17	n a
211-2, 02-04	6.34	27 17	5.0	2.84	1.80	0.67	1.08	0.36
2H-6 109-111	11.30	17 27	3.5	1.28	1.30	0.80	1.55	0.50
2H-7, 48-50	12.19	17 20	5.2	3.65	1.80	0.85	1.22	n 9
2H-CC	12.19	29 17	67	1.10	1.50	0.60	0.57	11.00.
3H-1 94-98	13.16	17 27	2.9	3.16	1.18	0.94	0.37	n a
3H-2 67-71	14 30	17 27	73	1.60	1 34	0.42	1 48	0.29
3H-CC	21 70	27 17	1.5	1.02	0.80	0.25	0.50	
4H-5 78-82	28.50	17 27	23.3	0.77	1 19	0.32	1.00	0.29
5H-2 63-67	33 35	17 27	173	0.78	1.22	0.11	1.29	0.26
5H-CC	40 70	29 20	12.1	3.63	1.50	0.46	0.44	0.28
6H-4 49-53	45.71	17 27	5.5	0.69	1 13	0.09	0.80	0.40
7H-4, 57-61	55.29	17, 27	2.8	0.76	1.33	0.40	1.36	0.28
139-856B-								
1H-CC	1.80	29, Pr	n.a.	3.49	2.07	1.38	1.15	-
2H-6, 123-127	10.55	17, 27	27.3	0.96	0.82	0.37	0.75	-
2H-CC	11.30	29, 17	2.0	1.35	0.78	0.24	1.13	_
3H-6, 88-92	19.70	17, 18, 25	3.0	1.72	2.86	0.40	0.16	n.a.
4H-5, 102-104	27.83	17,27	5.4	0.75	0.77	0.17	0.96	_
5H-4, 34-39	35.16	17, 27	6.2	0.95	1.09	0.25	0.76	-
7H-2, 119-121	52.00	17, 27	28.7	1.14	1.25	0.40	0.91	_
139-856C-1H-CC	2.00	29, 21	2.7	1.26	0.92	1.57	1.55	-
139-856D-1H-CC	5.00	17, 27	3.7	1.02	0.44	0.37	2.24	-
139-856E-1H-CC	2.40	20, 27	7.0	1.09	0.53	0.44	0.64	$\rightarrow$

Table 11. Various paramet	ers for the solvent soluble	organic matter in sediments	s from Site 856.
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Note: n.a. = not analyzed, --- = compounds not detected.

<sup>a</sup>Major homologs are listed in decreasing order of intensity (C<sub>max</sub>).

1990) are also shown. The alkenones were only detectable in the bitumen extracts of sediments from Hole 856A to about 55 mbsf. There are no previously published data for cold climates such as the Northeast Pacific. These compounds are not detectable in the deeper section of Hole 856A, nor in any section of Hole 856B. They are not stable under significant thermal stress and thus the distribution is consistent with the current thermal regime (see "Site Geophysics and Geology" section, this chapter).

#### **Elemental Analyses**

The results of total C, H, N, and S measurements are shown in Table 12 and in Figures 29 to 32. Total carbon levels are generally low in both Holes 856A and 856B (Figs. 29 and 30, respectively), with the highest values of 1.8% to 2% occurring in surficial sections of Hole 856A. Deeper sediments in the top 40 mbsf show percentages of about 0.5 to 1, which decrease to less than 0.5% in sediments below 50 mbsf, with the exception of one higher value (1.6%) in Sample 139-856A-6H-4, 49–51 cm (45.7 mbsf). The total carbon is generally evenly distributed between inorganic and organic carbon (Table 12 and Fig. 32).

Total carbon is low throughout Hole 856B (Fig. 30), even lower than values observed in Hole 856A below 50 mbsf (Fig. 29). The total carbon levels in both Holes 856A and 856B are surprisingly low considering the sporadic occurrence of carbonate concretions in these sediments (see "Lithostratigraphy and Sedimentology" section, this chapter). It is possible that the hydrochloric acid used in the coulometer does not completely dissolve all of the inorganic carbonate if refractory minerals, such as siderite, are present. Alternatively, fluid flow through deeper sections of both Holes 856A and 856B may have leached some of the carbon.

Downhole plots of H and N for Holes 856A and 856B (Figs. 29 and 30) are similar to those of total carbon. They show considerable noise in the top 30 mbsf and somewhat lower values and smoother maxima and minima in deeper sections. In contrast, the profile of S shows somewhat higher values below 40 mbsf than in the top 20 mbsf. However, some spikes in sulfur (e.g., Samples 139-856A-2H-3, 45-47 cm, at 6.1 mbsf, and 139-856A-4H-4, 92-94 cm, at 27.1 mbsf), as well as some sulfurdepleted zones (e.g., Samples 139-856A-4H-6, 101-103 cm, at 30 mbsf, and 139-856A-5H-3, 73-75 cm, at 34 mbsf) are also apparent above 40 mbsf (cf. Fig. 29). In Hole 856A below 50 mbsf, there is some suggestion of slight carbon depletion accompanying the small amounts of sulfur enrichment. This relationship also may be occurring in Sample 139-856A-2H-3, 45-47 cm, at 6 mbsf, where a relatively high sulfur value of 1.4% is accompanied by a low total carbon value (0.3%). In contrast, samples just above and below this interval (cf. Table 12) have considerably lower sulfur (0.2%) and higher carbon (0.77% and 1.18%) contents.

Hole 856B presents a very different picture. Both total C and N values are generally only about half of those observed in Hole 856A (cf. Figs. 29 and 30). Layers of clastic sulfide occur just above 20 mbsf in Hole 856B (see "Sulfide Petrology and Geochemistry" section, this chapter). Below this zone of clastic sulfide the sediment contains between 0.5% to 1.0% S, mainly as diagenetic pyrite (see "Sediment Geochemistry and Alteration" section, this chapter).



Figure 23. Weight percentages of total carbon, inorganic carbon, organic carbon, and concentration of carbon dioxide (ppm by volume) in headspace gas vs. depth for sediments from Hole 856A.

Profiles of C/H, C/N, and C/S for Holes 856A and 856B are shown in Figures 31 and 32, respectively. If the top 20 mbsf of the sediment section in Hole 856B were missing (see "Paleomagnetism" section, this chapter), then the C/H and C/N profiles for the two holes would overlap quite well, with the decreases in C/H and C/N below 40 mbsf in Hole 856A corresponding to similar decreases below 20 mbsf in Hole 856B. In addition, the maxima in C/H and C/N ratios at 87 mbsf in Hole 856A (Fig. 31) may correspond to similar maxima at 78 mbsf observed in Hole 856B (Fig. 32).

Various types of carbon are compared in Figures 23 and 33 for Holes 856A and 856B, respectively. The contribution of inorganic carbon is surprisingly low throughout Hole 856A, with TOC being about half of the total in shallower sections (about 0.3% to 0.5% above 40 mbsf) and almost 100% of the total in deeper sections. The headspace  $CO_2$  gas shows no correlation with any of the solid carbon phases in these cores. However, in Hole 856B, there is a possible correlation between the small amounts of methane and TOC (Fig. 33), suggesting that traces of methane present in headspace gas could have had an *in-situ* sediment source. However, further shore-based isotopic studies will be required to distinguish between local vs. deeper thermogenic methane sources.

## Conclusions

Solvent extractable biomarkers show that (1) deeper sections of both Holes 856A and 856B below 20 mbsf have experienced temperatures at least equivalent to those of the beginning of the petroleum generation window (>50°C); (2)  $C_{37}$  alkenones present in surface sections of Hole 856A indicate that surface waters in the area were probably cold, in the range of 5° to 6°C, at the time the organisms producing these compounds were living; and (3) solvent-extractable hydrocarbons in these sediments are probably indicative of *in-situ* source and maturation changes; alterations caused by biodegradation, primary expulsion and secondary migration are probably unimportant.

These sediments are not organic-rich enough in the ideal type of organic matter to have undergone primary petroleum (oil) expulsion. Therefore, ratios of solvent-extractable biomarkers sensitive to maturation processes can be used to place upper limits on past geothermal heating.

Sediments in both Holes 856A and 856B are generally lean in both organic and inorganic carbon. Low values of inorganic carbon were unexpected, considering the occurrence of carbonate concretions in the area. Very high contents of sulfur are found at 20 mbsf in Hole 856B in



Figure 24. Examples of gas chromatographic traces of the bitumen (hexane soluble matter) in sediments from Hole 856A. A. Sample 139-856A-2H-2, 62-64 cm. B. Sample 139-856A-2H-3, 83-85 cm. C. Sample 139-856A-1H-CC. D. Sample 139-856A-2H-CC. Numbers refer to carbon chain length of *n*-alkanes. Pr = pristane, Ph = phytane, UCM = unresolved complex mixture of branched and cyclic compounds, CPI = carbon preference index.

a clastic massive sulfide layer. Concentrations of methane in these sediments are small and probably have a localized and thermogenic rather than a microbial source.

# SEDIMENT GEOCHEMISTRY AND ALTERATION

Site 856 is situated over the summit and flank of a 60-m-high hill with a sulfide deposit near its southern flank (Fig. 8). Two important objectives of this site were to document the zonal distribution of hydrothermally altered sediment about a mature but presently inactive high-temperature discharge system that generated at least 94 m of massive sulfide (see "Sulfide Petrology and Geochemistry" section, this chapter), and to determine the origin of the hill. A secondary objective was to compare alteration assemblages that represent the time-integrated effects of a long-lived hydrothermal system with altered sediment at the active, but probably short-lived vent system at Site 858, about 3 km to the northwest.

# Alteration

Of the eight holes drilled at Site 856, three recovered sediments and the other five penetrated mostly massive sulfide. Holes 856A and 856B intersected altered and disrupted sediments and Hole 856H penetrated a narrow interval of altered and veined sediment interbedded with massive sulfide.

### Hole 856A

Strata in Hole 856A consist of interbedded hemipelagic and turbiditic sediment that becomes darker gray and increasingly indurated with depth (refer to "Lithostratigraphy and Sedimentology" section, this chapter). Carbonate concretions and cement first appear at 17 mbsf (139-856A-3H-5, 29–30 cm) and continue to 82 mbsf (139-856A-10X-CC, 0–20 cm). They are more common in coarser grained turbiditic sediment than in relatively impervious clay. The carbonate concretions are typically pale gray, have an ovoid to spherical shape and consist of mostly calcite. Individual concretions extend up to 50 cm in length (139-856A-10X-2, 25–75 cm). They are commonly zoned from a solid calcified core to a diffuse outer margin although the boundary with the surrounding sediment is generally sharp. Some concretions are solid throughout. Most concretions and concentric bands of pyrite.

Petrographic observations show that the concretions formed by infilling intergranular open space in sediment and by partially replacing biogenic components and detrital minerals. Olive green felted masses of authigenic clay and fine-grained euhedral pyrite are closely associated with the calcite concretions. The authigenic clay may be a Mg-rich smectite by analogy with carbonate nodules described earlier from the area of Site 858 (Goodfellow and Blaise, 1988). Barite was not observed in carbonate concretions, although the association of barite with concretions in the area around Site 858 (W. Goodfellow,



Figure 25. Plots of bitumen maturity parameters vs. depth for sediments from Hole 856A.

pers. comm., 1991) indicates that it may be present but is too finegrained and too low in abundance to detect visually or by XRD.

Carbonate concretions appear to form at different times in the history of sedimentation. The differential compaction of hemipelagic mud around some concretions indicates formation during the early stages of diagenesis. Differential compaction is not ubiquitous, however. Many concretions exhibit internal laminations that are parallel to those of the surrounding sediment, indicating that these concretions post-date sediment compaction.

Pyrite appears in minor amounts at 23 mbsf (139-856A-4H-1, 34–35 cm) and persists to the bottom of the hole. Pyrite forms concretions, fills worm burrows, is finely disseminated in hemipelagic mud and carbonate concretions, and infills pore space in turbiditic sand and silt. Near the base of Hole 856A, disseminated pyrite and molds of a mineral having a rectangular outline occur in indurated sediment adjacent to a basaltic sill (see "Lithostratigraphy and Sedimentology" section, this chapter). These molds coincide with an interval of elevated sulfate in pore water (see "Fluid Geochemistry" section, this chapter) and with the occurrence of anhydrite as determined by X-ray diffraction.

The appearance of carbonate concretions and disseminated pyrite coincides approximately with the gradual disappearance of nannofossils at depths greater than 21 mbsf (139-856A-3H-CC) (see "Biostratigraphy" section, this chapter). Foraminifers persist to 50 mbsf but they become progressively infilled, recrystallized, and radially overgrown by fibrous calcite between 30 and 50 mbsf. The disappearance of foraminifers and nannofossils at depths greater than 50 mbsf in hydrothermally altered rocks suggests that the microfossils were destroyed by hydrothermal fluids that permeated through the sedimentary sequence. The zone of foraminifer recrystallization and calcite overgrowth coincides with the depth interval where carbonate concretions are most abundant. This suggests that the processes of calcite precipitation are similar in both cases.

#### Hole 856B

Hole 856B was drilled on the southern flank of the hill 200 m south of Hole 856A, where the seafloor is 23 m deeper (Fig. 8). This hole penetrated layers of hemipelagic mud and turbiditic sediment that are locally interbedded with clastic sulfide sediment and intruded by basaltic sills (see "Lithostratigraphy and Sedimentology" section, this chapter). Between 18 mbsf (139-856B-3H-5, 69 cm) and 28.3 mbsf (139-856B-5H-5, 75 cm), interbedded sulfidic, hemipelagic, and turbiditic sediments are oriented at 20°–30° from horizontal. Within this interval, the proportion of sulfidic sediment generally decreases with depth, to a depth at which turbidites commonly fine upward from silt and sand beds containing mostly pyrite at the base to silty clay at



Figure 26. Plots of bitumen maturity parameters vs. depth for sediments from Holes 856B (circles), 856C (squares), 856D (diamonds), and 856E (triangles).

the top (see "Sulfide Petrology and Geochemistry" section, this chapter). A clastic origin has been suggested for the pyrite, although it is common for authigenic pyrite to form in the interstices of coarse-grained turbidites near areas of hydrothermal discharge in Middle Valley (W. Goodfellow, pers. comm., 1991).

Below the slumped sulfide to 66 mbsf (139-856B-9X-CC, 20 cm), indurated hemipelagic sediment is fractured and brecciated, and the turbiditic silt and sand are disrupted and slurried. Two major types of breccia are recognized. Crackle breccia is mostly clast-supported and consist of large angular clasts that have not been significantly rotated. Channelway breccias are composed of rounded to subrounded clasts with a finer grained matrix of pulverized sediment that has been altered to clay and pyrite. The pyrite forms clots and is finely disseminated throughout the channelway breccias and within breccia clasts near fluid channelways.

Cores 139-856B-8H and -10H were collected by piston coring, but the barrel stroke was incomplete in each case (see "Operations" section, this chapter). Core 139-856B-9X was recovered by XCB. The extent of brecciation of the sediment is difficult to establish due to the possibility that coring disturbance also brecciated the sediment. The preferential accumulation of pyrite in the breccia matrix and its association with altered sediment are interpreted as evidence that these breccias are not entirely an artifact of drilling. Some of the breccia may have formed *in situ* by hydraulic fracturing and brecciation of moderately indurated sediment during the upflow and lateral discharge of hydrothermal fluid. There are two possible origins of the hydrothermal fluid. The hydrothermal fluid may have been generated locally by the emplacement of a mafic sill into a water-saturated sedimentary sequence, and circulated under a local geothermal gradient. Alternatively, the sediments may have been brecciated by the metal-rich hydrothermal fluids that formed the sulfide deposit intersected in Holes 856G and 856H (Fig. 8).

Petrographic descriptions of smear slides and thin sections show that below the slumped clastic sulfide, authigenic clay increases in abundance and magnetite grains become ragged and partly replaced by pyrite. At depths greater than 70 mbsf, detrital plagioclase is partly altered to clay minerals. Nannofossils and foraminifers disappear below 30 mbsf (see "Biostratigraphy" section, this chapter). The alteration of magnetite corresponds to a marked decrease in the magnetic susceptibility, from values of 10<sup>-3</sup> to 10<sup>-2</sup> (SI) above 30 mbsf to less than about  $3 \times 10^{-4}$  (SI) below this depth (see "Physical Properties" section, this chapter). Because turbidites persist to the bottom of Hole 856B, a drop in the magnetic response is unlikely to have been caused by a change in the style of sedimentation. Furthermore, since Hole 856A has normal susceptibilities at these depths, the reduction of the magnetic susceptibility in Hole 856B is unlikely to have been caused by burial metamorphism, but rather must have been caused by a more localized hydrothermal alteration of magnetite. The advection of hydrothermal H2S through sediment most likely caused the sulfidization of magnetite. As a result, the content of pyrite may



Figure 27. Partial gas chromatographic trace showing the elution order of the  $C_{37}$  alkenones in Sample 139-856A-5H-CC (37:2M =  $C_{37}$  methylalkadienone, 37:3M =  $C_{37}$  methylalkatrienone, 38:3E =  $C_{38}$  ethylalkatrienone, 38:3M =  $C_{38}$  methylalkatrienone, 38:2E =  $C_{38}$  ethylalkadienone, 38:2M =  $C_{38}$  methylalkatrienone).

give a measure a original magnetite content of the different sedimentary facies and the extent of magnetite alteration, if we assume fairly uniform initial magnetite contents characterized the different sedimentary facies.

Between 40 and 60 mbsf, molds are common in fractured and brecciated hemipelagic silty clay and in silty clay that has not been brecciated or fractured. The molds are randomly distributed, have a lath-shape, and range between 2 and 6 mm in length. In the breccia, the molds occur most commonly within clay clasts but rarely in channelway breccias. The molds occur discontinuously to 66 mbsf (139-856B-9X-CC, 20 cm). Between 65 and 66 mbsf (139-856B-9X-2, 130–150 cm; 139-856B-9X-3, 0–18 cm), the molds are partly filled with pyrite. The shape of the molds and the high calcium and sulfate content of pore fluids (see "Fluid Geochemistry" section, this chapter) suggest that the molds represent anhydrite that was dissolved by reaction with pore waters.

The sequence of brecciated sediment is intruded by a mafic sill at 64 mbsf. Subrounded dark grey claystone clasts are more indurated in the 40-cm interval above the sill (139-856B-8H-4, 10-49 cm). Below the sill to 80 mbsf, the sediment consists of locally brecciated and highly fractured interbedded hemipelagic claystone, and turbiditic siltstone and sandstone containing several percent pyrite. There is no evidence of greater sediment induration adjacent to the basal contact of this sill, although it is possible that due to poor core recovery the sediment in contact with the sill was not recovered.

Below 66 mbsf, the core is composed of moderately indurated interbedded claystone, siltstone, and sandstone that persist to about 110 mbsf. Below this the sediment is progressively fractured, brecciated, silicified, and chloritized (refer to "Mineralogy," this section) adjacent to a basaltic sill at 120 mbsf. In the 10-m-thick interval above the sill, the sediments contain elevated contents of sphalerite, chalcopyrite, pyrrhotite, barite, and pyrite in the form of both disseminated grains and veins. Compared with chalcopyrite and pyrrhotite, the distribution of sphalerite is more widespread and extends about 18 m above the sill. Between 104 and 112 mbsf, brown disseminated sphalerite occurs discontinuously in coarser grained sediment, particularly in the basal parts of siltstone and sandstone turbidites (Fig. 34).

The sulfide and barite veins follow bedding planes and also cut strata at low to high angles; these are common between 111 mbsf and the basalt contact at 120 mbsf. The veins consist of chalcopyrite-sphaleritepyrrhotite, chalcopyrite-pyrrhotite, pyrite-chalcopyrite, barite-chalcopyrite, barite, chalcopyrite, and sphalerite mineral assemblages.

Chalcopyrite veins are commonly surrounded by green chlorite, followed outward by highly silicified pale gray sediment (interval 139-856B-15X-CC, 18–22 cm; Fig. 14). A gray-green silicified burrow with chalcopyrite and pyrrhotite occurs at 139-856B-15X-2, 65–70 cm. An anastomosing network of chalcopyrite with an envel-ope of dark gray alteration occurs at 139-856B-15X-4, 8–14 cm. The silicified sediment has a spotted gray-green alteration at 139-856B-15X-3, 12 cm. At 118.4 mbsf, a bedding-parallel chalcopyrite vein is cut by a barite vein.

Tabular barite crystals, 2 mm wide by up to 6 mm long, are disseminated in altered claystone. Associated with disseminated barite is chalcopyrite with minor pyrrhotite and pyrite. Chalcopyrite, locally with pyrrhotite cores, forms blebs 1 cm across in partly silicified sediment at 118.5 mbsf. Fine-grained chalcopyrite replaces diagenetic pyrite at 117 mbsf. Between 114 and 115 mbsf, coarse-grained crystals of chalcopyrite and pyrite are overgrown by dark brown sphalerite in semilithified claystone.

#### Mineralogy

XRD analysis of bulk samples shows that unaltered turbiditic and hemipelagic sediments in Middle Valley consist, in decreasing order

	Table	12.	Elemental	anal	vses (	of C	H	. N	. and	S	for sedimen	ts from	Holes	856A	and 8	56B.
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Core, section,	Depth	C (%)	H	S (%)	N (%)	С/На	C/N <sup>a</sup>	C/S <sup>a</sup>	Inorganic	TOC
139-856A-	(moar)	(10)	()()	(10)	()	Chi	CIT	cio		(20)
111 1 60 72	0.60	2.04	0.60	0.15	0.100	2.40	20.40	12.6	1.26	0.69
1H-1, 09-72	1.85	1.94	0.60	0.15	0.100	3.40	20.40	10.22	1.30	0.68
1H-2, 35-37	1.05	1.64	0.31	0.18	0.120	4.84	28.75	18.4	1.25	0.58
2H-1, 61-64	3 31	0.31	0.30	0.10	0.004	1.03	8.61	1.82	0.16	0.15
2H-1, 61-64	3.31	0.32	0.24	0.11	0.025	1.33	12.80	2.91	0.16	0.16
2H-2, 62-64	4.82	1.18	0.72	0.23	0.130	1.64	9.08	5.13	0.34	0.84
2H-3, 83-85	6.53	0.77	0.57	0.21	0.130	1.35	5.92	3.67	0.25	0.52
2H-4, 77-79	7.97	0.50	0.34	0.21	0.090	1.47	5.56	2.38	0.26	0.24
2H-5, 93-95	9.63	0.68	0.54	0.24	0.160	1.26	4.25	2.83	0.19	0.49
2H-6, 109-111	11.29	0.85	0.59	0.35	0.100	1.44	8.50	2.43	0.29	0.56
2H-7, 48-50	12.18	0.75	0.56	0.30	0.110	1.34	6.82	2.50	0.36	0.39
3H-1, 94-98	13.14	0.76	0.41	0.17	0.061	1.85	12.46	4.47	0.37	0.39
3H-2, 67-71	14.40	0.88	0.42	0.20	0.077	2.10	11.43	4.40	0.57	0.31
3H-3, 69-73	15.89	0.65	0.52	0.00	0.120	1.25	5.42		0.28	0.37
3H-3, 69-73	15.89	0.66	0.51	0.09	0.056	1.29	11.79	7.33	0.28	0.38
3H-4, 59-63	17.29	0.63	0.45	0.085	0.065	1.40	9.69	7.41	0.28	0.35
3H-5, 70-74	18.90	0.71	0.60	0.60	0.160	1.18	4.44	1.18	0.19	0.52
3H-6, 78-82	20.48	1.10	0.55	0.60	0.280	2.00	3.93	1.83	0.23	0.87
4H-1, /1-/5	22.41	0.82	0.43	0.16	0.039	1.91	21.03	5.13	0.56	0.20
411-1, /1-/3	22.41	0.62	0.41	0.093	0.062	2.00	17.58	11.72	0.56	0.55
4H-2, 86-90	24.00	0.62	0.41	0.10	0.087	1.51	7.15	3.88	0.30	0.20
41-4 92-96	27.12	0.56	0.39	1 71	0.081	2.15	15 56	0.02	0.30	0.19
4H-4, 92-96	27.12	0.50	0.20	1.10	0.030	2.15	12.05	0.33	0.38	0.19
4H-6 101-105	30.21	0.94	0.60	0.00	0.094	1.57	10.56	0.40	0.41	0.53
4H-6, 101-105	30.21	0.67	0.38	0.00	0.068	1.76	9.85	-	0.41	0.26
5H-6, 46-50	39.16	0.65	0.20	0.48	0.021	3 25	30.95	1.35	0.5	0.15
6H-2, 88-92	43.08	0.55	0.25	0.25	0.040	2.20	13.75	2.2	0.42	0.13
6H-4, 49-53	45.69	1.58	0.51	0.17	0.077	3.10	20.52	9.29	0.67	0.91
7H-2, 95-99	52.65	0.47	0.27	0.50	0.057	1.74	8.25	0.94	0.33	0.14
8H-3, 66-68	63.36	0.38	0.51	0.20	0.084	0.75	4.52	1.90	0.01	0.37
9H-2, 94-98	71.64	0.19	0.38	0.00	0.091	0.50	2.09		0.01	0.18
10X-1, 68-71	79.38	0.17	0.30	0.56	0.051	0.57	3.33	0.30	0.01	0.16
11X-1, 104-106	87.24	0.35	0.21	0.30	0.066	1.67	5.30	1.17	0.19	0.16
12X-1, 85-89 13X-2, 123-27	96.55 108.03	0.24 0.28	0.50 0.59	0.17 0.29	0.098 0.092	0.48 0.47	2.45 3.04	1.41 0.97	0.01	0.23 0.27
139-856B-										
IH-1, 123-127	1.23	1.87	0.54	0.25	0.095	3.46	19.68	7.48	1.29	0.58
1H-1, 123-127	1.23	1.92	0.58	0.42	0.054	3.31	36.00	4.57	1.29	0.63
2H-3, 45-49	6.15	0.30	0.28	1.40	0.079	1.07	3.80	0.21	0.02	0.28
2H-3, 45-49	6.15	0.24	0.30	1.19	0.022	0.80	10.90	0.02	0.22	0.22
2H-5, 76-80	8.56	0.40	0.37	0.65	0.025	1.08	16.00	0.62	0.01	0.39
2H-6, 123-127	10.53	0.41	0.34	0.41	0.030	1.21	13.67	1.00	0.01	0.41
3H-2, 31-35	13.10	n.d.	n.d.	n.d.	n.d.		-	_	0.04	
3H-4, 96-100	16.76	n.d.	n.d.	n.d.	n.d.		-		0.01	
3H-6, 20–22	19.00	n.d.	n.d.	n.d.	n.d.		—		0.01	
3H-6, 88-92	19.68	0.17	0.21	41.00	0.010	0.81	17.00	0.03	0.14	
3H-7, 2–7	20.32	n.d.	n.d.	n.d.	n.d.				0.62	0.26
4H-5, 21–23 4H-5, 102–104	24.00 27.82	0.39 n.d.	0.59 n.d.	6.32 n.d.	0.052 n.d.	0.66	7.50	0.06	0.03	0.36
139-856A-										
5H-2 73-77	34 90	0.71	0.36	0.00	0.100	1.97	7 10		0.43	0.28
5H-2, 73-77	34.90	0.29	0.46	1.06	0.022	0.63	13.16	0.27	0.02	0.27
139-856B-										
5H-4, 34-39	35.14	n.d.	n.d.	n.d.	n.d.		-		0.01	<del></del>
5H-5, 120-125	37.50	0.14	0.24	1.17	0.028	0.58	5.00	0.12	0.02	0.12
6H-4, 12-14	44.42	0.33	0.55	0.38	0.048	0.60	6.88	0.87	0.02	0.31
7H-2, 119-121	51.99	n.d.	n.d.	n.d.	n.d.		—		0.01	
7H-3, 130-130	53.60	0.34	0.50	1.16	0.045	0.68	7.56	0.29	0.03	0.31
7H-4, 11-15	53.91	n.d.	n.d.	n.d.	n.d.	<u></u>			0.01	
8H-2, 55-57	60.85	0.12	0.29	0.35	0.017	0.41	7.06	0.34	0.02	0.10
8H-3, 20-22	62.00	n.d.	n.d.	n.d.	n.d.			0.05	0.01	0.00
9X-2, 139-142	65.19	0.32	0.68	1.28	0.028	0.47	11.43	0.05	0.02	0.29
-11X-4, 18-21	77.80	0.34	0.40	1.24	0.036	0.85	9.44	0.27	0.02	0.32
12X-2, 52-56	83.62	0.08	0.42	1.48	0.005	0.19	17.17	0.05	0.01	0.07
12X-3, 12-10	84.72	0.21	0.60	1.55	0.014	0.35	15.00	0.14	0.01	0.20
13X-4 100 113	95.48	n.d.	0.45	0.72	n.d.	0.27	16.00	0.16	0.01	0.11
14X-1 55-50	101 35	0.00	0.45	0.75	0.073	0.15	1 16	0.10	0.01	0.06
14X-1.55-59	101.35	0.14	0.55	1.16	0.034	0.25	4.12	0.12	0.03	0.11
15X-3, 104-106	114.44	0.22	0.90	5.48	0.009	0.24	23.91	0.04	0.02	0.20

Note: n.d. = not determined, --- = not applicable. <sup>a</sup>Calculated as percentage ratios. <sup>b</sup>Wood present?



Figure 28.  $C_{37}$  alkenone parameter  $(U_5^{X})$  and temperature estimate of the ocean surface water vs. sub-bottom depth in Hole 856A. Other more tropical sites are also shown for comparison.

of abundance, of detrital quartz, feldspar, chlorite, mica, and hornblende. Near the seafloor, where biogenic components are abundant, calcite is also detected by XRD as a minor phase. In general, turbiditic silt and sand contain relatively higher contents of quartz and feldspar, whereas finer grained hemipelagic clay and silty clay are relatively enriched in detrital chlorite and mica.

In Hole 856A, calcite and hornblende are not detectable by XRD below Sections 139-856A-9H-5 and -3H-2, respectively (Table 13). The disappearance of hornblende is probably due to hydrothermal alteration. Trace or minor amounts of anhydrite occur between Sections 139-856A-7H-2 and -11X-1 and lie above the interval where

molds were observed in Cores 139-856A-11X through -13X (see "Lithostratigraphy and Sedimentology" section, this chapter). Plagioclase is more abundant below the base of Core 139-856A-10X and may have formed by the albitization of detrital feldspar.

In Hole 856B, hornblende persists to 15 mbsf, and calcite disappears as a minor or major phase at depths greater than 30 mbsf (Table 14). Plagioclase is a major phase between 78 and 100 mbsf, but decreases to trace amounts or disappears below 100 mbsf. The disappearance of plagioclase corresponds to the destruction of mica and a marked and systematic buildup of chlorite at depths greater than 100 mbsf. Feldspar peak intensities are higher in altered sediment (Sample 139-856B-12X-CC, 12-16 cm; Fig. 35) than in unaltered sediment from near the seafloor (Sample 139-856B-1H-1, 123-127 cm; Fig. 36) although both samples are fine-grained hemipelagic clay. These intense feldspar peaks observed in XRD traces from Sample 139-856B-12X-CC, 12-16 cm, are also observed in samples between Sections 139-856B-11X-3 and -13X-CC (Table 14). At depths below 100 mbsf (Sample 139-856B-14X-3, 55-59 cm; Table 14), feldspar peak intensities decrease markedly. This sharp decrease of feldspar content corresponds to the formation of authigenic chlorite (Fig. 37). Sediment samples taken between Sections 139-856B-13X-CC and -15X-3 contain chlorite as the predominant (Sample 139-856B-14X-3, 91-94 cm; Fig. 37) or almost monophase mineral (Samples 139-856B-15X-3, 104-106 cm; Fig. 38).

The (060) peaks of chlorite in Sample 139-856B-15X-3, 104–106 cm, and the chlorite in the clay fractions from Sample 139-856B-14X-3, 91–94 cm, occur at about 1.554 Å and 1.547 Å, respectively. These values indicate that the chlorite is trioctahedral Mg-Fe-chlorite and suggests that the Fe content of chlorite from Sample 139-856B-15X-3, 104–106 cm (Fig. 38), is higher than in chlorite from Sample 139-856B-14X-3, 91–94 cm (Fig. 39). A comparison of basal-XRD-peak intensity ratios of these chlorite minerals shows that chlorite from Sample 139-856B-15X-3, 104–106 cm, is characterized by a higher *I*(7A)/*I*(14) intensity ratio.

The powder XRD pattern for the clay fraction from Sample 139-856B-15X-6, 10–12 cm, is characterized by the presence of a small 30.5-Å peak and a high, broad 15-Å peak (Fig. 40). These peaks indicate that the predominant clay mineral in this sample is a chlorite/smectite mixed-layer clay.

Table 13. X-ray diffraction mineralogy for bulk samples from Hole 856A.

Core, section, interval (cm)	Quartz	Feldspars	Hornblende	Chlorite	Mica	Calcite	Anhydrite
139-856A-							
1H-1, 69-72	***	***	*	*		*****	
2H-2, 62-64	***	***	*		*	*	
3H-2, 67-71	*****	***	-	***	***	*	
4H-2, 86-90	***	***		***	***	16	
5H-3, 73-77	******	***				***	
6H-1, 54-58	******	***				冰水街	
6H-2, 88-92	*****	*****		-		***	
7H-1, 64-68	***	***		***	*	*	
7H-2, 95-99	******	*****		*	*	sje	
7H-3, 89-93	***	*		<b>ц</b> е			
7H-5, 80-84	*****	***		*	*	*	
8H-1, 115-117	*****	*****		*		*	*
8H-3, 102-105	******	*****		*		185	***
8H-7, 38-36	***	***		***	*		
9H-2, 94-98	*****	***		***	***		
9H-5, 100-104	*****	**				*	
10X-1, 68-71	*****	******			*		
11X-1, 104-106	*****	*****		*			
12X-1, 85-89	***	非非非		***			
13X-4, 109-113	*****	***		非非非	*		

Notes: Relative mineral abundances were determined by peak heights and are indicated as follows: \* = trace, \*\*\* = minor, \*\*\*\*\*\*\* = major, and \*\*\*\*\*\*\* = dominant. Because peak heights are determined by mineral morphology in addition to mineral abundance, this table cannot be used to quantitatively determine the relative abundances of different minerals. See "Sediment Geochemistry and Alteration" section, "Explanatory Notes" chapter, for a description of X-ray diffraction methods.



Figure 29. Weight percentage of C, H, N, and S vs. depth of sediments from Hole 856A.

The major element composition of bulk sediment samples suggests that chlorite consists of two distinct types, a Mg-rich chlorite which is the most common and widespread, and an Fe-rich chlorite which is associated with sulfide veins cutting highly altered sediment. The Fe-rich chlorite is interpreted to have formed from higher temperature, metal-rich hydrothermal fluid whereas the Mg-rich chlorite probably formed in a broad lower temperature zone of mixing between pore fluid and hydrothermal fluid that has migrated outward from the discharge conduit.

The mineralogy of unaltered sediment determined by XRD methods agrees with the mineralogy of surface sediment cores determined by Goodfellow and Blaise (1988). Late Pleistocene and Holocene silty clay in Middle Valley consists of about 73% clay, 25% silt, and 2% sand. The sand fraction of hemipelagic sediment is composed of mostly biogenic components, with generally less than 5% of combined quartz, hornblende, and other nonbiogenic minerals. Biogenic components consist of 55% foraminifers, 25% radiolarians, and the remainder of diatoms, fecal pellets, and other biogenic material. The <2 µm clay fraction contains in decreasing order of abundance, smectite (40%), chlorite (30%), illite (20%), irregular mixed-layer clays (10%), and minor quartz, plagioclase, and hornblende.

# Geochemistry

Major and minor element data for Holes 856A and 856B are presented in Table 15; trace elements for Hole 856A are listed in Table 16. Depth profiles for major and minor elements are plotted in Figures 41 and 42, respectively; major and minor trace element profiles for Hole 856B are presented in Figures 43 and 44, respectively.

In Hole 856Å, the contents of MgO, MnO, Fe<sub>2</sub>O<sub>3</sub>, and S are generally higher below 60 mbsf than above, and CaO, CO<sub>2</sub>, and K<sub>2</sub>O are lower. SiO<sub>2</sub>, Na<sub>2</sub>O, and Sr covary with depth whereas Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> behave inversely to these elements. Depth profiles of Rb, Ni, Zn, V, and Cu are similar to K<sub>2</sub>O and H<sub>2</sub>O, whereas P<sub>2</sub>O<sub>5</sub>, Y, and Nb covary with depth. Most of the remaining elements determined (Tables 15 and 16) are either invariant or do not show any systematic variations.

In Hole 856B, MgO, MnO, TiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub> generally increase downward, and CaO, Ba, and Sr show a marked decrease. Similar to Hole 856A, Na<sub>2</sub>O and SiO<sub>2</sub> have a high covariance whereas Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, MgO, and MnO behave inversely to these elements. Zn and Cu are highly concentrated (0.31% and 1.09%, respectively) in Sample 139-856B-4H-3, 21–23 cm, due to the presence of massive sulfide. The remaining elements do not display any systematic downhole variations.



Figure 30. Weight percentage of C, H, N, and S vs. depth of sediments from Hole 856B.

To evaluate the effects of hydrothermal alteration on the chemical composition of sediment cores at Site 856, depth profiles of elements highly affected by alteration in Holes 856A and 856B are compared with elemental profiles of a composite section constructed with samples from Holes 855A, 855B, and 855C. Because Site 855 is situated in an area of low heat flow near the eastern margin of Middle Valley, sediment from this site shows none of the effects of hydrothermal alteration observed at Site 856. As such, Holes 855A, 855B, and 855C serve as reference holes against which chemical data from Site 856 have been compared.

Many of the downhole chemical changes noted in Holes 856A and 856B are similar to the compositional variations between Site 855 and Site 856. Compared with Holes 855A, 855B, and 855C, sediment below 60 mbsf in 856A and below 30 mbsf in Hole 856B are enriched in MgO and MnO, and depleted in CaO and Sr (Figs. 45 through 48). Hole 856B is also enriched in Fe<sub>2</sub>O<sub>3</sub> and depleted in Na<sub>2</sub>O compared to Holes 856A, 855A, 855B, and 855C. The low Na<sub>2</sub>O abundance in Hole 856B corresponds to low contents of "plagioclase CaO" that were calculated by subtracting CaO bound in calcite from total CaO. This calculation assumes that all the CO<sub>2</sub> occurs as CaCO<sub>3</sub> and that there are no other major calcium phases. Barium is abundant in the upper 60 m of Hole 856B relative to Holes 855A, 855B, and 855C, and is depleted between 60 and 120 mbsf in Hole 856B (Fig. 49).

The downhole chemical changes in Holes 856A and 856B are consistent with the mineral assemblages determined by petrographic examination of smear slide and polished thin-section examinations, and by XRD analysis. In unaltered turbiditic and hemipelagic sediment, the content of most major and many trace elements is controlled by the relative proportions of detrital minerals, particularly quartz, plagioclase, clay, mica, and chlorite. Because turbiditic silt and sand contain generally higher proportions of quartz, plagioclase, magnetite, zircon, and probably other heavy minerals relative to mica, chlorite, and clay, they are enriched in SiO2, CaO, Na2O, and Zr, and depleted in Al<sub>2</sub>O<sub>3</sub>, MgO, K<sub>2</sub>O, and H<sub>2</sub>O. As a result, there is a general inverse relationship between elements bound in coarser grained quartz and feldspar and those concentrated in finer grained clays, mica, and chlorite that is controlled by sedimentary processes. Elements preferentially bound in the coarser detrital minerals tend to covary with each other but they vary inversely with elements forming clay-size minerals. The distribution of element oxides, such as SiO2, Al2O3, and CaO, that are partitioned between coarser grained minerals (e.g., quartz, plagioclase), biogenic components (e.g., foraminifer), and finer-grained detrital phases (e.g., mica, chlorite) is more complex and is controlled by the dominant mineralogy. Although foraminifers are typically silt-size, they are more concentrated in finer grained silty clay due to slower rates of accumulation of fine-grained sediment.

At Site 856, the chemical composition of hemipelagic and turbiditic sediment has been altered to varying degrees by hydrothermal processes. The marked increase of MgO below 50 mbsf in Holes 856A and 856B (Fig. 45) corresponds to the infilling and variable replacement of



Figure 31. Ratios of weight percentages of C/H, C/N, and C/S vs. depth for sediments from Hole 856A.

sediment by chlorite. The chlorite content as determined by XRD analysis of the <2  $\mu$ m clay fraction follows the trend of increasing MgO content with depth. The Mg/Fe molar ratio estimated from the bulk compositions, assuming that all the Mg and Fe are bound by chlorite, also shows a systematic increase with depth. This suggests that the composition of hydrothermal chlorite is relatively Mg-rich compared to detrital chlorite above 60 mbsf in Hole 856A or in Holes 855A, 855B, and 855C (Fig. 50). In Hole 856B, the Mg/Fe molar ratio exceeds ratios for detrital chlorite (about 0.2) below 60 mbsf.

The sharp drop of Mg/Fe molar ratios at 87 mbsf in Hole 856A, below values for detrital chlorite, is probably controlled by the formation of an Fe-rich chlorite. Massive Fe-rich chlorite is also associated with sulfide veins cutting altered sediment below 111 mbsf in Hole 856B.

A decrease of calcium below 60 mbsf in Hole 856B is related to the almost total dissolution of biogenic carbonates. Profiles of Na/Ca molar ratios for holes at Sites 855 and 856 show an increase in ratios with depth in both Holes 856A and 856B, and have generally higher ratios than for unaltered sediment at Site 855 (Fig. 51). These results suggest that the plagioclase in Holes 856A and 856B is albitized. Higher plagioclase contents are inferred from XRD measurements from these deeper sediments.

To evaluate the possible addition or removal of silica during hydrothermal alteration, a  $SiO_2/Zr$  ratio was plotted against depth for holes from Sites 855 and 856. Zirconium was chosen because it occurs with quartz as a detrital mineral in turbiditic silt and sand, and because it is more likely to behave conservatively during hydrothermal alteration. In Holes 855A, 855B, 855C, and 856A, the  $SiO_2/Zr$  ratios are fairly uniform and range between 0.28 and 0.40 (Fig. 52). In Hole 856B, however, these ratios exceed 0.4 below about 60 mbsf and extend the zone of silicification observed visually below about 111 mbsf to shallower depths.

The distribution of barium is probably controlled by the formation of barite above about 50 mbsf in Hole 856B, and the removal of Ba, probably by the dissolution of biogenic organisms (e.g., diatoms) below 60 mbsf (Fig. 49).

The depth distributions of inorganic C, total S, and organic C/S ratios in Holes 855C, 856A, and 856B are plotted in Figures 53



Figure 32. Ratios of weight percentages of C/H, C/N, and C/S vs. depth for sediments from Hole 856B.

through 55, respectively. The inorganic carbon content in Hole 855C reflects the higher biogenic carbonate content in the upper 20 mbsf, but decreases to between 0.1% and 0.3% at greater depth. Sulfur rarely exceeds 0.3% in the upper 20 m of Hole 855C. The ratio of organic carbon to sulfur in Hole 855C and 856A is about 3, which is indirectly controlled by the stoichiometry relating the number of atoms of carbon oxidized to the number of atoms of S reduced during bacterial sulfate reduction under open conditions (Goldhaber and Kaplan, 1974).

The lower part of Hole 856B has a low ratio of organic carbon to sulfur due to the addition of diagenetic pyrite replacing magnetite. In Hole 856A, inorganic carbon increases to values consistently greater than 0.3% in a zone extending from the surface to 50 mbsf, where carbonate concretions are most common. Below about 50 mbsf, the content of inorganic C decreases to values less than those measured in Hole 855C. This implies that carbonate has been leached from the sediment by hydrothermal fluids. In Hole 856B, the depletion of inorganic C is more pronounced, with values rarely exceeding 0.03%.

Unlike inorganic C, the S content is higher in Holes 856A and 856B compared with Hole 855C. In Hole 855C, the S content rarely exceeds 0.3%, whereas in Hole 856A, it commonly exceeds values of 0.3%. In Hole 856B, it ranges between values of 0.3% and 1.5%. The high content of S in Holes 856A and 856B corresponds well with higher visual estimates of disseminated pyrite.

### Discussion

Most of the alteration minerals observed in Holes 856A and 856B have already been documented in hydrothermally altered near-surface sediment adjacent to areas of high heat flow and active venting near Site 858 (Davis et al., 1987; Goodfellow and Blaise, 1988). Of the 37 shallow (12 m or less) piston and gravity cores taken between 1985 and 1990 in the area of Site 858, 10 contained carbonate concretions. The carbonate concretions formed in a zone of elevated heat flow (>4 W/m<sup>2</sup>) adjacent to centers of hydrothermal fluid discharge. The concretions are restricted to discrete stratigraphic intervals, suggesting a temporal or lithological control on their formation. Highly negative  $\delta^{13}$ C values (-40 to -60 per mil) in the carbonate indicate



Figure 33. Weight percentages of total carbon, inorganic carbon, organic carbon, and concentration of methane (ppm by volume) in headspace gas vs. depth for sediments from Hole 856B.

that the carbon originated from oxidation of organic compounds such as methane (Goodfellow and Blaise, 1988).

In Hole 856A, the association of carbonate concretions with elevated contents of euhedral pyrite and green authigenic clays suggests that this assemblage probably formed by the lateral migration of hydrothermal fluids from the vent system that generated the massive sulfide deposit intersected in Holes 856G and 856H. Carbonate fossils were either dissolved completely or infilled and overgrown by calcite, depending on the chemical composition of the interstitial fluids. The composition of pore fluids is controlled by a number of processes including *in-situ* reactions with sediment under elevated thermal conditions, the upward and outward migration of hydrothermal fluids from discharge conduits, and the shallow recharge of seawater into the zone of fluid upflow.

In Hole 856B, the sediments are moderately to intensely indurated, brecciated and fractured, and enriched in pyrite (up to 3%); feldspar has been albitized and replaced by chlorite and/or mixed-layer chlorite-smectite clay. The disappearance of microfossils and a very low  $CO_2$  content indicates that carbonate was dissolved by hydrothermal fluids. The occurrence of anhydrite, Mg-Fe-chlorite, and mixed-layer clays, the alteration of plagioclase, high pyrite content, and evidence of fluid discharge in the form of breccias are consistent with Hole 856B being closer than Hole 856A to the center of hydrothermal fluid discharge. Although it is possible that anhydrite formed by the heating of pore waters during sill emplacement, the occurrence of authigenic anhydrite in hydrothermally altered sediment at Site 858 indicates that anhydrite is probably of hydrothermal origin. Anhydrite most likely precipitated from pore fluids that were heated by hydrothermal fluids that migrated outward from upflow zones.

Alteration of sediment associated with the sills penetrated by Holes 856A and 856B is generally localized to within a few meters of the sill, and is represented by sediment with a higher degree of induration. In Hole 856B, however, a zone extending 20 m above the sill encountered at 120 mbsf consists of turbiditic and hemipelagic sediment that is variably silicified and chloritized, cut by sulfide and barite veins, and impregnated with sulfide blebs and disseminations. The sulfide consists of chalcopyrite, pyrrhotite, sphalerite, and pyrite. Individual chalcopyrite veins are surrounded by envelopes of chlorite and silicified sediment. The bulk chemistry indicates that chlorite compositions of the veins are more iron-rich compared with more widely distributed Mg-rich chlorite. The chalcopyrite-pyrrhotite assemblage, Fe-rich chlorite, and associated silicification all indicate higher temperature conditions. The presence of mixed-layer chloritesmectite clay in Sample 139-856B-15X-6, 10-12 cm (Table 14), adjacent to the sill, is not consistent with the formation of this alteration assemblage by local hydrothermal circulation driven by the sill complex. It seems more likely that this mineral assemblage formed by the lateral migration of metalliferous fluids from the conduit



Figure 34. Disseminated sphalerite (dark specks) in turbiditic silt and sand, Site 856, Middle Valley (interval 139-856B-14X-4, 8-16 cm).

associated with the massive sulfide penetrated in Holes 856G and 856H. If this interpretation is correct, the sulfide veins intersected in Hole 856B represent part of the feeder system that generated the massive sulfide deposit at Site 856.

Figure 56 is a south-north cross section of Site 856 showing the hill, the sulfide mound, an active vent site, and the distribution of massive sulfide and hydrothermal alteration zones. The massive sulfide deposit penetrated in Holes 856H and 856G is surrounded by an inner zone consisting of pyritized, clay- and chlorite-altered sediments depleted in inorganic carbonate, and an outer zone characterized by the appearance of calcite concretions and carbonate cement. Authigenic anhydrite and secondary albite occur near the outer margins of the inner zone and as such may constitute a distinct hydrothermal facies. This zonal pattern of hydrothermal alteration minerals is very similar to the concentric pattern of alteration minerals recognized previously in surficial (<12 mbsf) sediment recovered in piston and gravity cores in the area of Site 858 (W. Goodfellow, pers. comm., 1991).

# SULFIDE PETROLOGY AND GEOCHEMISTRY

Holes 856A through 856H form a north-south cross section from the center of a hill (856A) to the southern flank of a mound of massive sulfide that occurs south of the hill (Figs. 8 and 57). Hydrothermally precipitated sulfide minerals were recovered in Holes 856B through 856H. Hydrothermal sulfide in Hole 856B consists of clastic massive sulfide in Cores 139-856B-3H and -4H, and disseminated sulfide and sulfide veins in Cores 139-856B-14X to -16X. In addition, sediment in Hole 856B below the interval of clastic massive sulfide has anomalously high contents of disseminated and nodular pyrite that may have formed, in part, by hydrothermal addition of sulfur ("Sediment Alteration and Geochemistry" section, this chapter). Holes 856C through 856H recovered predominantly massive sulfide clasts or sulfide sand, partly disaggregated by coring or drilling disturbance. The thickest massive sulfide intervals were recovered in Holes 856G and 856H, which penetrated 65.4 m and 93.8 m of sulfide, respectively, before the holes had to be abandoned due to adverse drilling conditions.

This section describes the mode of occurrence, mineralogy, composition, and dominant textural features of hydrothermal sulfide in each hole and classifies the sulfide into sulfide types (see "Sulfide Petrology and Geochemistry" section, "Explanatory Notes" chapter, this volume). Generalizations on the relative timing and sequence of mineral precipitation and replacement, based on both hand-sample descriptions and petrographic observations of representative polished thin sections, are presented. The mineralogical composition of each sulfide type is estimated from thin-section petrography. The Cu and Zn content of representative sulfide samples was measured by flame atomic absorption spectrophotometry ("Sulfide Petrology and Geochemistry" section, "Explanatory Notes" chapter, this volume).

# Hole 856B

Resedimented, hydrothermally precipitated sulfide occurs in Cores 139-856B-3H and -4H, at 18.4–24.2 mbsf. This interval consists of turbiditic and hemipelagic sediment interbedded with clastic massive sulfide beds. The massive sulfide beds are generally 3 to 10 cm thick and fine upward. These units are described in detail in the "Lithostratigraphy and Sedimentology" section (this chapter). Fragments of pyritic massive sulfide beds. Some of the larger fragments are composed of botryoidal pyrite, with minor amounts of white amorphous silica. Most of the sulfide is coarse- to fine-sand size grains and aggregates of pyrite, accompanied by sand-size clasts of white botryoidal amorphous silica and minor amounts of magnetite.

Beds or clasts of hard, waxy, dark green to black sulfidic clay overlie some of the clastic sulfide layers. This clay has the appearance and feel of massive chlorite, but the mineral assemblage was not confirmed. This clay is distinct from typical unaltered sedimentary clay observed elsewhere in Middle Valley sediment and is interpreted to have formed by hydrothermal alteration. The close association of the clay with resedimented massive sulfide and its occurrence as discrete beds suggest that the clay represents a sedimentary accumulation of hydrothermal alteration products rather than an *in-situ* alteration of clay-rich sediment. However, this interpretation is open to question for some of the altered clay layers, because the sediment interbedded with sulfide is more highly indurated than sediment above or below the sulfide-rich interval, consistent with enhanced diagenesis of the sediment at elevated temperatures within the thermal areole of the hydrothermal system that precipitated the massive sulfide.

Additional evidence of elevated temperature in the sediment is provided by the growth of thin (<1 mm) pyrite and/or marcasite coatings on hairline fractures that cut some of the more indurated clay-rich sediment. These thin veinlets are the only features that suggest *in-situ* deposition of sulfide. All other observations of the sedimentary structures and sulfide textures suggest that the sulfide was deposited by sedimentation from a source area that included material formed by both hydrothermal precipitation and oxidation of sulfide on the seafloor (see "Lithostratigraphy and Sedimentology" section, this chapter).

Sediment in the interval below Core 139-856B-4H to the bottom of the hole does not contain massive sulfide. Much of the sediment in the lower part of Hole 856B is moderately to well indurated, brecciated, and has disseminated and nodular pyrite in greater abundance than observed in Hole 856A. This interval is interpreted to have undergone enhanced thermal diagenesis and/or hydrothermal alteration due to intrusion of basaltic sills and/or proximity to a high temperature hydrothermal discharge zone ("Sediment Alteration and Geochemistry" section, this chapter). Although this process has apparently resulted in alteration of the sediment and addition of hydrothermally precipitated pyrite to these sediments and sedimentary rocks, the levels rarely exceed 1% pyrite. However, near the base of Hole 856B, these rocks are overprinted by a distinct alteration event that locally precipitated minor amounts of pyrrhotite, chalcopyrite, sphalerite, and barite.

Core, section, interval (cm)	Quartz	Feldspars	Hornblende	Chlorite	Mica	Mixed layered chlorite/smectite	Calcite
39-856B-							
1H-1, 123-127	***		*	*	*		*****
2H-3 45-49	******	***	*	*			
2H-5, 76-80	***	***					
2H-6 123-127	***	***	*	*	*		
3H-2 31-35	*****	***		***	***		
3H-4 96-100	******	***		*****			
44-2 30-32	***	*			*		***
41-2, 00-02	***				*		***
4H-5 102-104	***	***		***	*		
411-6, 102-104	***	***		***	*		
54.1 50.63	***	***		*	*		
5H-2 73-77	***	非非非		***	*		
54-3 20-34	***	***		***	*		
54-5, 120-125	******	*****		*	*		
5H-6, 61-66	***	***			*		
64.2.1.6	***	***		***	*		
64 4 12 14	***	***		***	*		
64 6 49 50	***			***	*		
64 6 120 122	***			***	*		
711 1 19 21	***	*		***	*		
711 1 99 02	-			***			*
711-1, 00-95	*****	***		***	***		ं म
711 2 120 122	******	*		***	*		
711-5, 150-155	***				*		
7H-5, 119-122	******	***					
711-0, 8-12	******	***		***			
/H-0, 9/-102	******			***	Ţ.		
8H-1, 80-82	****	***			2		
811-2, 55-57		***			<u> </u>		
8H-3, 20-23		******					
9X-1, 45-47	******	*		***	Ţ.,		
9X-2, 123-127	******	<u> </u>		******			
9X-2, 139-142		***		***	<u> </u>		
11X-1, 92-93		***		***	2		
11X-2, 109-110	*****	***					
11X-3, 148-149	*****	*****		*			
11X-4, 20–21	*****	*****			~		
11X-4, 125–126	******	******			÷.		
12X-2, 19-23	******	*****		***	. Č		
12X-2, 52-56	******	*****		***			
12X-3, 12-16	***	***		***	- 0		
12X-CC, 12-16	*****	*****			<u></u>		
13X-1, 76-80	******	******		***	- Č		
13X-2, 88-92	***	***		***	*		
13X-4, 109-113	******	*****		非非非	÷.		
13X-CC, 22–26	***	*****		非非非非非	*		
14X-1, 55-59	******	*		非市市市市	*		
14X-2, 89-92	****	19 <b>#</b> 1		南南南南南南	*		
14X-3, 91-94	***	*		非非专业主要	*		
14X-4, 42-44	<b>张玲琤</b>			市场 非非非法			
15X-2, 127-129	***			*****			
15X-3, 104-106				*******			
15X-6, 10-12	***					冰市市市市市	

#### Table 14. X-ray diffraction mineralogy of bulk samples from Hole 856B.

Note: Symbols are the same as for Table 13.

Pyrite in the sandy and silty intervals of turbidites and disseminated and nodular pyrite in clay-rich sediment changes in visual appearance downcore starting at approximately Section 139-856B-14X-3. From this interval down through the next section pyrite appears to be partly leached from the sediment. Remaining pyrite is tarnished with a sooty black appearance. Minor amounts of coarser, bladed iron sulfide with the morphology of marcasite occur disseminated in the sediment. The uppermost occurrence of disseminated sphalerite is in interval 139-856B-14X-4, 23–30 cm, as disseminated grains in silty claystone. Some of the darker material occurring in the silty and sandy portions of turbidites appears to be fine-grained marcasite and sphalerite, as opposed to pyrite in the overlying sections of core.

Chalcopyrite first appears in Section 139-856B-15X-1, intergrown with pyrite and sphalerite filling a burrow at 132 cm. Beginning with Core 139-856B-15X the sediment becomes more lithified and locally silicified. In Section 139-856B-15X-2, lithified rock is locally green due to superimposed patchy hydrothermal chlorite alteration. Areas that do not show silicification or the greenish alteration contain disseminated pyrite. Silicified and altered rocks are cut by small veinlets of silica-pyrite-sphalerite-pyrrhotite, pyrite-chalcopyrite, and pyrrhotite-chalcopyrite (Fig. 58). Barite first appears as 1- to 4-mm disseminated crystals at interval 139-856B-15X-3, 41–49 cm.

Alteration and mineralization of the sediment continue to the base of the hole where a mafic sill is encountered. In general, the greenish alteration is developed preferentially in the sandy and silty intervals (Fig. 59). Minor disseminations and veinlets of pyrrhotite, chalcopyrite, and sphalerite occur throughout (Fig. 60). Pyrite occurs down to Section 139-856B-15X-5, but is generally replaced by sphalerite and chalcopyrite. Pyrrhotite becomes the dominant iron sulfide filling veins downhole. Barite is generally present in only minor amounts as disseminated crystals, but locally forms 1- to 2-mm-wide veinlets





Figure 35. X-ray diffractogram for Sample 139-856B-12X-CC, 12-16 cm, showing albite-chlorite in hydrothermally altered hemipelagic sediment (Qz = quartz; Ch = chlorite; F = feldspar; M = mica).

cross-cutting the bedding planes. A barite vein with a chalcopyrite core and dark chloritic selvages cuts greenish altered siltstone recovered in Section 139-856B-15X-CC (Fig. 60).

Core 139-856B-16X, the last core drilled in Hole 856B, is highly brecciated by drilling. Breccia fragments include lithified siltstone veined by pyrrhotite-chalcopyrite and mafic igneous rock. The chilled margin of some mafic fragments in contact with baked sediment is stained red by hematite. This mafic unit is interpreted to be a sill intruded into slightly lithified sediment ("Igneous Petrology and Geochemistry" section, this chapter). The silicification, green chloritic alteration, and sulfide mineralization are superimposed on unaltered but weakly lithified sediment. Lithification of the sediment above the area of chloritic alteration does not appear to increase downhole as the sill at the bottom Hole 856B is approached. Enhanced lithification of this shallowly buried sediment is interpreted to have resulted from a high regional geothermal gradient and is not directly related to the sill at the bottom of Hole 856B. The green chloritic alteration, silicification, and base-metal mineralization are spatially related to the sill and increase in intensity as the sill is approached. This alteration and mineralization may have formed by localized hydrothermal flux driven by the heat of the sill. Alternatively, they may have been precipitated from hydrothermal fluid that generated massive sulfide in Holes 856G and 856H ("Sediment Alteration and Geochemistry" section, this chapter).

### Holes 856C, 856D, 856E, and 856F

Holes 856C-856E represent a north-south transect (Figs. 8 and 57) across the surface of a massive sulfide mound explored during

*Alvin* dive 2253. Piston coring, towed camera mapping, and submersible observations indicate that the sulfide mound is partly sediment covered, with minor amounts of sulfide talus occurring on the flanks of the mound. Single APC cores were collected from Holes 856C, 856D, and 856E to determine the extent of sulfide mineralization in the shallow subsurface and to define the top of the sulfide mound, in order to site Hole 856F at the top of the sulfide mound in an area interpreted from previous work to be the core of the hydrothermal system. Hole 856F was drilled by XCB at the top of the mound near Hole 856C, but was abandoned at 23.6 mbsf due to poor core recovery and adverse drilling conditions. Holes 856G and 856H were subsequently drilled by RCB near Holes 856C and 856F. Because Holes 856C– 856F are all shallow and recovered similar surface material highly disturbed by drilling, they are described together.

Section 139-856C-1H-1 contains two 10-cm intervals that have black clasts of pyrrhotite-rich massive sulfide. Pyrrhotite ranges in grain size from 0.5 to 1 mm and is intergrown with minor amounts of chalcopyrite. The sediment between the two intervals with pyrrhotite clasts and the section below this level are highly disturbed to soupy silty clay that is interpreted to have flowed into the core barrel during piston withdrawal, due to an incomplete stroke of the APC (see "Operations" section, this chapter).

Hole 856D is composed entirely of massive sulfide clasts suspended in a highly disturbed sulfide sand and mud matrix (Fig. 61). Sulfide fragments consist of both pyrrhotite-rich and pyrite-rich massive sulfide. Fine-grained bladed pyrrhotite in many samples has been pseudomorphically replaced by pyrite (Fig. 62). Most have abundant interstitial white amorphous silica. The sandy matrix con-



Degrees (20)

Figure 36. X-ray diffractogram for Sample 139-856B-1H-1, 123-127 cm, showing mineral assemblages in unaltered hemipelagic silty clay (Q = quartz; F = feldspar; H = hornblende; Ch = chlorite; M = mica; Cal = calcite; NaCl = halite).

sists of pyrite, pyrrhotite, botryoidal amorphous silica, and barite, with minor amounts of sphalerite and chalcopyrite. Some intervals contain minor amounts of detrital silicate mud and silt. Extreme coring disturbance has destroyed any original vertical variation in the cored section.

Core 139-856E-1H recovered 1.5 m of massive sulfide rubble overlain by 1 m of gossanous mud. Although the core is all fragmental material and has been disturbed by coring, the original "stratigraphy" appears to have been partly preserved. The top section of the core recovered iron-oxide-rich gossanous mud that apparently formed by the oxidation of the fragmental massive sulfide at the seafloor. The massive sulfide fragments in Section 139-856E-1H-1 are predominantly composed of interpenetrating fine-grained bladed pyrrhotite that forms open network, with minor amounts of interstitial Cu-Fe sulfide and sphalerite. The matrix to the fragments is sulfide sand of similar composition. Sulfide fragments in Section 139-856E-1H-2 are similar, but include more pyrite, which pseudomorphically replaces pyrrhotite and forms crustiform aggregates. Variable amounts of white amorphous silica and barite occur in the sulfide sand matrix.

Hole 856F was sited at the top of the massive sulfide mound in an attempt to use the XCB to drill through the core of the massive sulfide deposit. The rubbly nature of the sulfide near the summit of the mound resulted in poor core recovery; less than 0.5 m of sulfide rubble were recovered over a cored interval of 23.6 m. The sulfide rubble consists of pyrrhotite- and pyrite-rich massive sulfide with interstitial white amorphous silica, similar to clasts recovered from Holes 856C, 856D, and 856E. It was decided to abandon Hole 856F and attempt to drill the same location with the RCB.

# Holes 856G and 856H

Holes 856G and 856H were drilled near the location of Hole 856F on the top of the sulfide ridge in the presumed center of the hydrothermal sulfide deposit. Hole 856G penetrated 65.4 m of sulfide before the hole was abandoned due to accumulation of sulfide sand in the bottom of the hole. Hole 856H was spudded with a mini–reentry cone attached to 12 m of 16-in.-diameter drill-in casing, in an attempt to limit the flow of sulfide sand into the hole. Hole 856H penetrated 93.8 m of sulfide before it also had to be abandoned due to sticking of the drill string in sulfide sand. Because Holes 856G and 856H are located approximately 20 m apart (Figs. 8 and 57) and have penetrated similar sections of sulfide, they are described together.

# Description and Classification of Sulfide Samples in Holes 856G and 856H

Sulfide samples from Holes 856G and 856H are classified on the basis of the macroscopic descriptive attributes of the core ("Sulfide Petrology and Geochemistry" section, "Explanatory Notes" chapter, this volume). Sulfide is classified into six types on the basis of the content of principal minerals, as determined by hand-sample examination, and the most prominent textural attributes. The major characteristics of the different types are summarized in table 5 of the "Sulfide Petrology and Geochemistry" section, "Explanatory Notes" chapter (this volume). Disaggregated sulfide-rich sediment, whether formed by seafloor weathering or fragmented during drilling, is referred to as sulfide sand and is not included in the classification scheme.



Figure 37. X-ray diffractogram for Sample 139-856B-14X-3, 91-94 cm, showing chlorite in hydrothermally altered hemipelagic sediment (Qz = quartz; Ch = chlorite).

The various sulfide types are determined without any particular reference to stratigraphic or genetic relationships. However, the defined massive sulfide types do have a generally systematic distribution through Holes 856G and 856H. Additionally, the transition between sulfide types appears, in general, to relate to progressive evolution of the sulfide deposit by sulfide mineral cementation, replacement, dissolution, and reprecipitation. Sulfide samples recovered in 856G and 856H are described below. These descriptions are followed by a discussion of the spatial and genetic relationships between different sulfide types.

#### Type 1 Sulfide: Homogeneous, Massive, Fine-grained Pyrrhotite

Pyrrhotite is the dominant sulfide mineral in type 1 sulfide and occurs as anhedral aggregates and interpenetrating blades, typically 0.1 to 0.3 mm in length. The interpenetrating texture of the pyrrhotite blades produces a network of open space that may comprise 50% by volume of the rock (Figs. 62 and 63). Samples of this type are generally dark brown, and lack a distinctive metallic luster. They have an "earthy" appearance because of their characteristic fine grain size, homogeneity, and dominance of pyrrhotite.

Both chalcopyrite (and/or isocubanite) and sphalerite are ubiquitous, each typically forming 2%-4% by volume. The base-metal minerals are interstitial to the pyrite and pyrrhotite. Sphalerite is commonly affected by "chalcopyrite disease," where <10-µm blebs of chalcopyrite occur throughout sphalerite, forming up to about 5% of the latter. Magnetite is neither ubiquitous nor prominent in this type, and typically forms about 2% of each sample.

Pyrite may form up to 30% of this type but is generally present in amounts less than 10%. Most of the pyrite formed by pseudomorphic replacement of pyrrhotite and, therefore, pyrite aggregates have a similar grain size. Marcasite intergrown with pyrite was observed in polished thin sections, but is only present in minor amounts and is not distinguishable in hand samples. Some samples are cut by veins a few millimeters wide, composed of coarser grained euhedral pyrite, generally with dark green clay. Late-stage growth of coarse-grained euhedral pyrite gives some samples a "porphyroblastic" texture (Fig. 64).

Nonopaque minerals all occur interstitially to the principal sulfide minerals, and include green smectite and very minor colorless chlorite (?), intergrown with amorphous silica.

In general, the samples are homogeneous in texture and composition. Some samples have a brecciated or clastic appearance defined by fragments of fine-grained pyrrhotite in a matrix with similar composition, but with slightly different grain size and/or porosity (Fig. 65).

Chemical analyses of samples of type 1 sulfide indicate that average base-metal contents are approximately 0.9% Zn and 0.9% Cu (Table 17).

# Type 2 Sulfide: Homogeneous, Massive, Fine-grained Pyrite-Pyrrhotite

Type 2 sulfide is distinguished from type 1 by a greater content of pyrite which occurs in amounts subequal to or greater than pyrrhotite. Type 2 sulfide is similar in grain size to type 1. Samples are brown to dark bronze and have a submetallic luster. Pyrite usually forms about



Figure 38. X-ray diffractogram for Sample 139-856B-15X-3, 104-106 cm, showing Fe-rich chlorite in hydrothermally altered hemipelagic sediment (Ch = chlorite).

30%-60% of each sample, but may form up to 90%. Pyrrhotite may form as much as 60%, but usually less than 20%, and is only present in trace amounts in some type 2 samples. Petrographic observations show that much of the pyrite formed by pseudomorphic replacement of pyrrhotite (Fig. 66). In some samples the replacement is incomplete and the pyrite and pyrrhotite are intimately intergrown on the scale of a few microns. The fine scale of replacement and the pseudomorphing of pyrrhotite by pyrite make it very difficult to estimate reliably the relative contents of pyrite and pyrrhotite in these samples, and accounts for the wide range of estimated pyrite and pyrrhotite contents of samples classified as type 2. Diffuse and irregular zones of replacement can produce a rock with a pseudobrecciated texture (Fig. 67). Samples may contain pyrite "porphyroblasts" or be veined by coarse-grained pyrite, due to growth of larger pyrite crystals within the fine-grained pyrrhotite or replaced pyrrhotite matrix (Fig. 66). Chalcopyrite occurs in the interstitial spaces between iron sulfide minerals and is present in similar or slightly lower amounts than in type 1 sulfide. Copper content ranges from 0.1% to 1.1% and averages approximately 0.6% (Table 17). Sphalerite is less abundant than in type 1 sulfide. Zn content ranges from 0% to 1.0% and averages 0.2%. Magnetite is present in variable amounts-typically 5%, but some samples contain up to 15%. Magnetite abundance is generally proportional to pyrite abundance and the two minerals can occur intergrown, especially in areas of coarse-grained pyrite (Fig. 68). Hematite (1%-3%) is locally intergrown with magnetite and replaces pyrite in hematite-rich samples.

Although this sulfide type is typically homogeneous, some samples are slightly vuggy (Fig. 66). Green smectite(?) and intergrown amorphous silica are common nonopaque phases, along with minor carbonate. Interstitial carbonate of some samples ranges up to 10%. Most of the interstitial carbonate is white, and powdered samples effervesce slowly in cold 6 N HCl. The dominant carbonate mineral in sulfide samples is probably ankerite, but the mineral identification was not confirmed by XRD aboard ship. The nonopaque minerals typically form less than 15% of the rock.

# Type 3 Sulfide: Homogeneous Medium- to Coarse-grained Pyrite-Pyrrhotite

Pyrite and pyrrhotite are coarser grained in type 3 sulfide than in the previous two types, and typically form aggregates or grains of 0.5 to 1.0 mm width. Pyrite is dominant and generally forms 30%–65% of the rock; pyrrhotite is generally present as a minor mineral, but can comprise up to 30% of the rock. Pyrite occurs as aggregates and subhedral to anhedral grains, typically evenly and closely spaced, with finer grained pyrite and pyrrhotite forming a matrix (Fig. 69). Bands and veins of coarser grained pyrite cut some samples (Fig. 70). Pyrrhotite also occurs as distinct euhedral grains, similar in size to the pyrite aggregates. Magnetite is ubiquitous and typically forms about 10% of the rock, but some samples contain as much as 25%. Pyrite and magnetite contents tend to correlate with each other.

Chalcopyrite and sphalerite occur interstitially to other sulfide and oxide minerals, and as inclusions in pyrite. The abundance of sphalerite and chalcopyrite is variable in type 3 sulfide, although most samples have low contents of base-metal sulfides. Some samples contain relict grains of sphalerite, chalcopyrite, and pyrrhotite that are partly dissolved (Fig. 71). In contrast to type 1 and type 2 sulfide, type 3 sulfide contains less sphalerite than chalcopyrite. The Zn and Cu contents of

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Figure 39. X-ray diffractogram for the clay fraction of Sample 139-856B-14X-3, 91–94 cm, showing Mg-Fe chlorite in hydrothermally altered hemipelagic sediment (Ch = chlorite; Qz = quartz).

type 3 samples are typically <0.2% for each metal although some samples are enriched in base metal, especially Zn (Table 17), resulting in average grades of 0.2% Cu and 0.6% Zn. Base-metal-enriched samples contain late-stage medium- to coarse-grained patches of sphalerite accompanied by less abundant chalcopyrite.

Nonopaque minerals occur interstitially to opaque minerals, and are characterized by green smectite(?), carbonate, and white amorphous silica with chlorite(?). Carbonate is more abundant in type 3 than in types 1 and 2, and can form up to 45% of the rock. Although the nonopaque minerals usually form less than 20% of the samples, a few samples may contain up to 70%. In these, pyrite occurs as aggregates of disseminated subhedral crystals.

### Type 4 Sulfide: Heterogeneous and Veined Coarse-grained Pyrite-Pyrrhotite

Textural inhomogeneity and coarse grain size are the distinguishing features of type 4 sulfide (Fig. 72). Pyrite is generally the principal sulfide mineral (usually 10%–50%), but is less abundant than pyrrhotite in many samples. Much of the pyrite is coarse-grained, typically 0.5- to 1.5-mm aggregates, and forms large anhedral masses (Fig. 73) and irregular "veins" traversing the samples (Fig. 74). Fine-grained pyrite also replaces fine-grained pyrrhotite in the matrix. The coarser grained pyrite crystals and the larger anhedral pyrite aggregates give the rock a "porphyritic" appearance. The larger crystals and masses of pyrite formed late in the paragenetic succession and commonly over-

print the matrix. Pyrrhotite content in type 4 samples is variable, ranging generally between 10% and 40%. Pyrrhotite occurs both as patches of fine-grained blades in the matrix, which are partly replaced by pyrite, and as late-stage coarse-grained crystals and aggregates. The former are similar to type 1 rocks. Pyrite and pyrrhotite also occur in veins and irregular vein-like replacements that cut the finer grained matrix (Fig. 75). Magnetite is ubiquitous in type 4 samples and forms 5% to 20% of the rock. Most of the magnetite occurs as fine- to medium-grained octahedra that are commonly associated with the coarser grained pyrite. Sphalerite and chalcopyrite have a bimodal distribution in type 4 samples. Some sphalerite and much of the chalcopyrite occurs interstitially to fine-grained pyrrhotite and/or pyrite, both in the matrix and as fine-grained inclusions in coarse-grained pyrite that has replaced matrix-pyrrhotite. Coarse-grained sphalerite and chalcopyrite occur in paragenetically late veins and replacements associated with late-stage coarse-grained pyrrhotite. The formation of late-stage, coarse-grained sphalerite and chalcopyrite results in high base-metal contents for many type 4 samples. Some samples exceed 1% Cu and 4% Zn (Table 17). Type 4 samples as a group have the highest combined base-metal contents (average 0.5%) and 2.5% Zn), even though the distribution of sphalerite and chalcopyrite is heterogeneous on the scale of a thin section.

The nonopaque minerals are as irregularly distributed as the opaque minerals. Silica and chlorite/smectite(?) occur in anastomosing veins, usually 1 to 2 mm wide. Interstitial carbonate is abundant in some samples and can form up to 20% of the rock (Fig. 76).

Core, section, interval (cm)	Depth (mbsf)	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	LOI	CO <sub>2</sub>	H <sub>2</sub> O	S	TOC
139-856A-					5.5											
1H-1, 69-72	0.69	51.04	0.78	15.04	7.23	0.12	3.37	8.83	2.06	2.19	0.17	9.16	4.97	5.40	0.15	0.68
2H-2, 62-64	4.82	56.23	0.83	16.18	8.12	0.10	3.99	3.36	1.97	2.51	0.17	6.54	1.25	6.48	0.23	0.84
3H-2, 67-71	14.37	60,40	0.86	14.80	6.58	0.11	3.29	4.13	1.83	2.47	0.21	5.32	2.09	3.78	0.20	0.31
4H-2, 86-90	24.06	58.36	0.87	16.48	7.10	0.10	3.68	3.05	2.03	2.97	0.22	5.13	1.32	3.69	0.16	0.26
5H-3, 73-77	33.81	63.02	0.86	14.99	5.94	0.09	3.28	3.67	2.25	1.95	0.20	3.74	1.59	3.24	0.00	0.28
6H-2, 88-92	43.08	63.80	0.83	14.53	5.86	0.08	2.73	4.36	2.66	1.89	0.19	3.07	1.54	2.25	0.25	0.13
7H-2, 95-99	52.65	64.23	0.82	14.43	5.74	0.08	2.98	3.76	2.78	1.58	0.19	3.41	1.21	2.43	0.50	0.14
8H-3, 66-68	63.36	56.12	0.93	17.36	8.77	0.11	6.34	1.27	2.09	2.36	0.18	4.46	0.04	4.59	0.20	0.37
9H-2, 94-98	71.64	58.08	0.88	15.18	9.17	0.25	8.75	0.36	1.95	1.16	0.22	4.01	0.04	3.42	0.00	0.18
10X-1, 68-71	79.38	59.50	0.84	15.78	7.36	0.10	5.55	1.60	2.46	1.89	0.19	4.74	0.04	2.70	0.56	0.16
11X-1, 104-106	87.24	63.61	0.72	13.34	3.89	0.15	1.60	7.00	2.84	1.49	0.17	5.19	0.07	1.89	0.30	0.16
12X-1, 85-89	96.55	57.42	0.86	16.34	8.42	0.12	7.52	0.79	2.02	2.20	0.19	4.12	0.04	4.50	0.17	0.23
13X-2, 123-127	108.03	57.04	0.81	16.60	7.60	0.11	7.77	0.53	1.95	2.31	0.17	5.10	0.04	5.31	0.29	0.27
139-856B-																
1H-1, 123-127	1.23	51.16	0.68	14.78	7.97	0.07	3.64	7.72	1.81	2.55	0.14	9.48	4.73	5.22	0.42	0.63
2H-3, 45-49	5.25	59.36	0.89	16.31	8.34	0.10	3.86	3.41	2.52	2.27	0.18	2.76	0.07	2.70	1.19	0.22
4H-3, 21-23	24.01												0.11	5.31	6.32	0.36
5H-2, 73-77	32.53	60.81	0.90	15.96	7.22	0.10	5.21	0.92	2.22	2.88	0.19	3.60	0.99	4.14	1.06	0.02
6H-6, 130-132	48.60	55.00	0.91	16.87	8.55	0.10	8.23	0.34	1.18	2.75	0.20	5.88	0.04	7.02	0.63	1.85
7H-3, 130-133	53.60	59.74	0.91	15.62	7.31	0.08	7.36	0.32	1.37	2.04	0.19	5.05	0.11	4.50	1.16	0.31
8H-2, 55-57	60.85	74.07	0.80	11.79	3.06	0.05	3.44	0.36	2.55	1.08	0.18	2.62	0.07	2.61	0.35	0.10
8H-3, 20-23	62.00															
9X-2, 139-142	65.19	54.78	0.96	16.82	8.28	0.23	9.32	0.45	0.28	2.38	0.23	6.27	0.11	6.12	1.28	0.00
12X-2, 52-56	83.64	62.47	0.71	14.99	5.50	0.26	7.45	0.36	3.16	0.71	0.17	4.23	0.04	3.78	1.48	0.07
12X-3, 12-16	84.72	59.96	0.93	16.09	7.85	0.09	5.35	1.36	2.25	2.28	0.16	3.69	0.00	5.40	1.55	
13X-4, 109-113	96.69	58.50	0.84	15.85	6.05	0.68	8.47	0.41	3.05	0.67	0.24	5.24	0.04	4.05	0.73	
15X-3, 104-106	114.45	30.04	1.34	22.06	26.35	0.67	10.29	0.17	0.00	1.65	0.04	7.40	0.07	8.10	5.48	0.20

Table 15. Major element oxide and minor element data (in wt%) for sediments from Holes 856A and 856B determined by X-ray fluorescence, CHNS analyses, and coulometry.

Notes: All major elements have been normalized to 100% by multiplying all element oxides determined by XRF on the fused disk by (100.0 – LOI)/total%, where total% = the sum of all element oxides measured on the fused disk and LOI = loss on ignition at 900°C. See "Sediment Geochemistry and Alteration" section, "Explanatory Notes" chapter (this volume), for a detailed description of the analytical methods.

### Type 5 Sulfide: Massive Colloform and Vuggy Pyrite

Type 5 sulfide samples are nearly monomineralic and are composed of large inclusion-free pyrite aggregates that form both colloform and anhedral aggregates (Fig. 77). Colloform pyrite in many samples displays a wavy banding on a submillimeter to centimeter scale (Figs. 78 and 79). Minor amounts of framboidal pyrite occur in some samples with colloform-banded pyrite. Colloform-banded pyrite also forms overgrowths on pyrite that has replaced pyrrhotite. Reticulate boxwork texture with 0.1- to 2-mm prismatic open space bounded by 0.1- to 1-mm straight walls lined with fine-grained pyrite is also a common texture in this rock type (Fig. 80). Other samples show a mesh network of pyrite aggregates enclosing open space or silicate gangue. The monomineralic composition and massive texture make grain-size determination difficult, but the aggregate nature of some samples gives the rock a very coarse-grained appearance. This sulfide type has the highest metallic luster of all of the sulfide types. Pyrrhotite and chalcopyrite occur only in trace amounts as finegrained inclusions in pyrite. Sphalerite is very rare and magnetite is generally absent. Some samples with reticulate boxwork texture have partly dissolved remnants of medium- to coarse-grained pyrrhotite, sphalerite, and occasional chalcopyrite grains in the interstitial spaces between the pyrite septae that define the boxwork texture. Rare samples have a brecciated appearance (Fig. 81). This type of sulfide has the lowest base-metal content of all of the types, averaging approximately 0.3% Cu and 0.3% Zn (Table 17).

The nonopaque minerals fill vugs and the interstices of the pyrite aggregates. White amorphous silica and chlorite typically form 15% of the rock, providing a very distinctive white, chalky appearance to

the interstitial areas. Carbonate, and carbonate partially to totally replaced by silica, occurs in some samples. Open vugs 2–4 mm in diameter and comprising 10% of any sample are very common in this rock type (Fig. 82). The vugs are generally lined with euhedral pyrite crystals.

### Type 6 Sulfide: Sediment with Sulfide Veining

Sediment bands or blocks within the massive sulfide cores are highly veined and contain disseminated sulfide between the veins (Fig. 83). The veins anastomose irregularly throughout the sediment (Fig. 84) and comprise from 5% to 80% of the sample (Fig. 85). Pyrite and subequal amounts of pyrrhotite are the principal vein minerals, but are accompanied by up to 20% sphalerite and 5% chalcopyrite. Magnetite occurs in most samples of type 6 sulfide. The sulfide minerals in veins are typically coarse grained (Fig. 86). Sulfide growing in the sedimentary matrix occurs both as coarse-grained euhedral crystals and as highly porous anhedral grains and aggregates that have incorporated fine-grained sediment during sulfide growth. The type 6 sulfide examined in thin section is hosted by claystone. Alteration has not resulted in a significant increase in the grain size of the claystone; the mineral assemblage of the sediment has not been determined. Much of the altered sediment is fine-grained yellow clay with low birefringence that may be Mg-rich smectite. Carbonate occurs in type 6 samples as a late-stage mineral filling open space. Type 6 sulfide is relatively rare within the recovered material, but might be expected to be common at the base of the deposit, in its "stringer" zone. However, the only interval of type 6 sulfide recovered comes from depths between approximately 25 to 30 mbsf in the middle of the massive sulfide drilled in Hole 856H.

#### Table 15 (continued).

Core, section,		
nterval (cm)	N	Total
139-856A-		
1H-1, 69-72	0.10	100.30
2H-2, 62-64	0.13	99.90
3H-2, 67-71	0.08	100.64
4H-2, 86-90	0.09	100.83
5H-3, 73-77	0.10	98.81
6H-2, 88-92	0.04	100.12
7H-2, 95-99	0.06	98.86
8H-3, 66-68	0.08	99.86
9H-2, 94-98	0.09	97.58
10X-1, 68-71	0.05	100.06
11X-1, 104-106	0.07	98.51
12X-1, 85-89	0.10	99.78
13X-2, 123-127	0.09	100.37
139-856B-		
1H-1, 123-127	0.05	97.65
2H-3, 45-49	0.02	98.30
4H-3, 21-23	0.05	
5H-2, 73-77	0.02	99.61
6H-6, 130-132	0.29	100.68
7H-3, 130-133	0.05	99.54
8H-2, 55-57	0.02	100.44
8H-3, 20-23		
9X-2, 139-142	0.03	99.74
12X-2, 52-56	0.00	99.56
12X-3, 12-16	0.01	100.99
13X-4, 109-113	0.01	99.98
15X-3, 104-106	0.01	100.19

# Spatial Distribution of Sulfide Types in 856G and 856H

The approximate vertical distribution of sulfide types is illustrated for Holes 856G and 856H in Figures 87A and 87B, respectively. Because of incomplete core recovery, the extent, depth below seafloor, and boundaries between sulfide types is uncertain. Figures 87A and 87B were constructed by arbitrarily assuming that the thickness of each type of sulfide in each cored interval was proportional to the thickness of each sulfide type recovered, and proportionally "expanding" the thickness of each sulfide type to fill the cored interval. This procedure may result in misrepresentation of the thickness of some sulfide types due to selective core recovery. The sulfide was formed by multiple stages of infilling deposition, dissolution, and replacement. Therefore, these vertical sections through the massive sulfide do not imply any temporal or stratigraphic relationships between the sulfide types. However, Figure 87A and 87B shows that the different sulfide types are not randomly mixed, but tend to occupy continuous intervals in each hole. Each hole contains a zone of sulfide sand at the top, which is partly formed by disaggregation of massive sulfide by weathering, but also includes material disaggregated by drilling. Below this is a zone with type 4 sulfide, intermixed mostly with types 2 and 3 in Hole 856G and with mostly type 2 in Hole 856H. Farther downhole, type 5 sulfide becomes abundant and is accompanied by types 2 and 3 in Hole 856G and type 2 in 856H. The deepest part of Hole 856H is type 1 sulfide, which occurs below the depth of the bottom of Hole 856G. Type 6 sulfide was recovered only from Hole 856H, even though Hole 856 was cored through the equivalent depth interval. The occurrence of sediment only in the upper part of Hole 856H suggests that this material may have accumulated in a local

Table 16. Trace element data (in ppm) for samples from Holes 856A and 856B.

Core, section, interval (mbsf)	Depth (mbsf)	Ba	Ce	Cr	Cu	Nb	Ni	Rb	Sr	v	Y	Zn	Zr
139-856A-		12470			2029-0	(213)							
1H-1 60-72	0.60	034	2	87	50	10	62	73	416	156	22	120	165
2H-2 62-64	4.82	740	20	06	59	11	50	86	252	162	24	156	152
3H-2 67-71	14 37	730	26	100	45	14	40	01	205	151	25	112	217
4H-2 86-00	24.06	762	23	103	45	14	61	00	240	152	24	118	164
5H_3 73_77	33.81	711	17	112	37	12	61	76	250	138	22	00	180
6H-2 88-92	43.08	581	7	06	26	0	30	40	350	153	19	69	190
7H-2, 95-99	52.65	488	12	80	24	0	32	42	321	148	24	65	207
8H-3 66-68	63 36	569	0	114	57	6	68	60	197	189	22	131	135
9H-2 94-98	71.64	582	23	83	44	13	42	61	228	150	22	89	213
10X-1 68-71	79 38	489	12	96	41	0	42	36	324	136	22	53	184
11X-1, 104-106	87.24	754	õ	88	18	8	28	39	386	124	18	34	229
12X-1.85-89	96.55	691	0	95	39	10	48	51	168	166	20	108	143
13X-2, 123-127	108.03	533	19	90	41	10	56	59	120	176	27	110	128
139-856B-													
1H-1, 123-127	1.23	801	10	85	49	10	57	92	338	136	19	117	143
2H-3, 45-49	5.25	783	15	95	48	11	48	70	284	182	24	74	170
4H-3, 21-23	24.01	622	4	130	10,868	9	57	55	82	340	11	3127	101
5H-2, 73-77	32.53	647	6	93	43	9	53	70	123	183	28	131	125
6H-6, 130-132	48.60	759	2	104	157	9	64	87	52	191	22	391	110
7H-3, 130-133	53.60	847	13	94	17	12	39	68	55	170	24	63	150
8H-2, 55-57	60.85	326	26	95	6	10	31	44	65	133	17	34	199
8H-3, 20-23	62.00	262	24	91	6	9	37	50	56	148	15	47	164
9X-2, 139-142	65.19	232	14	97	51	9	52	50	45	187	21	115	115
12X-2, 52-56	83.64												
12X-3, 12-16	84.72	80	16	71	5	7	22	17	58	148	17	117	169
13X-4, 109-113	96.69	111	13	83	16	8	35	15	44	127	18	59	120
15X-3, 104-106	114.45	801	0	160	3516	12	64	21	130	311	23	184	164

Note: Trace elements were determined by X-ray fluorescence on pressed powders. See "Sediment Geochemistry and Alteration" section, "Explanatory Notes" chapter (this volume), for a detailed description of the analytical method.



Figure 40. X-ray diffractogram for the clay fraction of Sample 139-856B-15X-6, 10–12 cm, showing chlorite/smectite mixed-layer mineral in hydrothermally altered hemipelagic sediment (Ch/S = chlorite/smectite mixed layer mineral).

pocket of sediment ponded in irregularities on the upper surface of the sulfide deposit while it was actively forming.

# Genetic Implications of Sulfide Types

Inferred genetic relationships between the sulfide types, on the basis of paragenesis observed in polished thin section, suggest that the spatial relationships between the sulfide types are related to evolution of the massive sulfide from "primitive" type 1 sulfide to "mature" type 4 and type 5 sulfide through progressive dissolution, replacement, and reprecipitation of sulfide minerals. This proposed evolution of sulfide types is diagrammed in Figure 88.

Type 1 massive sulfide is similar to most samples collected by piston coring, gravity coring, and dredging in Middle Valley before Leg 139 drilling (Goodfellow and Blaise, 1988). These studies, and observations of polished thin sections of type 1 sulfide onboard, suggest that type 1 sulfide is the typical sulfide assemblage formed from rapidly cooled hydrothermal fluid at Middle Valley. This assemblage is typical of the earliest paragenetic stage observable in polished thin section and can usually be recognized as the precursor for the other types of sulfide, which are interpreted to have formed predominantly by replacement of type 1 sulfide. Type 1 sulfide most closely reflects the nature of the hydrothermal fluid in the immediate subsurface of the deposit, before cooling and oxidation by mixing with seawater and/or pore fluid in the shallow subsurface in the hydrothermal discharge area.

Type 2 sulfide generally appears to have formed directly from type 1 sulfide through pseudomorphic replacement of pyrrhotite by pyrite. The texture of type 2 samples is directly inherited from the type 1 precursor. Limited shipboard chemical analyses and thin-section petrography suggest that chalcopyrite abundance stays the same or decreases slightly during formation of type 2 sulfide, but sphalerite content decreases by approximately one half, relative to type 1 samples. Magnetite abundance increases in type 2 sulfide, apparently in relation to the amount of pyrite (Fig. 89).

Continuation of this replacement process results in further destruction of pyrrhotite accompanied by precipitation of pyrite, some of which forms coarser grained pyrite crystals, aggregates, and "porphyroblastic" replacements that define type 3 sulfide. Precipitation of pyrite is accompanied by growth of magnetite. Some sphalerite and chalcopyrite remain as inclusions in pyrite crystals, but type 3 sulfide generally has low Cu and Zn contents due to dissolution of these phases. Although many type 3 samples appear to be transitional to type 2 samples through continued replacement, some samples of this type appear to be transitionally related to type 4 samples through precipitation of minor amounts of late-stage, coarse-grained pyrrhotite, chalcopyrite, and sphalerite. The result is that Cu and Zn contents of type 3 samples are generally lower than in type 1 or type 2 samples, but are erratic, with some high values similar to type 4 sulfide.

Increased veining and replacement by late-stage, coarse-grained pyrrhotite, pyrite, magnetite, chalcopyrite, and sphalerite results in the heterogeneous texture that defines type 4 sulfide. The Cu and Zn contents are generally high, but irregular, due to variable proportions of replaced and leached primary sulfide and late-stage precipitation of pyrrhotite, chalcopyrite, and sphalerite.



Figure 41. Depth profiles of SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO, MgO, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, CO<sub>2</sub>, H<sub>2</sub>O, S, and TOC (total organic carbon) for Hole 856A.



Figure 42. Depth profiles of Ba, Ce, Cr, Cu, Nb, Ni, Rb, Sr, V, Y, Zn, and Zr for Hole 856A.



Figure 43. Depth profiles of SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO, MgO, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, CO<sub>2</sub>, H<sub>2</sub>O, S, and TOC (total organic carbon) for Hole 856B.



Figure 44. Depth profiles of Ba, Ce, Cr, Cu, Nb, Ni, Rb, Sr, V, Y, Zn, and Zr for Hole 856B.



Figure 45. Depth profiles of MgO in Holes 855A–855C, Hole 856A, and Hole 856B, showing the major chemical enrichments and depletions.

The general progression from type 1 to type 4 sulfide should not be interpreted as a simple paragenetic succession from pyrrhotite-rich sulfide to pyrite-rich sulfide followed by a second generation of pyrrhotite-rich sulfide. Textural observations on polished thin sections show a much more complex evolution in most samples, and much more detailed work is required to delineate the history of any given sample. Many samples show multiple stages of mineral replacement, inclusion, dissolution, and overgrowth, locally separated by precipitation and replacement of gangue minerals and oxidation of sulfide minerals. However, the complex paragenetic pathway that any



Figure 47. Depth profiles of CaO in Holes 855A–855C, Hole 856A, and Hole 856B, showing a decrease of calcium below 60 mbsf in Hole 856A and below about 5 mbsf in Hole 856B.

individual sample followed usually resulted in formation of semicontinuous zones of massive sulfide with similar composition and texture.

Type 5 sulfide appears to have followed a different evolutionary path. Samples of type 5 sulfide contain areas where pyrite has pseudomorphically replaced pyrrhotite. However, the dominant and defining texture of type 5 sulfide is dissolution of precursor sulfide followed by precipitation of pyrite. The reticulate texture common to type 5 sulfide resembles boxwork gossans that form by oxidative dissolution of massive sulfide. However, in the case of type 5 sulfide,



Figure 46. Depth profiles of MnO in Holes 855A–855C, Hole 856A, and Hole 856B, showing an increase in manganese below 65 mbsf in Hole 856B.



Figure 48. Depth profiles of Sr in Holes 855A-855C, Hole 856A, and Hole 856B, showing a major depletion of Sr in Hole 856B.



Figure 49. Depth profiles of Ba in Holes 855A–855C, Hole 856A, and Hole 856B, showing high concentrations of Ba above 40 mbsf in Hole 856A and above 60 mbsf in Hole 856B, and a marked decrease in Ba below 60 mbsf in Hole 856B.



Figure 50. Depth profiles of Mg/Fe mole ratios in Holes 855A–855C, Hole 856A, and Hole 856B, showing that most of the hydrothermal chlorite is Mg-rich whereas the detrital chlorite is Fe-rich. The Mg/Fe mole ratio was calculated from bulk sediment compositions assuming all the Mg and Fe is bound in chlorite.

the frame of the boxwork has been replaced and overgrown by pyrite. Partly dissolved remnants of pyrrhotite, chalcopyrite, and sphalerite remain in the vuggy spaces of some samples. Chalcopyrite and sphalerite generally occur only as trace, fine-grained inclusions enclosed in pyrite. The dissolution of chalcopyrite and sphalerite results in uniformly low Cu and Zn contents. Precipitating pyrite forms encrustations and botryoidal bands. In contrast to sulfide types 2–4,



Figure 51. Depth profiles of Na/Ca mole ratios in Holes 855A–855C, Hole 856A, and Hole 856B, showing greater albitization of plagioclase in Holes 856A and 856B. The CaO value was calculated by subtracting calcite-CaO with the assumption that all the  $CO_2$  occurs as calcite.



Figure 52. Depth profiles of  $SiO_2/Zr$  weight ratios in Holes 855A–855C, Hole 856A, and Hole 856B, showing the extent of silicification in Hole 856B.

pyrite formation in type 5 samples is not coupled to magnetite formation (Fig. 89).

# Alteration of Sulfide by Seawater

The two proposed alteration pathways, diagrammed in Figure 88, both involve oxidation-reduction reactions in the sulfur system. Pyrrhotite, with a formal oxidation state of  $S^{-2}$ , is transformed to pyrite,



Figure 53. Comparative depth profiles of inorganic C in Holes 855C, 856A, and 856B.

with a formal oxidation state of  $S^{-1}$ . The path leading to type 5 sulfide appears to proceed predominantly by dissolution and reprecipitation. The path leading to type 3 sulfide appears to proceed predominantly by replacement. This replacement pathway may release excess Fe, which is precipitated as magnetite. Precipitation of magnetite from ferrous Fe, either released during pyrrhotite replacement or supplied directly by hydrothermal fluid, also requires oxidation.

Seawater sulfate is the most abundant, readily available oxidant and could be supplied to the sulfide deposit by secondary hydrothermal circulation cells that draw seawater into the upper part of a sulfide mound. Reaction of hot hydrothermal fluid with cooler seawater



Figure 54. Comparative depth profiles of total S in Holes 855C, 856A, and 856B.



Figure 55. Comparative depth profiles of C/S ratios in Holes 855C, 856A, and 856B.

within a mound could change  $f S_2$  and  $f O_2$ , and result in replacement of pyrrhotite by pyrite ± magnetite. A consequence of the circulation of sulfate-bearing seawater through an active hydrothermal mound should be precipitation of sulfate minerals in the cooler edges of the mound (<250°C) where oxidation-reduction equilibrium between sulfide and sulfate is kinetically inhibited (Ohmoto and Lasaga, 1983). Both anhydrite and barite are likely to precipitate, depending on the temperature and Ca and Ba activities of the fluid. Any precipitated anhydrite is likely to be removed by dissolution as the system cools and is flushed by seawater undersaturated with respect to anhydrite. The lack of anhydrite in the upper part of the deposit is consistent with the observed oxidation of massive sulfide to hematite and iron oxyhydroxide, interpreted as the result of interaction with cold seawater. Barite is much less soluble at low temperature than anhydrite and might be locally preserved in the weathered part of the deposit. However, initial precipitation of barite may have been limited by low barium contents in the hydrothermal fluid, if the major source for metals in the fluid was basaltic rocks, as proposed below.

Barite is present in minor amounts in a few of the sulfide samples, where it forms as late-stage vug-filling crystals, but the abundance of barite through the central part of the sulfide deposit sampled in Holes 856G and 856H is low. The geochemical log from Hole 856H shows a significant peak in natural gamma rays emitted by a radionuclide daughter of the uranium decay series ("Downhole Logging" section, this chapter). This peak in the uranium channel of the natural gamma log is attributable to the decay products of <sup>226</sup>Ra, which is highly concentrated in barite precipitated in active seafloor hydrothermal systems (Grasty et al., 1988). The extent of this zone of inferred barite enrichment overlaps an area of the sulfide deposit that is extensively replaced by pyrite and magnetite, consistent with flow of sulfate-bearing seawater through the upper part of the deposit.

### **Metal Zoning**

Much more extensive and detailed work than is possible aboard ship will be necessary to establish the relationships, if any, between the sulfide types described. However, it is tempting to speculate that the spatial distribution of sulfide types shown in Figure 87A and 87B is related to the processes proposed above to account for the apparent



Figure 56. South-north cross section (A–B) of Bent Hill and sulfide mound showing the major stratigraphic units, brecciated and fracture indurated sediment, and the distribution of the major hydrothermal alteration assemblages relative to Bent Hill and adjacent and massive sulfide deposit. A plan view appears in Figure 8.

transitions between sulfide types. The type 1 sulfide at the bottom of Hole 856H might represent the protolith to the type 5 and type 2 material that occurs between approximately 40 and 70 mbsf in both Holes 856G and 856H. Chalcopyrite and sphalerite removed by dissolution and replacement in this zone may be the source for late-stage veins and replacements that locally formed base-metal enriched type 3 and type 4 sulfide between approximately 10 and 40 mbsf in Holes 856G and 856H. This process of "zone refining" has been proposed to explain metal distribution in massive sulfide deposits mined on land (Franklin et al., 1981; Knuckey et al., 1982). However, the existence, extent, and efficiency of this process can only be tested by further drilling with enhanced core recovery and increased spatial density of drill holes.

# Extent and Geometry of the Sulfide Deposit

An important question that remains unanswered after the drilling is the vertical extent of the sulfide mineralization and the nature of mineralization and alteration in the rocks underlying the sulfide deposit. The extent and geometry of the sulfide deposit near the seafloor can be inferred from side-scan sonar imagery and nearsurface samples of sulfide by coring, and is shown in Figure 8. Drilling in Hole 856H established that the massive sulfide deposit is a minimum of 95 m thick at this location. This thickness exceeds even the most optimistic pre-drilling estimates of the vertical extent of sulfide. This deposit clearly represents a major accumulation of hydrothermally precipitated metal sulfide, by comparison with both active seafloor hydrothermal deposits and ancient ore deposits.

All of the shipboard observations, including the polished thin-section petrography, suggest that the majority of the recovered core was deposited near and above the seafloor, and did not form by infiltration and replacement of sediment. Type 6 samples that include veined and replaced sediment represent a minor proportion of the recovered samples (Fig. 87B). Massive sulfide samples that lack obvious sedimentary material also appear to lack the textures observed in other massive sulfide deposits where sediment replacement has been observed (Zierenberg and Schmidt, 1987; Turner, 1990). Selective recovery of massive sulfide during drilling could potentially provide a biased impression of the abundance of sediment interbedded with sulfide. The lack of any recovered sedimentary material outside of the thin zones of type 6 sulfide suggests that this is unlikely. Support for the interpretation that Hole 856H penetrated sulfide without significant intermixed sediment is provided by the downhole geochemical and electrical resistivity logging. The logged interval of Hole 856H shows consistently high concentrations of Fe and S, and low concentrations of elements such as Si, Al, Ti, and K, which would be expected to be associated with sediment or hydrothermally altered sediment ("Downhole Logging" section, this chapter). The



Figure 57. South-north cross section (A–B) across Bent Hill, continuing to the area of a massive sulfide mound with an active hydrothermal vent sampled during Alvin dive 2253. The cross section shows the relative position of the holes, the depths and subsurface extent of drilling (at 5× vertical exaggeration), and the intervals where hydrothermal sulfide and igneous rock were cored. A plan view appears in Figure 8.

electrical resistivity is low throughout the logged interval and the formation microscanner records do not show bedding ("Downhole Logging" section, this chapter).

The base of the massive sulfide deposit is a minimum of 60 m below the present level of turbidite fill of Middle Valley. If the interpretation that the 95 m of sulfide penetrated by Hole 856H formed near and above the seafloor is correct, then either the formation of the deposit spanned the history of sedimentation at this location or the upper part of the deposit formed as a large sulfide edifice, perhaps in excess of 95 m high. Growth rate of the sulfide mound relative to sedimentation rate remains unknown, but the lack of interbedded sediment argues for rapid growth of sulfide relative to turbidite deposition, and/or nondeposition of sediment on the highstanding sulfide mound. The timing and growth history of the sulfide deposit can best be addressed by drilling a series of holes on the flanks of the deposit to investigate interlayering of sediment with sulfide, produced both by hydrothermal plume fallout and by clastic deposition of sulfide shed from the mound. Hole 856B is the only hole that records evidence of clastic deposition of massive sulfide. However, interpretation of the timing of these events is complicated by uplift history of the adjacent hill and potentially by sediment slumping, the timing of which is also unresolved by present drilling ("Lithostratigraphy and Sedimentology" section, this chapter).

#### **Chemical Composition and Metal Sources**

Although the drilling did not penetrate the base of the massive sulfide deposit, the regional seismic reflection surveys suggest that the area of the sulfide deposit must be underlain by a section of sedimentary rock several hundred meters thick (Davis and Villinger, this volume), presumably now partly altered by passage of hydrothermal fluid. High-temperature alteration of sediment can be a significant source of metals in sediment-hosted massive sulfide deposits. Elements such as As, Bi, Pb, Sn, and Sb that are more abundant in sediment relative to basalt are also typically enriched in sediment-



Figure 58. Turbiditic sediment in interval 139-856B-15X-4, 20–34 cm, containing sphalerite and chalcopyrite. Fracture filling sphalerite-chalcopyrite is visible in the clay rich interval at 25–26 cm. Coarse-grained disseminated sphalerite occurs in the laminated silt at 18–20 cm and 32–34 cm.

hosted massive sulfide deposits, relative to basalt-hosted massive sulfide deposits (Franklin et al., 1981; Koski et al., 1988). Previous geochemical and isotopic studies suggest that the predominant metal source for massive sulfide recovered from Middle Valley is basaltic rock, with relatively minor input from sedimentary sources (J. Franklin, pers. comm., 1991). Shipboard petrographic and geochemical analyses support this conclusion. No As-, Bi-, Pb-, Sn-, or Sbbearing minerals were identified in polished thin sections. Although phases that incorporate these elements may be found during more detailed post-cruise investigation of the samples, they clearly are not volumetrically significant phases. Further geochemical and isotopic studies of these samples should place some limits on the relative contributions of basaltic and sedimentary source rocks. However, the present data, including average Cu, Zn, and Pb contents of 0.5%, 0.9%, and 105 ppm, suggest that this sulfide deposit is geochemically most similar to basalt-hosted sulfide deposits, even though the present-day host of the deposit is interpreted to be sedimentary.



Figure 59. Fine sand to silt turbidites in interval 139-856B-15X-3, 115-128 cm, showing spotted green chloritic alteration, especially in the sandy interval 128-131 cm, and sphalerite mineralization at 117-118 cm, 120-121 cm, and 123-125 cm.

# IGNEOUS PETROLOGY AND GEOCHEMISTRY

Igneous rocks were recovered in Holes 856A and 856B, located on the summit and flank, respectively, of a prominent hill immediately north of an area of sulfide outcrop (Fig. 8). These igneous rocks were examined to establish whether they form sills or flows, and to compare them compositionally to the volcanic rocks from other sites.

# **Distribution of Igneous Rocks**

Igneous rocks were recovered from one depth in Hole 856A and two depths in Hole 856B (Fig. 57 and Table 18). Also, three contacts between sediment and igneous rocks were recovered. Mafic igneous rocks (aphyric and microcrystalline) and a milled contact with sediment occur in Section 139-856A-13X-CC (Piece 1, 5–10 cm) at approximately 112 mbsf. Chips of fresh glass are embedded in the sediment as a halo around the contact (Fig. 90) and diabasic texture characterizes Piece 2, less than 10 cm downcore. Core 139-856A-14X contains 1.42 m of diabase and microgabbro, including pieces up to 30 cm long (Section 139-856A-14X-1). The bottom of Hole 856A is composed of holocrystalline diabase beginning at 115.7 mbsf



Figure 60. Fine sand and silt turbidites in interval 139-856B-15X-5, 97–110 cm, with well-developed spotted green chloritic alteration with disseminated sphalerite (100–109 cm).

(through 139-856A-14X-CC, Piece 10, 70–74 cm). These contact relationships indicate that the igneous rocks from Hole 856A are from the upper portion of a sill and include both its fine-grained margin and microgabbroic interior.

Hole 856B is approximately 185 m south of Hole 856A on the southern flank of the hill. Fine-grained basalt clasts with quench textures, and glassy margins with rinds of baked sediment were recovered in Sections 139-856B-8H-CC and 139-856B-16X-CC, marking the contacts of two sills penetrated at 62 and 120 mbsf, respectively. Recovery of samples from these sills is very sparse. Section 139-856B-8H-CC contains four pieces of basalt in 48 cm of core. Sample 139-856B-8H-CC (Piece 2, 10–12 cm) has an altered, relict chilled margin with a thin coating of baked sediment. In Core 139-856B-9X, 8.5 m of penetration (from 62.3 to 70.8 mbsf) produced 24 cm of pebble-sized chips, each typically 2 to 4 cm wide. These chips are composed of hydrothermally altered, sparsely plagioclase-phyric basalt. Subsequent drilling penetrated sediment. The basaltic fragments in Sections 139-856B-8H-CC to -9X-1 apparently represent a thin sill, no more than 5–6 m thick.


Figure 61. Clasts of massive pyrrhotite-pyrite in a matrix of sulfide sand and mud highly disturbed by drilling (interval 139-856D-1H-4, 55-75 cm).

Table 17. Copper, zinc, and lead content of massive sulfide samples determined by flame atomic absorption spectroscopy.

Core, section, interval (cm)	Piece	Depth (mbsf)	Туре	Cu (ppm)	Zn (ppm)	Pb (ppm)
139-856G-						
3P-1 12-14	2	17 72	5	2380	3100	68
3P 1 30 32	5	17.00	2	5202	9600	71
2P 1 25 27	6	17.90	2	10762	4600	64
5P 1 34 36	5	37.04	2	2057	4000	50
6P 1 24 29	5	16.54	5	2007	400	122
6P 2 80 82	12	40.54	3	200	100	112
6P 2 12 16	2	40.00	2	1500	100	112
6P 2 12 16	2	49.45	3	1515	100	110
6R-3, 13-10 6R-2, 120, 121	17	49.43	2	1607	1900	110
OR-5, 129-151	17	56.01	2	2070	28500	95
7R-1, 21-23	5	56.22	50	1222	28300	226
7R-1, 42-45	2	52.26	512	1225	8100	320
/R-1, 40-4/	0	57.66	2	0753	100	120
7R-2, 40-48	0	50.72	5	6733	100	108
7R-3A, 103-100	14A	59.72	5	6790	100	150
7R-3A, 103-100	14A	50.72	3	0/89	2200	154
/R-3B, 103-100	14B	59.72	э	839	3200	113
139-856H-						
3R-1, 26-27	3	22.36	4	2936	47041	59
3R-1, 26-27	3	22.36	4	2992	33002	56
3R-1, 38-40	3	22.48	4	4061	100	69
3R-2, 75–77	1	24.01	4	10596	44200	75
3R-2, 75-77	1	24.01	4	10979	45200	74
3R-3, 108-109	11	25.46	4	6453	12479	69
4R-1, 65-67	9	27.25	6	5566	52500	59
4R-1, 124-126	15	27.84	4	3318	7200	66
4R-2, 17-19	2	28.27	4	1498	1400	101
4R-2, 96-98	15	29.06	1	6319	25000	57
5R-1, 20-27	5	32.60	1	3185	1674	73
6R-1, 51-52	8	37.91	2	1102	2116	61
7R-1, 38-40	7	43.48	2	1496	500	92
8R-1, 28-30	5	48.28	2	6947	5600	76
8R-1, 72-74	11	48.72	5	692	8600	91
8R-1, 72-74	11	48.72	5	672	8300	83
9R-1, 58-60	8	53.08	5	5051	2225	144
11R-1, 108-110	18	62.38	2	10506	500	192
13R-1, 39-40	6	71.29	2	6961	275	161
13R-1, 43-46	6	71.33	2	7240	200	156
14R-1, 16-18	3	75.86	1	11587	500	128
15R-1, 73-76	11	81.23	1	9092	17600	123
15R-1, 84-86	12	81.34	1	9358	6822	132
16R-1, 68-69	13	85.88	1	16293	342	108

1

Drilling continued to 121.7 mbsf, where a second basaltic sill was intersected. Recovery here was equally sparse; 10 glassy basalt fragments are mixed with sediment in the lower 20 cm of Section 139-856B-16X-CC. Baked sediment is in contact with hydrothermally altered basalt fragments, marking this lower contact as a sill. This contact is cross-cut by chlorite veins that individually pass through both altered basalt and baked sediment.

No correlation of sills between Holes 856A and 856B was possible, even allowing for fault displacement of the two sections. Furthermore, no sills were recovered from Holes 856G and 856H, which are only about 150 m south of Hole 856B, and penetrated 65 and 94 mbsf, respectively. The sills are evidently discontinuous and are confined to the area immediately underlying the hill. All of the samples are petrographically similar and are considered to represent a single unit. No subunits are defined.



Figure 62. Photomicrograph of fine-grained interpenetrating bladed pyrrhotite pseudomorphically replaced by pyrite, with minor marcasite, in sulfide sand (interval 139-856D-1H-1, 140–146 cm). Dark areas are epoxy in void space.



Figure 63. Photomicrograph of fine-grained interpenetrating bladed pyrrhotite in type 1 sulfide (Sample 139-856H-4R-2, Piece 15). Dark areas are epoxy in void space.



Figure 64. Homogeneous, massive, fine-grained pyrrhotite (type 1) showing cross-cutting veins of coarser grained pyrite and incipient replacement by coarse-grained "porphyroblastic" pyrite (Sample 139-856H-16R-1, Piece 11).

### Lithological Description

Igneous rock recovered in Section 139-856A-13X-CC varies in little more than 10 cm from a glassy contact to fine-grained diabase. Small phenocrysts of plagioclase, olivine, and spinel are present. The groundmass includes plagioclase laths (60%) and pyroxene (40%), both with an average grain size of less than 0.4 mm. This lithology continues in Core 139-856A-14X, where the average grain size of the groundmass increases from microcrystalline to medium-grained, near the texture of equigranular microgabbro. Well-developed ophitic to subophitic texture, with poikilitic plagioclase and microphenocrysts of olivine, are visible. This core is composed of subequal amounts of plagioclase and pyroxene. The phenocrysts increase in size in a similar manner to the groundmass, such that some pieces are microporphyritic, with microphenocrysts of plagioclase and olivine.

Samples recovered from Hole 856B are primarily from the finegrained exterior of the sills and are sparsely phyric. Large (1–3 mm) tabular plagioclase phenocrysts are visible in Section 139-856B-8H-CC along with small, anhedral spinel and olivine crystals. Large phenocrysts (1–3 mm) of both plagioclase and olivine are visible in Section 139-856B-16X-CC. This latter core is composed entirely of partially altered glassy fragments with phenocrysts, in a matrix of thoroughly indurated and altered sediment. All pieces have glassy margins.

## **Petrographic Descriptions**

Four samples from Hole 856A and three samples from Hole 856B were examined petrographically. Four representative thin sections are summarized in Table 19. All seven specimens contain phenocrysts or microphenocrysts of plagioclase (An<sub>74-78</sub>), olivine, and spinel (Fig. 91). The groundmass consists of subequal quantities of plagioclase (An<sub>65</sub>) and clinopyroxene. Groundmass minerals have quench textures, including lantern shapes (for plagioclase) and thin spindles (for clinopyroxene), and also form microlitic and intergranular textures (Fig. 92). The holocrystalline rocks display a smooth variation in size and no difference in composition from phenocrysts to groundmass. Vesicles occur rarely in the more glassy samples from the sill



Figure 65. Homogeneous, massive, fine-grained pyrrhotite (type 1) showing poorly developed brecciation or fragmental texture. The pyrrhotite-rich fragments are defined by differences in grain size and porosity and occur in a pyrrhotite-rich matrix. Sample is cut by a vein of coarser grained pyrite with chlorite (Sample 139-856H-15R-1, Piece 3).

exteriors. Although fractures are filled with secondary minerals, penetrative alteration is minor. Olivine phenocrysts form 3% to 8% of the rock, as 0.3–1.0 mm equant to ovoid grains, and commonly are partially replaced by phyllosilicate minerals. Fracture surfaces and embayed margins in the larger, partially resorbed (?) olivine crystals in the diabase from Core 139-856A-14X are typically filled with aggregates of skeletal to lath-like quench crystals of plagioclase and clinopyroxene (Fig. 93). Spinel microphenocrysts are ubiquitous in the sills, appearing as deep red, euhedral diamond shapes (Fig. 91). Inclusions of glass occur locally in the cores of the spinel grains; these are commonly altered.

The major variation within the samples from Core 139-856A-14X is their variation in crystallinity and grain size of the groundmass minerals. Quench textures, including variolitic zones and mesostasis glass, are preserved in all samples from Hole 856B. Glassy margins are preserved, even in basalt that has been altered.





## **Alteration and Metamorphism**

Most of the rocks have been affected by incipient metamorphism, although the groundmass is notably fresh. Olivine phenocrysts in almost every sample were partially to completely replaced by phyllosilicate minerals, including talc, chlorite, and smectite (Fig. 94). Chlorite also replaced plagioclase and glass, and filled cracks and veins. This chlorite is extremely pale and is probably magnesian. Sulfide minerals, primarily pyrite and pyrrhotite, commonly are associated with chlorite and are also disseminated throughout the matrix, filling interstitial spaces and veins. Pale epidote replaced plagioclase and mesostasis in modest amounts in the coarser grained intervals (e.g., 139-856A-14X-CC, Piece 1A, 0-3 cm; Fig. 95). Two samples have baked sediment on their margins (Sections 139-856B-16X-CC, Piece 1, 11-13 cm, and 139-856B-8H-CC, Piece 2A, 10-12 cm). These originally glassy crusts are pervasively bleached and altered in hand specimen. Thin-section examination shows that over 20% of the rock has been replaced by secondary minerals, including talc, chlorite, and clay minerals. The 0.5-cm rind of baked sediment in contact with basalt is also altered to quartz, pyrite, and chlorite.

### **Results of Geochemical Analyses**

Data from five samples from Site 856 are presented in Tables 20 and 21. Major and trace elements were determined by XRF,  $H_2O$  and sulfur by CHNS analyzer, and  $CO_2$  by coulometry (Table 20) (see "Igneous Petrology and Geochemistry" section, "Explanatory Notes" chapter, this volume).



Figure 67. Type 2 massive sulfide with diffuse, irregular zones of replacement producing a pseudobrecciated texture (Sample 139-856H-2R-1, Piece 8).

The samples from Holes 856A and 856B are characterized by a narrow range of silica content (48.4% to 49.7%), variable and moderately high alumina content (16.05 to 18.51%), high MgO content (10.67 to 12.54%) and, in comparison with normal mid-ocean ridge basalt (MORB), low TiO<sub>2</sub> content (0.93% average) and very high contents of Cr (av. 700 ppm) and Ni (av. 270 ppm). These are the most primitive mafic rocks ever recovered from the Juan de Fuca Ridge. Only one other analysis (Karsten et al., 1990, sample O15-1) is compositionally close, and curiously, it is an "off-axis" sample, taken by Barr (1974) from the western margin of Middle Valley, about 12 km west of Site 855. This sample is also uniquely primitive among the data of Karsten et al. (1990).

Chemical alteration of the samples taken from Site 856 is minimal. As noted petrographically, most of the alteration is confined to

Table 18. Horizons of sill recovery at Site 856.

Unit	Location (top)	Depth (mbsf)	Location (bottom)	Depth (mbsf)	Recovery (m)
1A	139-856A-13X-CC	112.0	139-856A-14X-CC	116.5	2.0
1B	139-856B-8H-CC	62.3	139-856B-9X-1	67.3	0.5
1C	139-856B-16X-CC	120.8	139-856B-16X-CC	121.7	0.2



Figure 68. Photomicrograph of euhedral pyrite crystals (light) intergrown with magnetite (dark gray) in type 2 sulfide (Sample 139-856G-5R-1, Piece 5). The magnetite is partly replaced and veined by fine-grained hematite (lighter gray) and rimmed by pyrite. Dark areas are epoxy in void space.

fractures, particularly near the margins of the sills; the most obviously altered and veined samples were avoided during sampling. Corundum is absent from the norm (Table 21), indicating minimal gain or loss of alkali elements. Loss on ignition correlates well (R > 0.9) only with Ni and Cr, which suggests hydration of olivine (for the Ni correlation), and covariance of olivine and spinel (for Cr).

Major and minor element compositions and normative calculations indicate that the rocks are olivine-rich, with an average of 9.4 wt% in the norm compared with 1.5% for samples from Site 855. Their average plagioclase composition is  $An_{70}$  (compared with  $An_{61}$ for Site 855; see "Igneous Petrology and Geochemistry" section, "Site 855" chapter, this volume).

Table 19. Visual estimates of modal properties in representative thin section from Site 856.

Hole, core, section Sample interval (cm)	856A-13X-CC 11-15	856A-14X-1 84-88	856B-9X-1 4-8	856B-16X-CC
Piece number	2A	5	1	1
Primary minerals (%)				
Olivine	5	o.p.	4	o.p.
Plagioclase	49	53	26	16
Clinopyroxene	45	30	20	
Spinel	1	1	1	1
"Mesostasis		2	30	44
Secondary minerals (%)				
Smectite		3	6	30
Carbonate		1		
Chlorite		2	8	6
Sulfides		1		1
Talc	trace	6	4	2
Epidote		1	1	
Magnetite		1		

Note: o.p. indicates that olivine was originally present but is now totally replaced. All of the olivine and some of the plagioclase occurs as phenocrysts.

\* Interstitial or matrix glass.

Plots of immobile elements (Fig. 96) reflect the low abundance of incompatible elements in these samples, and these rocks plot in the low-K tholeiitic field of Pearce and Cann (1973). On a plot of Ti-Zr-Y (Fig. 96A), the compositions lie just outside the MORB field. The data do not form a well-defined linear array on a plot of Ti vs. Mg number (Fig. 97) and Ti vs. Zr (Fig. 98), in contrast with most MORB samples.

The three samples from Hole 856A (Sections 139-856A-13X-CC, 11-16 cm, -14X-1, 56-61 cm, and -14X CC, 3-7 cm) have downward-increasing MgO and normative plagioclase contents (An<sub>70</sub>, An<sub>73</sub>, and An<sub>75</sub>, respectively). This may indicate a slight amount of fractional crystallization within a single sill. Within the closely spaced samples in Hole 856B, however, the trend is reversed. In the latter case, some ambiguity exists as to the relative position of the samples.

A plot of Mg number vs. CaO/Al<sub>2</sub>O<sub>3</sub> ratio (Fig. 99) is particularly revealing of the contrasting composition of these rocks compared with normal MORB from the Juan de Fuca Ridge. The compositions lie well outside the field of all southern Juan de Fuca and Endeavour Ridge samples. They form an essentially vertical trend, indicating possible fractional crystallization of feldspar. However, the lack of a distinctive negative trend on the plot of Ti vs. Mg number (Fig. 97), and the lack of a convex-upward positive trend on the plot of Ti vs. Zr (Fig. 98), both indicate that fractional crystallization, either *in situ* or in a shallow-level magma chamber, has not been effective in establishing the principal compositional variations within the data set. Primary inhomogeneity of the melt may explain the observed variations.

In summary, the sills underlying the hill at Site 856 are unique among basalts from the Juan de Fuca Ridge. They are derived from a very primitive melt and have undergone very little modification through shallow-level crystal fractionation, either in their present positions or in a shallow-level magma chamber. The melt seems to have come directly from the mantle, with only a slight amount of *in-situ* fractionation. They resemble primitive MORB in many of their chemical characteristics. Their melt did not reside in a





Figure 69. Homogeneous medium- to coarse-grained pyrite-pyrrhotite (type 3) (Sample 139-856G-6R-3, Piece 17).

high-level magma chamber and thus they do not indicate an underlying local heat source for the hydrothermal system in this part of Middle Valley.

### Conclusions

The igneous rocks recovered from Holes 856A and 856B represent sills intruded into sediment. Two of the sediment-basalt contacts provide petrological evidence of magma intruded and chilled within the sedimentary pile (Hole 856B, 62 and 120 mbsf). A third contact (Hole 856A, 114 mbsf) is too disturbed by drilling to be conclusive; however, the narrow transition zone (within 10 cm) from quenched to crystalline diabase indicates that this is an intrusive contact. The single sill that was completely penetrated is less than 6 m thick. The sills do not have great lateral continuity, as they are not correlatable between Holes 856A and 856B, only 185 m apart, and were not intersected in Holes 856G and 856H, only 150 m farther south.

Along the contacts between the sills and sediments, the latter are baked and the fine-grained marginal diabase is locally altered. The holocrystalline portions of the sills all contain metamorphic minerals characteristic of greenschist facies. Although up to 20% of the rock is now dominated by a hydrous silicate assemblage, little gain or loss of components other than water is evident.

The three sills all crystallized from magma of a similar primitive composition and are characterized by phenocrysts and micropheno-

Figure 70. Type 3 sulfide with banding of coarser grained pyrite in a matrix of finer grained pyrite and pyrrhotite (Sample 139-856G-6R-3, Piece 3). Banded texture of this type is generally not present in type 3 samples.

crysts of plagioclase, olivine, and spinel. The magma type is one of the most primitive compositions of MORB found in any spreading axis, especially a medium-spreading axis such as the Juan de Fuca Ridge. It is characterized by high MgO, Cr, and Ni and by low abundances of Ti and Fe. The closest analogue to this MORB type is the primitive central volcanoes of the FAMOUS area of the Mid-Atlantic Ridge (Bryan et al., 1981). The unfractionated magmatic composition for these sills precludes a substantial episode of crystal fractionation in a shallow crustal magma chamber. This is in contrast to basalt recovered from Site 855 and elsewhere along the Juan de Fuca Ridge (Karsten et al, 1990). The most likely origin for these sills is a late magmatic event that postdated the existence of an axial magma chamber and thus retained compositions most similar to primitive mantle melts.

The late emplacement of these sills is manifest in the uplift of the hill at Site 856. This hill is not a volcanic basement "high" and was evidently uplifted recently (see "Lithostratigraphy and Sedimentology" section, this chapter). Uplift was probably concomitant with, and a result of, the emplacement of these sills.

## PHYSICAL PROPERTIES

Physical properties were measured on samples from Holes 856A, 856B, 856C, 856D, 856G, and 856H. Cores recovered include sulfiderich sediment and massive sulfide. Holes 856A and 856B are located



1 cm

Figure 71. Type 3 sulfide with leached texture and solution channelways. The dark area of the sample on the left is an open solution channelway partly lined with euhedral pyrrhotite and coated with late-stage fine-grained black magnetite. The final stage of channelway infilling preserved in this sample is botryoidal radial fibrous aggregates of marcasite (bulbous masses in center of photo) that overgrow the magnetite layer (Sample 139-856G-4R-1, Piece 18).

at the center and flank of an uplifted sediment hill. APC and XCB cores from these holes generally consist of numerous turbidites with individual units ranging from 10 to 116 cm in thickness. It was expected that the physical properties of turbidites would be best preserved in the APC cores. Therefore we sampled systematically the fine- and coarse-grained parts of turbidites, typically twice per section, from APC cores recovered from Hole 856A. From Hole 856B, samples were taken mainly from fine-grained parts of the section, in order to gain a volumetrically more representative suite of measurements.

Massive sulfide cores were recovered by RCB drilling from Hole 856C to Hole 856H. Samples were taken from each representative type of sulfide (see "Sulfide Petrology and Geochemistry" section, "Explanatory Notes" chapter, this volume).

A full program of physical properties measurements was run on all cores from Site 856 with the exception of gamma-ray attenuation porosity evaluator (GRAPE) measurements, as this instrument was not functional. All the data from discrete samples (velocity, index properties, and thermal conductivity) are listed in Tables 22 through 37. Techniques for measurement of these properties are described in the "Explanatory Notes" chapter (this volume).

### **Volume Magnetic Susceptibility**

Volume magnetic susceptibility reflects mainly the magnetite content of the core. Several attempts have been made to build empirical relationships between these parameters. According to Telford et al. (1976), the susceptibility, though variable, is generally low for sedimentary rocks (less than 0.001 in SI units) and higher in igneous rocks, especially in mafic rocks (0.01) as compared with silicic rocks (less than 0.01).

The susceptibility data we obtained from Site 856 vary greatly, from 0.0002 in altered sediment to higher than 0.1 in sulfide rock.



Figure 72. Heterogeneous and veined coarse-grained pyrite-pyrrhotite (type 4). Typical sample showing textural variations and veining (Sample 139-856H-3R-3, Piece 1).

Unfortunately, the MST instrument has an upper limit of around 0.1; we cannot resolve differences in susceptibility greater than this value.

In Hole 856A, background susceptibility values vary significantly with depth (Fig. 100). They gradually increase from 0 to 30 mbsf, where the maximum background value of 0.004 occurs, then decrease to 0.0003 at 39 mbsf. Deeper than 50 mbsf, the data vary from 0.0002 to 0.0005. High-frequency components, having peaks several times larger than the background, are found throughout the hole, except for



1 cm

Figure 73. Type 4 sulfide with coarse, anhedral pyrite aggregates (Sample 139-856H-4R-1, Piece 15).

some intervals (e.g., 36–39 mbsf, 64–69 mbsf). The high-frequency peaks correlate very well with turbidites (see "Lithostratigraphy and Sedimentology" section, this chapter).

The bases of turbidites detected at 24–28 mbsf in Hole 856A correspond to the largest peaks in susceptibility. Figure 101 shows an enlarged view of the susceptibility data from this interval, with velocity measured by the *P*-wave logger (PWL) and locations of the basal boundary of each turbidite. Susceptibility increases gradually with depth toward the base of turbidite; the peak values are about two to four times higher than background. Susceptibility decreases abruptly within 2 to 5 cm, below the base of each turbidite. This asymmetric pattern correlates well with the compressional wave velocity obtained by PWL (Fig. 101); these properties also probably correlate well with the grain-size distribution.

Hole 856B contains some particularly interesting features in the volume magnetic susceptibility data (Fig. 102A):

1. Anomalously high values between 18.6 and 21.0 mbsf correlate with sulfide-rich sediment (Fig. 102B; see "Lithostratigraphy and Sedimentology" section, this chapter). The maximum value is 0.1,



Figure 74. Type 4 sulfide cut by vein of coarse pyrite (Sample 139-856H-5R-1, Piece 3).

which is the same order of magnitude as that of the massive sulfide obtained from Holes 856G and 856H.

2. There is no distinct turbidite signal, even within turbidite-rich intervals at 6–10 mbsf, 15–18 mbsf, and below 34 mbsf.

3. A gradual decrease in background susceptibility by one order of magnitude occurs from 5 to 18 mbsf; susceptibility remains low below 34 mbsf down to the bottom of the hole, with the exception of high values at 71–72 mbsf. The latter interval corresponds to Core 139-856B-10H. The quiet zone of 15–18 mbsf may correlate with that observed in Hole 856A at 33–40 mbsf (see also "Paleomagnetism" section, this chapter). Hydrothermal alteration of magnetite below 34 mbsf could result in the generally low values there (see "Sediment Geochemistry and Alteration" section, this chapter).

The sampling is highly incomplete in Holes 856G and 856H, although with some caution, the susceptibility profiles can be said to be similar (Fig. 103). Except for the uppermost part of Hole 856G, the susceptibility is high, around 0.05, and variability is low above 45 mbsf and below 70 mbsf. Relatively low values (<0.001) appear at 55–65 mbsf in both holes. Massive colloform and vuggy pyrite (see "Sulfide Petrology and Geochemistry" section, this chapter) predominates in this interval. The observation of low susceptibility implies low magnetite content in this interval.

The topmost part of Hole 856G consists of sulfide sand (see "Lithostratigraphy and Sedimentology" section, this chapter). In that part of the hole, susceptibility is similar to or lower than at the top of Holes 856A and 856B.





Figure 75. Type 4 sulfide showing a mesh of veinlets of replacement pyrite and coarser patches of pyrite and pyrrhotite (Sample 139-856H-3R-2, Piece 4A).

Figure 76. Type 4 sulfide with late-stage carbonate (white) filling some vugs and coating fractures (Samples 139-856H-3R-2, Piece 1B).



1 GIII

Figure 77. Massive colloform and vuggy pyrite (type 5) with open voids and voids filled by white amorphous silica  $\pm$  chlorite (Sample 139-856G-6R-3, Piece 14).

### **Compressional Wave Velocity**

Compressional wave velocity was measured using the PWL for cores obtained by the APC method. XCB cores were not logged because of core disturbance. Velocity measured on cores from Holes 856A and 856B is shown in Figure 104. In Holes 856A and 856B, there is a general increase in velocity with depth from about 1500 m/s at the seafloor to about 1550 m/s at 60 mbsf. Below 30 mbsf, velocity in Hole 856B increases steadily with depth and is higher than 1700 m/s below 60 mbsf. Velocity in Hole 856A, however, does not increase at that depth, but stays at around 1550 m/s.

PWL data correlate well with turbidites and volume magnetic susceptibility; the velocity contrast across the base of turbidites is typically 100 m/s (Fig. 101).

### **Discrete Sample Measurements**

### Hole 856A

Physical properties measured on discrete samples from Hole 856A are plotted vs. sub-bottom depth in Figure 105. Data gaps are due to poor core recovery.

Table 20. Chemical composition of igneous rocks from Site 856.

Hole	856A	856A	856A	856B	856B
Core, section	13X-CC	14X-1	14X-CC	8X-CC	9X-1
Interval (cm)	11-16	56-61	3–7	6–7	4-8
(wt%)					
SiO <sub>2</sub>	49.42	48.25	48.55	49.46	50.03
TiO <sub>2</sub>	0.91	0.86	0.88	0.92	1.02
Al <sub>2</sub> O <sub>3</sub>	16.40	16.06	16.05	17.08	18.58
Fe <sub>2</sub> O <sub>3</sub>	9.35	9.02	9.16	8.65	8.05
MnO	0.15	0.15	0.16	0.12	0.07
MgO	10.67	11.90	12.40	12.68	11.31
CaO	12.46	11.87	11.22	9.84	8.46
Na <sub>2</sub> O	1.86	1.57	1.50	1.74	2.16
K <sub>2</sub> Õ	0.04	0.04	0.03	0.02	0.03
P <sub>2</sub> O <sub>5</sub>	0.05	0.05	0.05	0.06	0.05
Total	101.31	99.77	100.00	100.57	99.76
LOI	1.30	1.59	3.00	4.62	4.43
CO <sub>2</sub>		0.165	0.312		
H₂Õ		1.62	2.88		
(ppm)					
Rb	2	0	0	0	1
Sr	62	60	57	61	74
Y	22	21	21	22	20
Zr	46	45	44	46	50
Nb	1	1	2	1	1
Ni	221	266	275	309	304
Cr	628	657	679	769	804
v	214	195	201	214	248
Cu	83	75	74	75	95
Zn	48	39	42	69	122
Ba	15	23	0	0	10
S		0.033			

Compressional wave velocity was measured with either the digital sound velocimeter (DSV) or the Hamilton frame velocimeter (HFV), depending on the degree of consolidation of the sediment. Both methods were used at depths of 25 to 80 mbsf, which enabled a comparison between these two instruments and the PWL on the MST. Results were consistent within the error inherent in each method.

Compressional wave velocity increases gradually from the seafloor to 80 mbsf by about 100 m/s; this increase is systematically larger than possible measurement error (about 1%). Both the local variations and overall trends with depth are similar to the variation observed in the MST data. The variations are caused by local differences in grain size and by an increase in degree of induration with depth (see discussion below).

Wet-bulk density is highly scattered but on average increases gradually with depth, probably because of sediment compaction and induration. Samples having higher wet-bulk density and lower poros-

Table 21. Normative	calculations	(in wt%)	for	igneous	rocks
from Site 856.					

Hole	856A	856A	856A	856B	856B
Core, section	13X-CC	14X-1	14X-CC	8X-CC	9X-1
Interval (cm)	11-16	56-61	3-7	6–7	48
Anorthite	36.07	37.00	37.46	9.25	41.26
Albite	5.65	13.41	12.57	13.80	18.43
Orthoclase	0.24	0.24	0.18	0.12	0.18
Diopside	20.33	17.88	14.80	7.72	0.68
Hypersthene	13.90	16.12	20.64	28.37	31.33
Forsterite	7.17	8.63	7.92	5.58	3.58
Fayalite	3.59	3.75	3.34	2.13	1.39
Ilmenite	1.72	1.65	1.71	1.77	1.96
Magnetite	1.23	1.20	1.22	1.14	1.07
Apatite	0.11	0.11	0.13	0.11	0.11
Total	100.00	100.00	100.00	100.00	100.00



Figure 78. Photomicrograph of colloform-banded pyrite in type 5 sulfide (Sample 139-856G-7R-1, Piece 8). The dark spots are voids.

ity or water content come from the coarse-grained parts of turbidites. Preferential sampling of these layers in this hole results in an overall bias toward lower porosity and higher velocity.

The grain density stays constant throughout the cores. The average value of  $2.77 \pm 0.02$  g/cm<sup>3</sup> in Hole 856A is several percent higher than the predicted value of 2.67 g/cm<sup>3</sup> for terrigenous sediments or 2.70 g/cm<sup>3</sup> for deep-sea red clay (Hamilton, 1974).

A gradual increase in the thermal conductivity with depth corresponds to the decrease in porosity and water content. Local variations may originate from the differences in lithology on a small scale.

Physical properties were also measured on basalt samples obtained near the bottom of Hole 856A (Cores 139-856A-13X and -14X). Wet-bulk density, measured on three samples, averaged 2.86 g/cm<sup>3</sup>. The thermal conductivity is 1.78 W/(m·K) and the compressionalwave velocity is 5850 m/s, both measured on one sample from Core 139-856A-13X.

### **Physical Properties of Turbidites**

The interrelationship of various measured physical properties as they vary through a series of typical turbidites is shown in Figure 106. The intervals between discrete measurements are much larger than these for MST measurements; however, a qualitative comparison of the two data sets reveals strong correlations.

Compressional wave velocity measured by HFV is identical to that measured by the PWL, and it is higher (by up to 100 m/s) at the base of turbidite layers than at the top of the layers. At the base of turbidites, wet-bulk density is higher by about 0.3 g/cm<sup>3</sup>, and porosity and water content are lower by about 10% than they are at the top. Index properties and velocity in the half-round cores may be biased because of a loss of interstitial water. Highly permeable sandy layers may have drained more easily than clayey layers. This process would reduce measured velocity, porosity, and water content at the base of the turbidites.

Thermal conductivity is higher by up to 0.4  $W/(m \cdot K)$  at the base of turbidites. Also, Figure 107 shows that the data cluster into two

groups; one with lower porosity (40%-45%) corresponding to coarsegrained material, and the other with higher porosity (55%-60%) representing the fine-grained part. The respective thermal conductivities are 1.3-1.6 W/(m·K) and 1.1-1.5 W/(m·K).

# Hole 856B

Plots of the physical properties vs. sub-bottom depth in Hole 856B are shown in Figure 108. Down to 65 mbsf, the compressional wave velocity increases gradually, in a manner similar to Hole 856A. Local variability is similar, about 100 m/s. Below 80 mbsf the velocity increases more rapidly with depth, and the scatter in the data becomes larger. This scatter may be caused by the greater disturbance of the XCB vs. APC cores. Systematic patterns like those seen between 85 and 110 mbsf (Cores 139-856B-12X, -13X, and -14X) are probably artifacts of coring.

Index properties show similar features to those in Hole 856A. Wet-bulk density slowly increases and grain density remains fairly constant  $(2.78 \pm 0.03 \text{ g/cm}^3)$  with depth down to 80 m. Below 80 m, a stepwise increase in both the grain density and wet-bulk density is recognized. It implies a change in the characteristics or contents of the solid matrix.

With minor exceptions, thermal conductivity increases with depth in a similar manner to Hole 856A. At 19 mbsf, thermal conductivities of up to 2.7 W/(m·K) were measured in redeposited sulfide sediment. Thermal conductivity values largely scatter below 70 mbsf, probably due to coring with the XCB. A high and variable distribution of thermal conductivity was measured in the section below 110 mbsf, where the sediment becomes silicified.

The relation between thermal conductivity and porosity can be expressed as a geometric mean of a two-component system (solid grains and seawater), assuming a constant thermal conductivity for the grains. Figure 107 plots thermal conductivity vs. porosity for Holes 856A and 856B. A thermal conductivity value for seawater of 0.6 W/(m·K) was used; the best fit value of the solid grain thermal conductivity is estimated as 3.64 W/(m·K). The measured data appear

#### Table 22. Index properties, Hole 856A.

Table 22 (continued).

Core, section, interval (cm)	Depth (mbsf)	density (g/cm <sup>3</sup> )	density (g/cm <sup>3</sup> )	Wet porosity (%)	Wet water content (%)	Void ratio	Core, section, interval (cm)	Depth (mbsf)	density (g/cm <sup>3</sup> )	density (g/cm <sup>3</sup> )
139-856A-							6H-5, 65-69	47.35	1.80	2.78
14 1 72 77	0.73	1.40	2 70	76.9	\$2.7	2.21	611 6 76 90	40.04	1.60	2.75
111-7, 38, 40	1.88	1.49	2.79	76.5	52.1	3.31	64 7 28 42	40.90	1.57	2.77
211-2, 30-40	1.00	2.06	2.77	10.5	32.4	5.45	711 1 20 42	50.08	1.00	2.79
211-1, 07-09	3.37	2.00	2.77	40.5	23.0	0.80	711-1, 39-43	50.39	1.79	2.70
211-2, 03-00	4.65	1.54	2.75	13.4	48.7	2.76	7H-1, 71-75	50.91	1.08	2.70
211-3, 8089	0.50	1.57	2.19	60.8	43.5	2.01	/H-2, 82-80	52.52	1.08	2.70
211-4, 75-70	1.93	1.00	2.80	59.9	37.0	1.50	/H-2, 91–95	52.01	1.98	2.75
211-5, 04-00	9.34	1.99	2.77	47.0	24.5	0.91	711-3, 72-70	53.92	1.05	2.01
20-5, 74-70	9.44	1.62	2.77	69.3	41.5	1.89	7H-3, 95-99	54.15	1.85	2.75
2H-0, 74-70	10.94	1.00	2.76	68.3	42.1	2.10	/H-4, 38-42	55.08	1.75	2.77
2H-7, 43-40	12.13	1.81	2.79	59.1	33.4	1.44	/H-4, 60-64	55.30	1.96	2.75
3H-1, 24-20	12.44	2.00	2.75	48.7	24.9	0.95	/H-5, 83-87	57.03	2.09	2.73
3H-1, 91-93	13.11	1.61	2.76	/2.6	46.1	2.66	7H-5, 96–100	57.16	1.61	2.76
3H-2, 60-62	14.30	1.98	2.75	47.2	24.4	0.89	7H-6, 72-76	58.42	2.04	2.14
3H-2, 68-72	14.38	1.71	2.77	64.2	38.5	1.80	7H-6, 91–95	58.61	1.77	2.76
3H-3, 59-61	15.79	1.95	2.76	51.3	27.0	1.01	7H-7, 24–28	59.44	2.05	2.74
3H-3, 67-69	15.87	1.51	2.77	61.0	41.4	1.57	7H-7, 38-42	59.58	1.78	2.75
3H-4, 46-48	17.16	2.05	2.77	47.4	23.7	0.90	8H-1, 88-92	60.58	1.78	2.78
3H-5, 56-58	18.76	1.71	2.79	65.8	39.5	1.92	8H-1, 111-115	60.81	2.04	2.74
3H-5, 69-71	18.89	1.67	2.76	67.8	41.5	2.11	8H-2, 56-58	61.76	2.07	2.75
3H-6, 76-78	20.46	1.55	2.72	64.3	42.6	1.80	8H-2, 65-68	61.85	1.84	2.74
3H-7, 41-43	21.61	1.85	2.77	55.9	30.9	1.27	8H-3, 68-72	63.38	1.86	2.76
4H-1, 66-70	22.36	1.68	2.76	58.0	35.5	1.38	8H-3, 98-102	63.68	2.07	2.74
4H-2, 55-59	23.75	1.97	2.76	50.1	26.0	1.00	8H-4, 68-72	64.88	1.83	2.78
4H-2, 68-70	23.88	1.75	2.77	63.6	37.3	1.75	8H-5, 70-72	66.40	1.82	2.76
4H-3, 70-74	25.40	2.00	2.75	47.7	24.4	0.91	8H-6, 69-72	67.89	1.73	2.76
4H-3, 82-86	25.52	1.81	2.75	58.1	32.9	1.39	8H-7, 35-38	69.05	1.83	2.78
4H-4, 72-76	26.92	1.64	2,79	55.8	34.9	1.26	9H-1, 72-75	69.92	1.86	2.78
4H-4, 110-114	27.30	2.06	2.74	45.0	22.4	0.82	9H-2, 40-42	71.10	2.05	2.77
4H-5, 72-76	28.42	1.82	2.78	58.9	33.2	1.43	9H-2, 90-92	71.60	1.76	2.82
4H-6, 63-67	29.83	2.01	2.73	45.8	23.3	0.85	9H-3, 59-61	72.79	1.79	2.75
4H-6, 93-97	30.13	1.60	2.79	53.6	34.3	1.16	9H-3, 98-100	73.18	1.97	2.77
4H-7, 36-40	31.06	1.63	2.76	48.8	30.8	0.95	9H-4, 18-20	73.88	2.01	2.74
5H-2, 59-63	32.17	1.85	2.77	49.3	27.3	0.97	9H-4, 71-73	74.41	1.84	2.79
5H-2, 102-106	32.60	1.73	2.78	61.4	36.3	1.59	9H-5, 95-97	76.15	1.99	2.76
5H-3, 66-70	33.74	1.83	2.78	57.3	32.1	1.34	9H-6, 39-41	77.09	1.87	2.78
5H-4, 66-70	35.24	1.87	2.77	51.5	28.2	1.06	9H-6, 55-57	77.25	2.07	2.76
5H-5, 48-52	36.56	1.66	2.80	57.3	35.5	1.34	9H-7, 23-25	78.43	2.15	2.78
5H-5, 79-83	36.87	2.06	2.74	43.6	21.7	0.77	10X-1.69-71	79.39	1.88	2.76
5H-6, 50-54	38.08	1.96	2.77	49.7	25.9	0.99	11X-1, 87-89	87.07	1.62	2.75
5H-6, 61-65	38.19	1.82	2.78	59.7	33.7	1.48	11X-2 31-33	88.01	1.84	2.80
5H-7, 66-70	39.74	1.73	2.79	61.8	36.6	1.62	11X-CC 14-16	88 51	2.02	2.77
5H-8, 50-54	41.08	1.62	2.81	58.9	37.3	1.43	13X-2, 121-122	108.01	1.98	2.77
6H-1, 60-64	41.30	1.78	2.79	57.5	33.1	1.35	13X-4, 106-109	110.86	1.88	2.70
6H-2, 84-88	43.04	2.02	2.77	45.0	22.8	0.82	13X-CC. 19-21	113.36	2.95	2.92
6H-2, 97-101	43.17	1.68	2.81	57.0	34.9	1.33	14X-1 12-14	114.62	2.70	*
6H-3, 73-77	44.43	1.88	2.77	52.3	28.4	1.10	14X-1 108-110	115 58	2.94	*
6H-3, 106-110	44.76	2.00	2.75	44.9	23.0	0.82	147-1, 100-110	110.00	- 441 (X-11)	
6H-4, 31-35	45.51	2.01	2.75	44.6	22.7	0.81	March and L		and the second second	duran meda
6H-4, 45-49	45.65	1.73	2.79	59.5	35.3	1.47	Note: *Paleomagnetism	cube sampl	es; no dry ana	nyses made
	101100		and the second sec	10 S 10 10 S	af all saf					

to agree well with the best-fit line, implying constant thermal conductivity for the grains throughout the core and between the two holes. The value is also consistent with that determined from measurements at Site 855 (see "Physical Properties" section, "Site 855" chapter, this volume).

# Holes 856G and 856H

Over 50 m of massive sulfide was recovered from Holes 856G and 856H, which were drilled to 65 and 94 mbsf, respectively. Figure 109 shows the results of physical properties measurements at these holes. Velocity, index properties, and thermal conductivity were measured on individual samples.

Thermal conductivity is extremely high throughout the recovered core. This can be attributed to a combination of low porosity and the high concentration of high-conductivity minerals such as pyrite, which has a conductivity of 19.2 W/(m·K) (Horai, 1971). Thermal conductivity in both holes is highest and most variable in the interval from 55 to 65 mbsf. As noted previously, massive colloform and vuggy pyrite predominates in this interval. The high values and variation of thermal conductivity may therefore correspond to the high but variable percentage of pyrite. Assuming pyrite and amorphous-silica contents are

65% and 15%, respectively, and porosity is 20% (typical for this sulfide), the yield is an estimated geometrical mean thermal conductivity of 8.4 W/(m·K). This is close to the average measured thermal conductivity of 9.3 W/(m·K) for this material.

Wet

porosity

(%)

58.5

49.4

56.3

46.9

55.2

57.4

56.1

478

62.1

54.4

58.4

487

43.3

52.0

45.2

55 9

43.6

56.1

60.4

47.2

44.0

60.8

57.1

48.0

56.8

56.4

55.2

56.9

54 3

48.6

60.6

59.6

49.2

48.8

56.3

49.5

56.6

45.6

47.2

60.2

41.8

58.9

47.7

50.8 52.7

1.06

Wet water

content (%)

33.2

28.1

36.8

28.6

31.5

35.0

34.2

247

38.6

30.0

34.2

25.5

21.2

33.1

22.7

32.4

21.8

32.2

34.9

23.8

21.8

33.9

31.5

23.8

31.8

31.7

32.8

31.8

20 0

24.2

35.2

34.1

25.6

24.9

31.3

25.5

31.0

22 5

22.5

32.8

26.5

32.8

24.1

26.3

28.6

0.37

Void

ratio

1.41

0.98

1.29

0.88

1.23

1.34

1.28

0.91

1.64

1.19

1.40

0.95

0.76

1.08

0.82

1.27

0.77

1.28

1.53

0.89

0.78

1.55

0.92

1.32

1.30

1.23

1.19

0.94

1.54

0.97

0.95

1.29

0.98

1.31

0.84

0.89

1.52

0.72

1.43

0.91

1.03

1.11

0.01

Such high thermal conductivity may require significant postcruise correction, because the half-space instrument was calibrated only for values lower than 2 W/(m·K). Also, in these high-conductivity samples, boundary effects probably become important and cause systematic errors. Steady-state divided-bar thermal conductivity measurements are planned as part of a shore-based study of these rocks in order to deal with this problem.

Compressional wave velocity was measured on cube samples of the sulfide rocks. Velocity is generally high and anisotropy is less than 10%. Velocity is quite variable, from 3000 to 6000 m/s. Also, the velocity is generally low where porosity is high and thermal conductivity is low. This correlation probably results from a difference in sulfide rock type.

The average grain density is high, around 4.5 g/cm<sup>3</sup>, and is more variable in Hole 856H (4.07 to 4.79 g/cm<sup>3</sup>) than in Hole 856G (4.52 to 4.66 g/cm<sup>3</sup>). Dense sulfide minerals such as pyrite (4.9 g/cm<sup>3</sup>) and pyrrhotite (4.5 g/cm<sup>3</sup>) could produce these high average grain-density values. Comparison with the mineral content of each piece will be included in a post-cruise study.

Table 23. Compressional wave velocity (DSV), Hole 856A.

Sample	Depth (mbsf)	DSV velocity (m/s)
139-856A-	10 - 15 -	Q 8
1H-2 75	0.75	1497
1H-2, 40	1.90	1497
2H-1.67	3 37	1459
2H-2, 67	4.87	1508
2H-3, 87	6.57	1452
2H-4, 75	7.95	1463
2H-5, 64	9.34	1466
2H-5, 75	9.45	1508
2H-6, 75	10.95	1541
2H-7, 45	12.15	1562
3H-1, 26	12.46	1705
3H-1, 92	13.12	1523
3H-2, 62	14.32	1553
3H-2, 70	14.40	1534
3H-3, 59	15.79	1642
3H-3, 68	15.88	1531
3H-4, 48	17.18	1602
3H-4, 56	17.26	1570
3H-5, 70	18.90	1577
3H-6, 76	20.46	1510
3H-7, 42	21.62	1414
4H-1,08	22.38	1555
411-2, 37	23.77	1531
411-2, 70	25.90	1596
41-5, 64	26.94	1574
4H-5 74	28.44	1588
4H-6.95	30.15	1577
4H-7, 38	31.08	1657
6H-1, 62	41.32	1599
6H-2, 86	43.06	1665
6H-2, 99	43.19	1601
6H-3, 75	44.45	1818
6H-3, 10	44.78	1695
6H-4, 33	45.53	1463
6H-4, 47	45.67	1549
6H-5, 67	47.37	1632
6H-6, 66	48.86	1644
6H-6, 78	48.98	1583
6H-7, 40	50.10	1663
/H-1, /3	50.93	1538
7H-2, 84	52.54	1581
711-3, 74	53.94	1505
711-3, 97	55 10	1505
7H-4, 40	55.10	1393
7H-6 93	58.63	1577
7H-7, 40	59.60	1579
8H-1, 90	60.60	1569
8H-2, 67	61.87	1565
8H-3, 70	63.40	1592
8H-4, 71	64.91	1563
8H-5, 71	66.41	1584
8H-6, 71	67.91	1541
8H-7, 37	69.07	1534
9H-1, 73	69.93	1608
9H-2, 40	71.10	1665
9H-2, 90	71.60	1563
9H-3, 59	72.79	1569
9H-4, 20	73.90	1518
9H-4, 71	74.41	1533
9H-5, 96	76.16	1581
911-0, 40	77.10	1518

Note: All velocities were measured parallel to the axis of the core

Table	24.	Compressional	wave	velocity	(HFV)
Hole 8	356A				

Core, section, interval (cm)	Depth (mbsf)	Direction (a, b, c)	HFV velocity (m/s)
39-856A-			
4H-3, 71-73	25.41	с	1674
4H-4, 111-113	27.31	c	1635
4H-6, 64-66	29.84	с	1656
5H-2, 103-105	32.61	с	1548
5H-3, 67-69	33.75	с	1574
5H-4, 67-69	35.25	с	1649
5H-5, 49-51	36.57	с	1534
5H-6, 62-64	38.20	с	1619
5H-7, 67-69	39.75	с	1541
5H-8, 51-53	41.09	c	1520
7H-1, 40-42	50.60	c	1570
7H-2, 83-85	52.53	c	1498
7H-2, 92-94	52.62	с	1555
7H-4, 61-63	55.31	с	1594
7H-5, 84-86	57.04	с	1688
7H-5, 97-99	57.17	с	1514
7H-6, 73-75	58.43	c	1619
7H-6, 92-94	58.62	с	1535
7H-7, 25-27	59.45	с	1603
8H-1, 112-114	60.82	с	1473
8H-2, 56-58	61.76	c	1630
8H-3, 99-101	63.69	c	1682
9H-3, 97-99	73.17	с	1571
9H-6, 56-58	77.26	с	1640
9H-7, 23-25	78.43	с	1609
10X-1, 71-73	79.41	с	1470
11X-1, 87-89	87.07	с	1707
11X-2, 31-33	88.01	c	1595
11X-CC, 14-16	88.51	с	1891
12X-2, 22-24	97.42	с	1803
13X-2, 116-118	107.96	c	1871
13X-3, 55-57	108.85	с	1781
13X-3, 85-87	109.15	c	1846
13X-3, 120-122	109.50	c	1842
13X-4, 9-11	109.89	с	2008
13X-4, 101-103	110.81	c	1676
13X-4, 130-132	111.10	c	1681
13X-5, 22-24	111.52	c	2278
13X-5, 85-87	112.15	c	1962
13X-5, 113-115	112.43	с	1689
13X-CC, 19-21	113.36	a	5497
13X-CC, 19-21	113.36	b	6289
13X-CC, 19-21	113.36	c	5758

### **Correlation between Holes and Sites**

A large difference in compressional wave velocity between Hole 856A (1650–2300 m/s) and Hole 856B (1900–3900 m/s) in the deeper part probably reflects a difference in the degree of induration with depth (see also "Lithostratigraphy and Sedimentology" and "Sediment Geochemistry and Alteration" sections, this chapter).

The sampling strategy for Hole 856A caused a bias in index properties. Figure 110 shows the porosity variation with depth in Holes 856A and 856B. The lower porosities of samples from Hole 856A were obtained on coarse-grained parts of turbidites. The higher values from Hole 856A samples correspond to mostly finegrained parts of the cores. These latter values decrease with depth similarly to these from Hole 856B. The higher values decrease more steeply with depth at Site 856 than at Site 855 (Figs. 102 to 104 and Fig. 110). The difference between properties of samples from the two sites is as high as 10% below 20 mbsf. Higher temperatures at depth

Table 25. Thermal conductivity, Hole 856A.

Sample (cm)	Full-space/ half-space (F/H)	Depth (mbsf)	Thermal conductivity (W/[m·K])
139-856A-			
1H-1 75	F	0.75	0.88
1H-2, 35	F	1.85	0.94
2H-1, 68	F	3.38	1.51
2H-2, 68	F	4.88	0.94
2H-3, 75	F	6.45	0.92
2H-4, 75	F	7.95	1.26
2H-5, 08 2H-6, 75	F	9.38	1.01
2H-7, 45	F	12.15	1.27
3H-1, 70	F	12.90	1.11
3H-2, 75	F	14.45	1.30
3H-3, 75	F	15.95	1.35
3H-4, 75	F	17.45	1.05
3H-6 75	F	20.45	1.09
3H-7, 33	F	21.53	1.20
4H-1, 68	F	22.38	1.09
4H-2, 75	F	23.95	1.21
4H-3, 75	F	25.45	1.48
4H-4, 75	F	26.95	1.33
4H-5, 75	F	28.45	1.05
4H-0, 75 4H-7 40	F	29.95	1.02
5H-2, 72	F	32.30	1.46
5H-3, 77	F	33.85	1.20
5H-4, 75	F	35.33	1.39
5H-5, 75	F	36.83	1.52
5H-6, 75	F	38.33	1.20
5H-7, 75	F	39.83	1.06
5H-8, 48	F	41.00	1.42
6H-2 75	F	41.54	1.22
6H-3, 75	F	44.45	1.33
6H-4, 77	F	45.97	1.46
6H-5, 68	F	47.38	1.44
6H-6, 75	F	48.95	1.28
6H-7, 35	F	50.05	1.32
/H-1, 45 7H 1 75	F	50.05	1.40
7H-1, 75 7H-2, 75	F	52.45	1.50
7H-2, 97	F	52.67	1.30
7H-3, 95	F	54.15	1.43
7H-4, 40	F	55.10	1.19
7H-4, 68	F	55.38	1.58
7H-5, 87	F	57.07	1.93
7H-5, 105 7H-6, 73	F	58 43	1.25
7H-6, 90	F	58.60	1.45
7H-7, 30	F	59.50	1.51
7H-7,40	F	59.60	1.36
8H-1, 90	F	60.60	1.16
8H-1, 117	F	60.87	1.68
8H-2, 53	F	61.73	1.67
8H-3 70	F	63.40	1.24
8H-3, 100	F	63.70	1.56
8H-4,70	F	64.90	1.26
8H-5, 70	F	66.40	1.29
8H-6, 70	F	67.90	1.25
8H-7, 36	F	69.06	1.12
9H-1, 75	F	69.95	1.37
9H-2, 40 9H-2, 90	F	71.10	1.44
9H-3, 60	F	72.80	1.34
9H-3, 100	F	73.20	1.39
9H-4, 20	F	73.90	1.55
9H-4, 75	F	74.45	1.66
9H-5, 40	F	75.60	1.44
9H-5, 103	F	76.23	1.51
9H-0, 40	F	77.10	1.22
9H-7 25	F	78.45	1.55
10X-1, 85	F	79.55	1.34
10X-1, 115	F	79.85	1.47

Table 25 (continued).

Sample (cm)	Full-space/ half-space (F/H)	Depth (mbsf)	Thermal conductivity (W/[m·K])
10X-2, 50	F	80.70	1.22
10X-2, 85	F	81.05	1.98
11X-1,40	F	86.60	1.39
11X-1, 100	F	87.20	1.33
11X-2, 30	F	88.00	1.33
12X-1,45	F	96.15	1.27
12X-2, 32	F	97.52	1.66
13X-1,70	F	106.00	1.36
13X-1, 110	F	106.40	1.79
13X-2, 78	F	107.58	1.40
13X-2, 130	F	108.10	1.28
13X-3, 50	F	108.80	1.05
13X-3, 110	F	109.40	1.73
13X-4, 120	F	111.00	1.30
13X-5.68	F	111.98	1.42
13X-6, 20	F	113.00	1.51
13X-CC, 12	н	113.29	<sup>a</sup> 1.78

<sup>a</sup>Mean of eight measurements.

at Site 856 at present (see "Heat Flow" section, this chapter) and in the past (see "Sediment Geochemistry and Alteration" section, this chapter) may have had a significant effect on diagenesis.

### Summary

Physical properties of the sedimentary section at Site 856 correlate well with each other. They reflect variations within turbidites locally and an increase in the degree of compaction and lithification with depth on a larger scale. Velocity and thermal conductivity increase with depth, and wet-bulk density, porosity, and water content decrease with depth. Grain density and grain thermal conductivity remain relatively constant. There is also a significant difference in volume magnetic susceptibility between Holes 856A and 856B, with the latter showing possible signs of hydrothermal alteration. Sulfide cores show an extremely high and variable thermal conductivity which correlate positively with velocity. Their grain density is also high.

#### Table 26. Index properties, Hole 856B.

Core, section, interval (cm)	Depth (mbsf)	Wet-bulk density (g/cm <sup>3</sup> )	Grain density (g/cm <sup>3</sup> )	Wet porosity (%)	Wet water content (%)	Void ratio
139-856B-						
1H-1, 119-123	1.19	1.40	2.80	77.4	56.6	3.42
2H-3, 50-54	5.30	1.73	2.81	61.8	36.7	1.62
2H-5, 82-86	8.62	1.66	2.74	64.7	39.8	1.83
2H-6, 127-131	10.57	1.68	2.79	63.5	38.6	1.74
3H-2, 25-29	13.05	1.70	2.83	63.4	38.3	1.73
3H-4, 92-96	16.72	1.71	2.79	64.2	38.5	1.79
4H-5, 105-109	27.85	1.75	2.81	61.8	36.2	1.62
4H-6, 123-127	29.53	1.76	2.78	61.1	35.6	1.57
5H-3, 24-27	33.54	1.72	2.77	63.6	37.9	1.74
5H-6, 77-80	38.57	1.81	2.76	56.6	32.1	1.30
6H-2, 5-9	41.35	1.72	2.81	66.3	39.6	1.97
6H-4, 16-19	44.46	1.82	2.77	58.9	33.2	1.43
7H-3, 125-128	53.55	1.80	2.78	57.2	32.5	1.34
8H-3, 103-105	62.12	1.73	2.76	62.1	36.7	1.64
11X-4, 36-38	78.16	1.99	2.82	53.4	27.6	1.15
12X-2, 58-60	83.68	2.10	2.82	43.7	21.3	0.78
12X-3, 2-5	84.62	2.02	2.75	47.4	24.1	0.90
12X-4, 88-90	86.98	1.87	2.78	58.8	32.2	1.43
13X-1, 28-30	91.38	2.09	2.89	47.3	23.1	0.90
13X-2, 84-86	93.44	2.02	2.81	49.6	25.2	0.98
13X-4, 104-106	96.64	2.06	2.92	52.8	26.3	1.12
14X-2, 26-28	102.56	1.96	2.88	52.6	27,4	1.11



1 cm

Figure 79. Type 5 sulfide with well-developed colloform banding, especially on the bottom edge (Sample 139-856G-6R-3, Piece 9).

# Table 27. Compressional wave velocity (DSV), Hole 856B.

Core, section, interval (cm)	Depth (mbsf)	DSV velocity (m/s)
39-856B-		
1H-1, 120-120	1.20	1502
2H-1, 80-80	2.60	1502
2H-2, 71-71	4.01	1539
2H-3, 52-52	5.32	1521
2H-4, 94-94	7.24	1528
2H-4, 133-133	7.63	1524
2H-5, 47-47	8.27	1521
2H-5, 84-84	8.64	1523
2H-5, 117-117	8.97	1521
2H-6, 42-42	9.72	1533
2H-6, 129-129	10.59	1516
2H-7, 46-46	11.26	1521
3H-1, 99-99	12.29	1528
3H-2, 27-27	13.07	1528
3H-2, 109-109	13.89	1534
3H-3, 10-10	14.40	1606

Note: All velocities were measured parallel to the axis of the core.



1 cm

Figure 80. Type 5 sulfide with unusually coarse reticulate boxwork texture (Sample 139-856G-7R-1, Piece 9).

# DOWNHOLE LOGGING

Hole 856H, which penetrated a massive sulfide body to 93.8 mbsf, was the only hole logged at Site 856. The logs in Hole 856H were the first ever run in such a deposit on the deep seafloor. We positioned the bottom of the drill pipe at 20 mbsf to gain the longest possible interval for logging in this relatively shallow hole. Four deployments of tools or tool strings were used in the logging program for Hole 856H (see Table 38).

# **Temperature Measurements**

Four temperature profiles were measured in Hole 856H at different times after coring was completed (Fig. 111 and Table 39). During run 1 with the pressure/temperature/flow (PTF) tool, three passes were made at intervals of about 2 hr to log temperatures in the zone from about 30 to 80 mbsf. The fourth profile was measured about 10 hr later during run 2 with the LDGO/TLT temperature tool, which was included in the first Schlumberger logging string. There is a relatively large uncertainty ( $\pm 4$  m) in the sub-bottom depths of the

Table	28.	Compressional	wave	velocity	(HFV),
Hole 8	56B	I.			

Table 28	(continued).
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Core, section, interval (cm)	Depth (mbsf)	Direction (a, b, c)	HFV velocity (m/s)
39-856B-			
3H-3 126-128	15 56	c	1582
3H-4, 37-39	16.17	c	1620
3H-4, 93-95	16.73	с	1532
4H-2, 70-72	23.00	с	1629
4H-4, 30-32	25.60	с	1522
4H-4, 102-104	26.32	с	1597
4H-5, 106–108	27.86	с	1544
4H-6, 49–51	28.79	с	1507
4H-6, 124-126	29.54	с	1527
SH-1, 100-108	31.30	c	1543
54-2, 44-40	32.24	c	1540
5H-4 104-106	35.55	c	1633
5H-5 89-91	37.19	c	1582
5H-6, 77-79	38.57	c	1747
5H-7, 38-40	39.68	c	1759
6H-1, 76-78	40.56	c	1596
6H-1, 117-119	40.97	c	1611
6H-3, 14-16	42.94	c	1671
6H-3, 104-106	43.84	с	1547
6H-4, 14-16	44.44	с	1547
6H-4, 114-116	45.44	с	1539
6H-5, 16-18	45.96	с	1826
6H-5, 87-89	46.67	С	1880
6H-6, 10–12	47.40	c	1594
6H-6, 84-86	48.14	с	1517
6H-7, 27-29	49.07	с	1726
7H-1, 79-81 7H 2, 67, 60	51.47	c	1555
7H-2, 07-09	54.67	c	1740
7H-5 45-47	55 75	c	1667
7H-6 34-36	57.14	c	1648
8H-1, 48-50	59.19	c	1567
8H-1, 88-90	59.53	с	1552
8H-2, 87-89	60.75	с	1605
8H-3, 59-61	61.76	с	1540
8H-3, 103-105	62.12	с	1529
9X-1, 84-86	63.14	с	1744
9X-1, 110-112	63.40	c	1741
9X-2, 8-11	63.88	с	1893
9X-2, 134-136	65.14	с	1860
12X-2, 48-50	83.58	с	2613
12X-2, 33-33	83.03	c	2339
12X-2, 70-72	84.05	c	2505
12X-2, 33-37	84.42	c	2052
12X-3 13-15	84.73	c	2056
12X-3, 59-61	85.19	c	1926
12X-4, 59-61	86.69	c	2044
12X-4, 113-115	87.23	с	2084
12X-5, 9-11	87.69	с	1974
12X-5, 20-22	87.80	с	2087
12X-5, 100-102	88.60	с	2139
13X-1, 36–38	91.46	с	2262
13X-1, 101–103	92.11	С	2130
13X-1, 121-123	92.31	с	1975
13X-2, 8-10	92.68	с	2333
13X-2, 22-24	92.82	c	2307
13X-2, 29-31 13X-2, 40, 42	92.89	c	2229
13X-2, 125-127	93.85	c	2045
13X-3, 57-59	94.67	c	2383
13X-3, 96-98	95.06	c	2325
13X-3, 114-116	95.24	c	2307
13X-4, 10-12	95.70	c	2605
13X-4, 76-78	96.36	c	2558
13X-4, 85-87	96.45	с	2504
13X-CC, 33-35	97.36	С	2534
14X-1, 23-25	101.03	с	2105
14X-1, 86-88	101.66	С	2318
14X-1, 119-121	101.99	с	2191
14X-2, 36–38	102.66	с	2391
14X-2, 59-61	102.89	C	2139

Core, section, interval (cm)	Depth (mbsf)	Direction (a, b, c)	HFV velocity (m/s)
14X-2, 106-108	103.36	с	2448
14X-2, 131-133	103.61	с	2446
14X-3, 28-30	104.08	с	2610
14X-3, 52-54	104.32	с	2362
14X-3, 64-66	104.44	с	2483
14X-3, 78-80	104.58	с	2518
14X-3, 103-105	104.83	с	2264
14X-3, 143-145	105.23	c	2474
14X-4, 51-53	105.81	с	2599
14X-CC, 30-32	106.47	с	2732
15X-1, 46-48	110.86	с	2504
15X-1, 133-135	111.73	с	2892
15X-2, 10-12	112.00	c	2973
15X-2, 24-26	112.14	с	3375
15X-2, 66-68	112.56	с	3907
15X-2, 79-81	112.69	c	2804
15X-3, 25-26	113.65	с	2167
15X-3, 44-46	113.84	с	2250
15X-3, 101-103	114.41	c	1909
15X-3, 111-113	114.51	с	2243
15X-3, 136-138	114.76	с	2938
15X-4, 24-26	115.14	с	2398
15X-4, 63-65	115.53	с	2569
15X-5, 14-16	116.54	с	1961
15X-5, 94-96	117.34	с	3345
15X-CC, 11-13	118.13	с	3362



1 cm

Figure 81. Type 5 sulfide with rare brecciated texture (Sample 139-856G-7R-1, Piece 15).

# Table 29. Thermal conductivity, Hole 856B.

1

		Thermal
Sample (cm)	Depth (mbsf)	conductivity (W/[m·K])
39-856B-		
1H-1, 120	1.20	0.96
2H-1, 50	2.30	1.19
2H-2, 50	3.80	1.24
2H-3, 10	4.90	1.30
2H-3, 60	5.40	1.21
2H-4, 75	7.05	1.45
2H-5, 70	8.50	1.24
2H-6, 90 2H-6, 115	10.20	1.31
2H-7, 45	11.25	1.16
3H-1, 50	11.80	1.21
3H-1, 80	12.10	1.39
3H-2, 65	13.45	1.14
3H-2, 85	13.65	1.31
3H-3, 25	14.55	1.42
3H-4 68	15.30	1.74
3H-5, 50	17.80	1.44
3H-6, 40	19.20	2.05
3H-6, 65	19.45	2.68
3H-6, 80	19.60	1.31
3H-6, 105	19.85	1.30
3H-6, 112	19.92	1.22
3H-7, 40	20.70	1.23
4H-1,00 4H-1,00	21.40	1.30
4H-2, 75	23.05	1.10
4H-2, 120	23.50	1.27
4H-3, 50	24.30	1.13
4H-3, 90	24.70	1.18
4H-4, 70	26.00	1.13
4H-4, 110	26.40	1.40
4H-5, 55 4H-5, 110	27.35	1.13
4H-6, 75	29.05	1.17
4H-7, 40	30.20	1.26
5H-1, 50	30.80	1.09
5H-1,80	31.10	1.77
5H-2, 40	32.20	1.32
5H-2, 55	32.35	1.91
5H-2, 105	32.85	1.50
5H-3, 120	34.10	1.64
5H-4, 70	35.50	1.34
5H-5, 75	37.05	1.25
5H-5, 100	37.30	1.30
5H-6, 75	38.55	1.28
5H-7, 35	39.65	1.59
6H-1, /0	40.50	1.41
6H-3, 70	43.50	1.02
6H-4, 70	45.00	1.61
6H-5,70	46.50	1.23
6H-6, 70	48.00	1.37
6H-7, 40	49.20	1.52
7H-1, 70	50.00	1.17
7H-2, 70	51.50	1.25
7H-3, 70	54.50	1.55
7H-5, 70	56.00	1.36
7H-6, 70	57.50	1.40
7H-7, 35	58.65	1.26
8H-1,48	59.20	1.21
8H-2, 93	60.80	1.32
8H-3, 62	61.78	1.31
9X-1, 75	64.55	1.29
10H-1, 68	71.48	1.75
10H-2, 30	72.60	1.79
11X-1, 75	74.05	1.37
11X-2, 75	75.55	1.44
11X-3, 75	77.05	1.37
11X-4, 75	78.55	1.55
11A-5, 80	80.10	1.51

Table 29 (continued).

Sample (cm)	Depth (mbsf)	Thermal conductivity (W/[m·K])	
12X-1, 75	82.35	1.75	
12X-2, 75	83.85	1.81	
12X-3, 75	85.35	1.90	
12X-4, 115	87.25	1.22	
12X-5, 75	88.35	1.79	
13X-1, 75	91.85	1.55	
13X-2, 80	93.40	1.41	
13X-3, 75	94.85	1.25	
13X-4, 65	96.25	2.01	
14X-1, 70	101.50	1.28	
14X-2, 68	102.98	1.64	
14X-3, 84	104.64	1.88	
14X-4, 49	105.79	2.11	
15X-1,85	111.25	1.88	
15X-2, 83	112.73	2.84	
15X-3, 85	114.25	1.25	
15X-4,68	115.58	2.17	
15X-5, 75	117.15	2.63	

Note: All measurements were made in fullspace configuration.

temperature logs, since they are based on wireline counter readings that were not calibrated relative to the drill-pipe depth.

The general features of all four temperature profiles are similar (Fig. 111). The upper 60 m of the hole show an extremely low temperature gradient (~0.06°C/m) that changes very little between lowerings. This gradient is only about 10% of the conductive gradient estimated from nearby seafloor and downhole heat flow measurements (see "Heat Flow" sections, this chapter). Such a large reduction in gradient is characteristic of borehole temperature profiles where there is drilling disturbance and a significant drawdown of water into



Figure 82. Type 5 sulfide with abundant open vugs and poorly developed reticulate boxwork texture near the top of the sample (139-856G-7R-1, Piece 10).



1 cm

Figure 83. Sediment veined and partly replaced by sulfide (type 6). Disseminated sulfide occurs in the unreplaced sediment fragments (white) (Sample 139-856H-4R-1, Piece 12).

the hole after it has been opened by drilling (Hyndman et al., 1976; Becker et al., 1983; Langseth et al., 1984).

The rate of drawdown can be estimated by comparing the temperature profile above 60 mbsf with a theoretical model simulating the thermal effects of drawdown in a borehole (Becker et al., 1983). Figure 112 shows the profile from the last run compared to theoretically predicted profiles for various rates of drawdown. The comparison shows that a rate of drawdown between 20 and 30 m/hr (about 1500 L/hr) is required to depress the gradient to the level observed. There is an abrupt increase in gradient at about 60 mbsf, which we interpret to correspond to the location in the hole where the downflow of water slows greatly or stops. The caliper logs show that this location is near the bottom of a zone of enlarged, irregular hole diameter (Fig. 112B). This zone is probably

Table 30. Therma	l conductivity,	Hole 856C.
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Sample (cm)	Depth (mbsf)	Thermal conductivity (W/[m·K])
139-856C-		
1H-1, 75	0.75	0.64
1H-2, 75	2.25	0.75
1H-3, 75	3.75	0.54
1H-4, 75	5.25	0.79
1H-5, 40	6.40	0.96

Note: All measurements were made in fullspace configuration.



Figure 84. Type 6 sulfide with anastomosing sulfide veins cutting light-colored sediment (Sample 139-856H-4R-1, Piece 4).

more permeable and is therefore the likely place for water to flow into the formation. Below this break the four temperature profiles differ significantly. The maximum temperatures for all profiles are observed in an interval between 72 and 78 mbsf. Between pass 1 and pass 2 the maximum temperature increased from 23° to 28°C, but by pass 3 it had fallen to 21°C. Ten hours later, pass 4 shows that the maximum temperature was only 15°C. We also observed rapid variations of temperature in this zone while holding the probe at one location during passes 1 and 2. In addition, three of the profiles indicate that there is a temperature inversion in the bottom few meters of the hole. The strongest evidence for this inversion comes from pass 4 because the probe depths during pass 4 are based on pressure readings, and the possibility of depth errors due to wireline readings is precluded. The temperature inversion is most likely produced by colder mud and rock that has fallen from higher in the hole. On run 1 the tool may have penetrated fill at the bottom



Core, section, interval (cm)	Depth (mbsf)	Wet-bulk density (g/cm <sup>3</sup> )	Grain density (g/cm <sup>3</sup> )	Wet porosity (%)	Wet water content (%)	Void ratio
139-856G-						
3R-1, 38-40	17.98	4.19	4.53	11.9	2.9	0.14
3R-1, 100-102	18.60	4.20	*	*		*
4R-1, 23-25	27.23	3.86	4.52	17.8	4.7	0.22
4R-1, 122-124	28.22	3.97	*	*	*	*
5R-1, 99-100	37.69	4.77	4.66	01.3	0.3	0.01
6R-1, 139-141	47.69	3.61	4.00	17.6	5.0	0.21
6R-1, 139-141	47.69	3.62	*	*	*	*
6R-4, 5-7	50.75	3.92	*	*	*	*
7R-1, 23-25	56.03	3.51	*	*		*
7R-4, 48-50	60.58	4.30	4.56	14.0	3.3	0.16

Note: \*Paleomagnetism cube samples; dry analyses not made.

of the hole that was nearly 8° colder than water just 3 m above. The observed inversion could be stable for a long time since convective overturn would be inhibited and conductive equalization of temperatures would occur slowly.

## Schlumberger Logs

Summary log figures appear at the end of this chapter. An obstruction 20 m above the bottom of the hole prevented logging deeper than 74 mbsf; nonetheless, these logs provide continuous profiles that help fill in the sampling gaps that were the result of incomplete low recovery from Hole 856H.

### **Resistivity Logs**

A resistivity profile was logged with the dual-induction tool. Useful results were obtained from the spherically focused sensor (SFLU) and the intermediate focused (IMPH) sensor. Measurements with the deep sensing tool (IDHP) show large excursions, which make the results suspect. Figure 113A shows that the IMPH and SFLU sensors recorded unusually low resistivity values of 0.1 to 0.2 ohm-m. Such low values are indicative of the high percentages of the highly

# Table 33. Compressional wave velocity (HFV), Hole 856G.

Core, section, interval (cm)	Depth (mbsf)	Direction (a, b, c)	Average HFV velocity (m/s)
139-856G-			
3R-1, 30-40	17.90	а	4876 (3)
3R-1, 30-40	17.90	b	4691 (3)
3R-1, 30-40	17.90	c	4795 (3)
3R-1, 100-102	18.60	<sup>a</sup> b/c	4921 (2)
4R-1, 23-25	27.23	а	4166 (3)
4R-1, 23-25	27.23	b	4288 (3)
4R-1, 23-25	27.23	с	4105 (3)
4R-1, 122-124	28.22	<sup>a</sup> b/c	4910 (3)
6R-1, 139-141	47.69	а	4718 (3)
6R-1, 139-141	47.69	b	4671 (3)
6R-1, 139-141	47.69	с	4751 (3)
6R-4, 5-7	50.75	<sup>a</sup> b/c	5916 (3)
7R-1, 23-25	56.03	<sup>a</sup> b/c	4873 (3)
7R-4, 40-50	60.50	а	6046 (3)
7R-4, 40-50	60.50	b	5626 (3)
7R-4, 40-50	60.50	с	5892 (3)

<sup>a</sup> Minicore sample.



# 1 cm

Figure 85. Type 6 sulfide with minor veining by sulfide cutting light-colored sediment with disseminated sulfide (Sample 139-856H-4R-1, Piece 11).

### Table 31. Thermal conductivity, Hole 856D.

Sample (cm)	Depth (mbsf)	Thermal conductivity (W/[m·K])
139-856D-		
1H-1, 30	0.30	2.70
1H-1, 60	0.60	2.37
1H-1, 90	0.90	1.58
1H-1, 120	1.20	1.65
1H-2, 30	1.80	1.52
1H-2, 40	1.90	1.73
1H-2, 90	2.40	1.53
1H-2, 120	2.70	1.74
1H-3, 30	3.30	1.35
1H-3, 60	3.60	1.64
1H-3, 90	3.90	1.75
1H-3, 115	4.15	2.07
1H-4, 46	4.96	1.39
1H-4, 100	5.50	1.80
1H-5, 49	6.49	2.06
1H-5, 80	6.80	2.30
1H-7, 15	7.58	2.73
1H-7, 35	7.78	2.25
1H-7, 55	7.98	1.82
1H-7, 70	8.13	1.94

Note: All measurements were made in fullspace configuration.



Figure 86. Photomicrograph of coarse-grained vein of pyrrhotite (medium gray with cleavage), pyrite (white), and sphalerite (darker gray) cutting sediment in type 6 sulfide (Sample 139-856H-4R-1, Piece 9).

Table 34. Thermal	conductivity,	Hole 856G.
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Core, section,	Diago	Depth	Average thermal
intervar (cm)	Fiece	(mosi)	(w/[m·K])
39-856G-			
3R-1, 35-45	6	17.95	6.18 (6)
3R-1, 56-65	8	18.16	4.83(1)
3R-1, 100-112	10	18.60	7.63 (5)
4R-1, 30-37	5	27.30	3.61 (2)
4R-1, 115-120	16	28.15	4.09(2)
5R-1, 53-62	6	37.23	3.68(2)
5R-1, 98-118	14	37.68	5.23 (2)
6R-1, 36-43	7	46.66	5.98 (2)
6R-1, 88-93	15	47.18	2.75 (2)
6R-2, 76-84	13	48.56	6.50(2)
6R-3, 61-67	9	49.91	10.58 (2)
6R-4, 6-10	1	50.76	5.06 (2)
7R-1, 17-26	3	55.97	8.58 (2)
7R-1, 105-115	14	56.85	7.25(2)
7R-1, 121-129	16	57.01	4.63 (2)
7R-2, 31-42	5	57.51	13.93 (2)
7R-2, 94-103	13	58.14	9.98 (2)
7R-2, 138-149	20	58.58	3.02 (2)
7R-3, 93-103	13	59.62	7.58 (2)
7R-3, 114-128	15	59.83	7.00(2)
7R-4, 12-23	2	60.22	12.01 (2)
7R-4, 30-38	4	60.40	15.66 (2)
7R-4, 41-50	5	60.51	7.19 (3)
7R-4, 62-69	7	60.72	7.76(2)

Note: All measurements were made in half-space configuration.

conductive minerals pyrite and pyrrhotite that are observed in the cores (see "Sulfide Petrology" section, this chapter). The profile of resistivity suggests that high abundances of these minerals persist throughout the zone from 40 to 75 mbsf, where reliable logs were obtained. The extremely low values of resistance measured by the SFLU above 48 mbsf and below 70 mbsf are not understood.

## Natural Gamma-ray Logs

The uranium log reveals a zone of elevated activity between 38 and 48 mbsf (Fig. 113B). This zone lies just above the rugose zone in the hole. The number of gamma rays detected depends on the density of the wall rock and the diameter of the hole as well as on the abundance of the naturally occurring radioisotopes of uranium. Some of the variation in the profile between 50 and 60 mbsf appears to be related to variations in hole diameter.

The level of uranium counts is associated directly with the uranium abundance of the adjacent rocks, provided that uranium and its daughter products are in equilibrium. If for some reason one of the members of the decay series is enhanced due to a chemical process such as the precipitation of barite, which is relatively rich in radium, then variations of total counts in this spectrum may not be directly related to the abundance of uranium.

# Gamma-ray Spectrometer Logs

The gamma-ray spectrometer tool (GST) bombards the hole wall with neutrons; atoms capture these neutrons and emit gamma rays



#### Table 35. Index properties, Hole 856H.

Figure 87. A. Distribution of sulfide types with depth in Hole 856G. Because core recovery in this hole averaged 30%, the extent, depth below seafloor, and boundaries between sulfide types are uncertain. Figure 87A was constructed by arbitrarily assuming that the amount of each type of sulfide recovered in each core was proportional to the amount of that sulfide type within the cored interval and proportionally "expanding" the extent of each sulfide type to fill the cored interval. **B.** Distribution of sulfide types with depth in Hole 856H. Because core recovery in this hole averaged 21%, the extent, depth below seafloor, and boundaries between sulfide types are uncertain. Figure 87B was constructed by arbitrarily assuming that the amount of each type of sulfide recovered in each core was proportional to the amount of that sulfide type within the cored interval and proportional to the amount of each type of sulfide recovered in each core was proportional to the amount of that sulfide type within the cored interval and proportional to the amount of that sulfide type to fill the cored interval and proportional to the amount of that sulfide type to fill the cored interval.

15**F** 

16F

17

80

100-

Core, section, interval (cm)	Depth (mbsf)	Wet-bulk density (g/cm <sup>3</sup> )	Grain density (g/cm <sup>3</sup> )	Wet porosity (%)	Wet water content (%)	Void ratio
139-856H-						
3R-1, 15-17	22.25	3.92	4.12	6.9	1.8	0.07
3R-2, 121-123	24.47	4.09	*	*	*	*
3R-3, 61-63	25.32	4.16	*	*	*	*
3R-3, 106-108	25.77	3.74	4.25	16.8	4.6	0.20
4R-1, 13-15	26.73	3.85	*	*	*	*
5R-1, 29-31	32.69	3.91	4.50	19.1	5.0	0.24
5R-1, 46-48	32.86	5.12	44	*	*	*
6R-1, 53-55	37.93	3.68	4.12	27.0	7.5	0.37
9R-1, 58-60	53.08	4.05	4.79	22.2	5.6	0.29
13R-1, 39-41	71.29	3.53	4.07	16.8	4.9	0.20
15R-1, 84-86	81.34	4.05	4.48	14.0	3.5	0.16
16R-1, 67-69	85.87	3.80	4.40	22.8	6.2	0.30

Note: \*Paleomagnetism cube samples; dry analyses not made.

Core, section, interval (cm)	Depth (mbsf)	Direction (a, b, c)	HFV velocity (m/s)
39-856H-			
3R-1, 15-17	22.25	а	4869
3R-1, 15-17	22.25	b	4929
3R-1, 15-17	22.25	с	5071
3R-2, 121-123	24.47	a	4341
3R-2, 121-123	24.47	ь	4449
3R-2, 121-123	24.47	c	4206
3R-3, 61-63	25.32	a	5046
3R-3, 61-63	25.32	ь	4705
3R-3, 61-63	25.32	c	4991
3R-3, 106-108	25.77	а	4351
3R-3, 106-108	25.77	b	4408
3R-3, 106-108	25.77	с	4151
4R-1, 13-15	26.73	a	4148
4R-1, 13-15	26.73	b	3993
4R-1, 13-15	26.73	с	4154
5R-1, 29-31	32.69	a	2996
5R-1, 29-31	32.69	b	2941
5R-1, 29-31	32.69	c	2851
5R-1, 46-48	32.86	a	2657
5R-1, 46-48	32.86	b	2757
5R-1, 46-48	32.86	с	3021
6R-1, 53-55	37.93	a	3383
6R-1, 53-55	37.93	b	3382
6R-1, 53-55	37.93	c	3159
9R-1, 58-60	53.08	a	5191
9R-1, 58-60	53.08	b	4950
9R-1, 58-60	53.08	с	5296
13R-1, 39-41	71.29	a	3357
13R-1, 39-41	71.29	b	3560
13R-1, 39-41	71.29	с	3682
15R-1, 84-86	81.34	a	3351
15R-1, 84-86	81.34	ь	3310
15R-1, 84-86	81.34	с	3386
16R-1, 67-69	85.87	a	3491
16R-1, 67-69	85.87	b	3540
16R-1, 67-69	85.87	c	3420

Table 36. Compressional wave velocity (HFV), Hole 856H.

## within a wide spectrum of energies. These gamma rays are detected by a sodium iodide detector in the GST. The elements Fe, S, Si, H, Cl, Ca, Ti, and Gd are usually abundant enough and/or have large enough capture cross sections to make a measurable contribution to the total spectrum of recorded gamma rays. Onboard processing of GST data calculates the yield of the first six elements listed above. The yields cannot be interpreted directly in terms of abundance, but they may provide an indication of the variation of abundances with depth in the hole.

Of particular interest in Hole 856H are the abundances of sulfur and iron. Figure 113C shows that the yields of these two elements are high throughout the interval from 20 to 62 mbsf. The yields of the elements silicon and calcium are very low, indicating that there is very little hemipelagic or turbiditic sediment interbedded with the massive sulfide deposit drilled in Hole 856H.

### Velocity Logs

The velocity data from the long-spacing sonic tool were of poor quality. One of the receivers in the sonde may not have been operating properly during the entire run. There are only a few sections of the log where the traveltimes look realistic. Additional information about the velocity structure may be salvageable with careful editing at a later date.

## Formation Microscanner

A single pass of the formation microscanner was made between 18.3 and 74 mbsf. The string was run up into the pipe to provide an

Core, section, interval (cm)	Piece	Depth (mbsf)	Average thermal conductivity (W/[m·K])
139-856H-			
3R-1, 28-34	2	22.38	3.77 (2)
3R-1, 102-116	12	23.12	6.61 (2)
3R-1, 60-70	6	22.70	6.36 (2)
3R-2, 36-44	1	23.61	5.29 (2)
3R-2, 60-76	1	23.86	5.16(2)
3R-2, 136-144	4	24.62	6.15 (2)
3R-3, 15-32	3	24.86	4.26 (2)
3R-3, 43-49	4	25.14	3.81 (2)
3R-3, 91-98	9	25.62	4.05 (2)
4R-1, 10-16	3	26.70	3.76 (2)
4R-1, 17-27	4	26.77	3.13 (2)
4R-1, 48-56	7	27.08	5.52 (2)
4R-1, 79-86	11	27.39	1.65 (2)
4R-1, 96-106	13	27.56	4.90 (2)
4R-1, 127-139	16	27.87	2.97 (2)
4R-2, 5-14	2	28.15	4.18 (2)
4R-2, 27-36	5	28.37	9.45(1)
4R-2, 103-111	17	29.13	4.98 (2)
5R-1, 24-31	5	32.64	1.85(2)
6R-1, 12-19	3	37.52	1.98 (2)
8R-1, 115-128	18	49.15	7.65 (2)
9R-1, 56-65	8	53.06	6.29 (2)
10R-1, 21-28	4	57.21	6.44 (2)
10R-1, 50-59	8	57.50	8.44 (2)
11R-1, 90-97	16	62.20	6.41 (2)
11R-1, 114-125	19	62.44	4.20(2)
13R-1, 30-42	5	71.20	4.64 (2)
14R-1, 11-18	3	75.81	1.74 (2)
14R-1, 79-89	13	76.49	1.98 (2)
15R-1, 14-23	3	80.64	2.24 (2)
15R-1, 80-87	12	81.30	2.15 (2)
15R-1, 118-123	19	81.68	2.90(2)



Figure 89. Magnetite vs. pyrite content estimated from examination of polished thin sections of representative samples of the different sulfide types. Type 1 "primitive" sulfide has only minor amounts of pyrite and magnetite. Formation of pyrite during replacement of pyrrhotite in type 1 sulfide forms types 2, 3, and 4 sulfide, and appears to be coupled to magnetite formation. Pyrite formation in type 5 sulfide proceeds without magnetite precipitation.



Logging run no.	Begin/End Date (July), Time (PST <sup>a</sup> )	String	Tools <sup>b</sup>	Interval logged (mbsf)
1 (3 passes)	25, 1230 25, 1800	Wireline high- temperature tool	JAPEX/GSC PFT tool	30-80
2	25, 2230 26, 0430	Seismic- stratigraphic	LSS/DIT/ NGT/TLT	30–74
3	26, 0620 26, 0900	Geochemical	GST/NGT	4–72
4	26, 0935 26, 1210	Formation microscanner	FMS/NGT/GPIT	18–75

<sup>a</sup> Pacific Standard Time

<sup>b</sup> Tool acronyms are listed in the "Downhole Logging" section, "Explanatory Notes" chapter (this volume).

"in pipe" signal so that the logging tool depths could be accurately referenced to the drill-pipe depths. The images processed on the ship are coherent and clear in zones where the borehole is smooth and the diameter close to bit size. In rugose sections of the hole there are frequent skids and twists of the pads on the FMS tool and the quality of the image is poor. Many of these defects in the image can be removed with further processing. The FMS images are presented on microfiche in the back of this volume.

The images show a considerable variation in resistivity of the hole walls (shades of gray on the FMS display). A summary of the obvious features in the image produced onboard ship are listed in Table 40. Overall, the resistivity image has a mottled, unorganized character at the scale of tens of centimeters. Only a few features, such as contacts between rock units or fractures that are intersected by the borehole, can be followed across all four swaths. In some zones there are numerous small black patches that are probably vugs similar to those found in some of the cores. Other zones show clear, subhorizontal light bands in a darker background.

### Summary

Logging in Hole 856H has contributed significantly to our effort to define the geometry and properties of a massive sulfide body. The geochemical and resistivity profiles show that the body is composed almost entirely of iron sulfide and has virtually no interbedded sediment within the section that was drilled. The strong drawdown of water into Hole 856H inferred from the temperature profiles indicates that the massive sulfide body is quite permeable and porous, particularly in a zone that lies between 45 and 60 mbsf. The formation microscanner revealed some zones with numerous vugs and other zones with clear subhorizontal banding.

#### Table 39. Schedule of drilling and temperature logging in Hole 856H.

Date (July)	Time <sup>a</sup> (PST)	Time after circulation stopped (min)	Activity	Instrument
23	1745		Begin drilling Hole 856H	-
24	1200		Hole drilled to 50 mbsf	_
25	0430	1	Pipe stuck at 93.8 mbsf	
25	0630	0	Pipe freed and raised to 20 mbsf	
25	1230	360	Temperature pass #1	GSC/TPF tool
25	1430	480	Temperature pass #2	GSC/TPF tool
25	1630	600	Temperature pass #3	GSC/TPF tool
26	0230	1200	Temperature pass #4	LDGO/TLT tool

Note: Tool acronyms are listed in the "Downhole Measurements" section, "Explanatory Notes" chapter (this volume). <sup>a</sup>Start of temperature recording.

cm

Figure 90. Photograph of contact between the sediment and the upper margin of sill, Section 139-856A-13X-CC, 0–20 cm. Small fragments of fresh glass embedded in the sediment form a halo around the upper pieces.

## HEAT FLOW

As noted in the "Background and Objectives" and "Site Geophysics" sections (this chapter), Site 856 encompasses an area of strong lateral gradients in surface heat flow, ranging from background values of about 0.5 W/m<sup>2</sup> to nearly 5 W/m<sup>2</sup> just south of where Holes 856C



Figure 91. Photomicrograph of dark red euhedral spinel, equant olivine, and tabular plagioclase phenocrysts, characteristic of the sill (Sample 139-856A-14X-1, Piece 4, 56-61 cm). 10x. Transmitted plane light.

# Table 40. Summary of features in Hole 856H discenible in the formation micrscanner image.

Depth interval (mbsf)	Record	Image	Scale	Special
(inclusion)	quanty	enaracteristics	(cm)	reatures
18.3-20.0	Poor			In pipe
20.0-20.8	Poor	Twists, skids		
20.8-34.4	Good	Dark background with light horizontal bands	1 to 5	No vugs or fractures
34.4-41.3	Good	Medium gray with lighter veins	1 to 3	Vugs and veins
41.3-49.4	Good	Dark gray with sub- horizontal bands	1 to 10	Few vugs, no fractures
49.4-61.4	Poor	Nearly featureless in the rugose part of the hole		Enlarged hole
61.4-68.3	Good	Medium gray, mottled	10 to 100	Small vugs at 62 mbsf
68.3-74.4	Good	Dark gray, relatively uniform in tone	100 to 200	Small vugs at 71 mbsf

through 856H were drilled. Drilling operations and formation conditions allowed sediment temperatures to be measured only at the first two holes drilled at the site, 856A and 856B. In addition, four logs of borehole temperatures were made in Hole 856H; these results are discussed in "Downhole Logging" section (this chapter). Table 41 summarizes the results of the 10 stations taken to measure sediment temperatures in Holes 856A and 856B. These measurements included three deployments of the WSTP as well as the first deployments of the long-awaited new temperature tool for the APC cutting shoe, which performed flawlessly during all seven runs!

The temperature records for the seven successful deployments of the APC tool and two successful runs with the WSTP are shown in Figures 114 and 115. The WSTP lowering after Core 139-856B-9X yielded a measured temperature less than that measured 13 m shallower during collection of Core 139-856B-7H, and cannot be a reliable result despite the otherwise well-behaved nature of the temperature-time record. To estimate *in-situ* temperatures, the APC temperature data were fit to the theoretical decay function of Horai and Von Herzen (1985), and the WSTP temperatures were fit to the theoretical decay function decay function of Bullard (1954), using the protocols described in the "*In-situ* Temperatures" section, "Explanatory Notes"



Figure 92. Photomicrograph of quenched plagioclase and pyroxene in groundmass (Sample 139-856A-14X-1, Piece 4, 56-61 cm). Note fresh black glass matrix. 10×. Transmitted polarized light.

Core <sup>a</sup>	Depth (mbsf)	Tool	Data quality	Temperature (° C)	Comments
139-856A-					
3H	21.7	APC	Excellent	$13.0 \pm 0.2$	
5H	40.7	APC		$21.8 \pm 0.2$	
7H	59.7	APC		$31.1 \pm 0.2$	
9H	78.7	APC		$40.8 \pm 0.2$	105-klb pullout
11 <b>X</b>	96.8	WSTP	Very good	$50.1\pm~0.3$	No data recorded before penetration
139-856B-					
3H	20.8	APC	Excellent	$22.9 \pm 0.2$	
4H	31.4	WSTP	None	—	Clock chip fell out of socket
5H	39.8	APC	Excellent	$59.4 \pm 0.2$	
7H	58.8	APC		$73.3 \pm 0.2$	
9X	71.9	WSTP	Very good	$(70.3 \pm 0.5)$	Low temperature measured in fill?

Table 41. Summary of operations and results of the sediment temperature measurements during coring in Holes 856A and 856B.

<sup>a</sup>APC measurements made during specified core at bottom of cored interval; WSTP measurement made after specified core at depth of 1.1 m beyond core depth.



Figure 93. Photomicrograph of olivine phenocrysts with groundmass minerals filling intergranular boundaries (Sample 139-856A-14X-1, Piece 4, 56–61 cm). 10×. A. Transmitted plane light. B. Transmitted polarized light. Complete extinction of olivine shows that this is a single grain.

chapter (this volume). Figures 116, 117, and 118 demonstrate that the data closely fit the theoretical curves calculated for an average thermal conductivity value of 1.2 W/(m-K) ("Physical Properties" section, this chapter).

Estimated *in-situ* temperatures vs. depth and integrated thermal resistance for both Holes 856A and 856B are shown in Figure 119. At both holes, the increase of sample thermal conductivities with depth in the core could be approximated by linear regression ("Physical Properties" section, this chapter). Accordingly, thermal resistances (Bullard, 1939) were calculated using the analytical solution for thermal conductivity increasing linearly with depth (Becker and Von Herzen, 1983). In a purely conductive system, a plot of temperature vs. thermal resistance will be linear, with the heat flow given by the slope of the plot.

The five measurements in Hole 856A form an exceptionally linear profile vs. depth, with an estimated gradient of 0.50° C/m. When plotted against thermal resistance, these measurements suggest a systematic but only slightly nonlinear variation about a purely conductive heat transfer of about 650 mW/m<sup>2</sup>. Assessing whether the slight nonlinearity in this profile is significant in terms of fluid flow will require a careful correction of the laboratory measurements of

thermal conductivity to *in-situ* conditions and further refinement of the thermal resistance calculation.

In contrast to the nearly linear profile in Hole 856A, downhole temperatures only 200 m away in Hole 856B show a large and irregular variation about a best-fit gradient and provide no conclusive evidence for the mode of heat transfer at this location. The symbols shown in Figure 119 are significantly larger than the possible errors associated with either depth determinations or temperature extrapolations. Thus, the nonlinearity of the thermal gradient in Hole 856B is significant and cannot be attributed to experimental errors.

A number of factors may have contributed to the contrast in sediment temperatures in Holes 856A and 856B, which are only 200 m apart. Hole 856A is located on top of a hill and farther away from any thermal anomalies. Hole 856B lies at the perimeter of this hill, which may be fault-bounded, and is very close (<100 m) to the massive sulfide body cored in Holes 856D–856H. The irregular gradient in Hole 856B can probably be attributed to some combination of (1) fluid flow associated with the sulfide body and/or the possible fault bounding the hill, (2) effects of the possible loss of the upper ~20 m of the section by slumping (see "Lithostratigraphy and Sedimentology" and "Paleomagnetism" sections, this chapter), and



Figure 93 (continued).

(3) the extreme variations in thermal conductivity associated with the sulfide body (see "Physical Properties" section, this chapter).

# SUMMARY AND CONCLUSIONS

Site 856 is located in the eastern part of Middle Valley, about 3 km west of Site 855 and the eastern boundary fault of the rift valley, and about 4 km east of the main structural boundary of the present rift axis. The underlying crust there could be as old as 320,000 yr (see Davis and Villinger, this volume). The site is situated on a small hill and a nearby outcropping ridge of massive sulfide just to the south. Farther south still, 600 m from the hill and 300 m from the sulfide outcrop, is an active hydrothermal field that is venting clear water at 264°C from a small mound of sulfide rubble. The hill at Site 856 is circular in plan view, about 500 m in diameter, has a flat, smooth top, and is about 60 m high. It is typical of other hills in Middle Valley and in similar sedimented rifts elsewhere, including Guaymas Basin and Escanaba Trough. Such hills are believed to form by uplift of the sediment section above sub- or intrasedimentary igneous intrusions, and often are spatially associated with hydrothermal mineralization.

Hole 856A was drilled on the summit of the hill. Hole 856B was drilled 190 m to the south, on the flank of the hill, at a location 20 m deeper than the summit. Both holes penetrated turbidite sediment that

has been variously hydrothermally altered, followed by basaltic rock at depths of 112 and 121 mbsf, respectively. This basaltic rock probably comes from the top of thick sills. Hole 856B also intersected a sill less than 6 m thick at 64 mbsf, and a zone of clastic sulfide sediment at 18 to 24 mbsf. Holes 856C through 856G were drilled on a 60-m-long north-south transect across the sulfide outcrop, which forms a low ridge that strikes east-west and is about 20 m high at its highest point, 160 m south of Hole 856B. Holes 856C through 856F penetrated only 2–24 mbsf and recovered mainly unconsolidated sulfide sediment ranging in size from clay to gravel. Holes 856G and 856H were drilled no more than 20 m apart and penetrated 65 and 94 mbsf, respectively, into a dense, lithified massive sulfide deposit. Deteriorating drilling conditions prevented us from penetrating all the way through the deposit in either hole, so that we were unable to determine its thickness or the nature of the underlying material.

Chilled contacts with rinds of baked sediment indicate that the basaltic rocks recovered from Holes 856A and 856B are intrusive. Diabase and microgabbro form the interior parts of the thicker sills. These rocks contain phenocrysts of plagioclase, olivine, and deep-red, euhedral spinel. Vesicles are rare. Most of the rocks are incipiently metamorphosed, although the groundmass is fresh and penetrative alteration is minor. Olivine is commonly replaced by talc, chlorite, and smectite. Glassy margins and mesostasis are altered to magnesian



Figure 94. Photomicrograph of a talc-magnetite pseudomorph after olivine. Note associated spinel. The olivine is 6 mm wide (Sample 856A-14X-1, Piece 5, 84–86 cm). 10×. Transmitted polarized light.

chlorite, iron sulfide minerals, and pale epidote. Fractures are filled with chlorite, pyrite, and pyrrhotite.

Chemically these are the most primitive mafic rocks ever recovered from the Juan de Fuca Ridge. They are low-K tholeiites and have moderately high  $Al_2O_3$ , high MgO, low TiO<sub>2</sub>, and very high Cr and Ni. They also are picritic, and may represent a parental magma to MORB; they have an average of 9.4 wt% olivine in the norm compared with 1.5% for basalt from Site 855. Their average plagioclase composition is  $An_{70}$ . Their chemical variation cannot be explained by fractional crystallization, either *in situ* or in a shallow-level magma chamber, but reflects instead variable melting at a pressure of about 5 to 6 kbar. The magma which formed these basalts is interpreted to have come directly from the mantle. This is significant because if this magma did not reside in a shallow-level magma chamber, it could not have provided an underlying local heat source for the hydrothermal system that deposited the massive sulfide at Site 856, or the hydrothermal system that is still active a few hundred meters to the south.

Sediment at Site 856 is divided into five lithostratigraphic units. Unit I, hemipelagic silty clay, is Holocene in age and was probably deposited during the last high stand of sea level. It is present only in Hole 856A at the summit of the hill. Unit II is alternating hemipelagic and turbiditic sediment and is subdivided into four subunits, three of which (Units IIA, C, and D) are distinguished by degree of hydrothermal alteration and mineralization. Unit III consists of surficial oxidized sediment overlying a breccia of massive sulfide. Unit IV is surficial sulfide sand and Unit V is lithified massive sulfide.

The fourth subunit of Unit II, Unit IIB, is found only between 12 and 28 mbsf in Hole 856B. It represents either a slump deposit or a tilted block and consists of interbedded turbidites and clastic sulfide debris, with irregular to inclined contacts that dip from 20° to 30°. The sulfide debris must have been shed from a local source, probably the sulfide mound just south of the hill. The present position of this subunit, buried under the flank of the hill, indicates that at least part of the large massive sulfide deposit south of the hill was already present before the hill was uplifted. The turbidite that overlies clastic sulfide both within and above this subunit, and the turbidites at the top of the hill itself, must have been deposited before uplift of the hill. The beds of the subunit may, in fact, have become tilted in the same event that formed the hill. It is unlikely, therefore, that the thick massive sulfide deposit penetrated in Holes 856G and 856H is genetically related to the magmatism and local deformation that created the hill into which Holes 856A and 856B were drilled.

Sediment alteration varies from weak in Unit IIA, to moderately altered and indurated in Unit IIC, to well indurated in Unit IID. Unit



Figure 95. Photomicrograph of pale chlorite, epidote, and actinolite replacement of mesostasis (Sample 139-856A-14X-CC, Piece 10, 71–73 cm). A. Transmitted plane light. B. Transmitted polarized light.

IIA extends to 86 mbsf in Hole 856A and to 40 mbsf in Hole 856B, and is characterized by decreasing preservation of calcareous fossils and hornblende with depth, general lack of cementation, and, in Hole 856A only, formation of diagenetic carbonate concretions that contain disseminated pyrite and often form in association with authigenic Mg-rich smectite. Unit IIC extends to the bottom of Hole 856A and from 40 to 62 mbsf in Hole 856B, that is, for about 25 m above the uppermost sills in both holes. Alteration in this subunit probably resulted from intrusion of the sills. It includes complete dissolution of carbonate, induration that preserved plastic deformation structures, precipitation of anhydrite now evident largely as molds, brittle fracturing and brecciation, and partial replacement of magnetite by pyrite. Unit IID occupies the lowermost 50 mbsf in Hole 856B. This subunit is well indurated and has been silicified, chloritized, brecciated, and fractured. It contains abundant sulfide minerals, including pyrite, sphalerite, chalcopyrite, and pyrrhotite, as fracture and burrow fills, laminations, and disseminated crystals. Barite and anhydrite are also found, along with molds of anhydrite that has redissolved. Coincident with the general increase in alteration with depth in both holes are changes in bulk sediment composition resulting from metasomatism: magnesium and manganese generally increase with depth, while potassium, calcium, strontium, barium, and inorganic and organic carbon generally decrease.

The massive sulfide deposit at Site 856 is at least 60 m wide (Holes 856C through 856F) and 95 m thick (Holes 856G and 856H). This deposit yielded six types of massive sulfide based on mineralogy and texture: (1) homogeneous, massive, fine-grained pyrrhotite, with <10%-30% pyrite and ubiquitous chalcopyrite and sphalerite (0.9% Cu, 0.9% Zn); (2) homogeneous, massive, fine-grained pyritepyrrhotite, with minor chalcopyrite and sphalerite (0.6% Cu, 0.2% Zn); (3) homogeneous, massive, medium- to coarse-grained pyrite-pyrrhotite, with very minor chalcopyrite and sphalerite (generally <0.2% Cu, Zn); (4) heterogeneous, veined, coarse-grained pyritepyrrhotite with major chalcopyrite and sphalerite (0.5% Cu, 2.3% Zn); (5) colloform and vuggy pyrite, with minor chalcopyrite and sphalerite (0.4% Cu, 0.3% Zn); and (6) sediment with sulfide veining. The relatively primitive type 1 sulfide, which is the typical sulfide deposited by rapidly cooled hydrothermal solutions in Middle Valley, is believed to evolve into the more mature types 4 and 5 by progressive dissolution, replacement, and reprecipitation of sulfide minerals within the deposit. Other minerals present include magnetite, hematite, green smectite, chlorite, amorphous silica, carbonate, and barite.



Figure 95 (continued).

All of the observations made aboard ship, ranging from petrography on polished thin sections to logging of Hole 856H, indicate that the massive sulfide deposit does not contain a significant amount of hemipelagic or turbiditic sediment. The deposit apparently formed by precipitation near and above the seafloor rather than by infiltration and replacement of detrital sediment. While it was forming it probably stood tens of meters higher than the surrounding seafloor. The lack of sedimentary interbeds suggests that it formed rapidly and without significant interruption.

Foraminifers and nannofossils were originally rare in the coarse fraction of the turbidites at Site 856, and hydrothermal alteration has reduced their abundance even further. More than half of all samples examined were found to be barren. Fossiliferous intervals in Holes 856A and 856B were dated mostly as late Pleistocene. Holocene-age sediment was recognized only in the tops of Holes 856A and 856E; in the latter case it lies unconformably atop massive sulfide, and it is unlikely that the Holocene-Pleistocene boundary is present. The topmost sediment from Holes 856B and 856C contains a glacial Pleistocene fauna, while Holes 856D, 856H, and probably 856F and 856G are barren. The depth at which carbonate fossils become rare to absent is 30 to 40 mbsf shallower in Hole 856B than in Hole 856A; this may be due to erosional loss of the uppermost 20 m of sediment at the location of Hole 856B as well as to differential alteration at the two sites.

Paleomagnetic measurements indicate that all sediment at Site 856 was deposited during the Brunhes Chron. Natural remanent magnetic intensity and volume magnetic susceptibility of the sediment are high and variable, and probably reflect the variable magnetic content of the turbidite and hemipelagic components of the sediment. Both magnetic intensity and susceptibility decrease with depth in both holes, especially in Hole 856B, where the sediment is more hydro-thermally altered. Susceptibility is both lower and more stable below than above 34 mbsf in Hole 856B, probably as a result of hydrothermal alteration of magnetite.

There are intervals of uniformly low magnetic intensity and susceptibility between 32 and 40 mbsf in Hole 856A and between 11 and 19 mbsf in Hole 856B. These intervals may contain a higher component of biogenic sediment than the turbidites above and below it, or their magnetite may have been altered to pyrite. Such intervals may be useful for correlating between holes in Middle Valley. The offset in depth to the layers in Holes 856A and 856B suggests that the upper 21 m of sediment is missing in Hole 856B. This conclusion is consistent with the absence of Holocene sediment in Hole 856B and with its position on the eroded flank of the hill.

**SITE 856** 



Figure 96. A. Plot of Ti-Zr-Y. Note that samples from Site 856 lie at the margin of the ocean-floor tholeiite compositions, in field B. Low-potassium tholeiite is in fields A and B, continental basalt in field D, and calc-alkali basalt in fields C and B. Field boundaries from Pearce and Cann (1973). B. Plot of Ti-Zr-Sr. Ocean-floor tholeiite compositions lie in field C, low-potassium tholeiite in field A, and calc-alkali compositions in field B. Field boundaries from Pearce and Cann (1973).

Profiles of sediment pore-water composition vs. depth in Holes 856A and 856B show the effects of hydrothermal processes. The chlorinity profile lacks the maximum seen at Site 855 that is caused by downward diffusion of more saline Pleistocene bottom seawater. This indicates that pore water has flowed vertically through the sediment column sometime in the past 20,000 yr, erasing the diffusive signal. Reaction with biogenic and igneous components in the sediment and basalt has caused increases in dissolved silica and calcium and decreases in sodium and potassium. Magnesium is little changed. Within the upper 20 mbsf, sulfate decreases and alkalinity, ammonium, and phosphate increase due to bacterial degradation of organic matter. At greater depths, however, and especially as the sills are approached, sulfate increases to concentrations about 10% higher than that in bottom seawater, apparently as a result of dissolution of anhydrite. This anhydrite precipitated within the sediment during an earlier episode of heating, probably associated with intrusion of the sills, and is now dissolving, leaving behind molds in the thermally indurated sediment. Intrusion of the sill at 64 mbsf in Hole 856B has produced elevated concentrations of sulfate, calcium, silica, and ammonium from about 36 to 64 mbsf, which, along with the sill, are absent in Hole 856A only 190 m away. A minimum in dissolved sulfate at 78 mbsf in Hole 856B, between the two sills in this hole, and sharp gradients in ammonium in both holes, suggest that these profiles are not at steady state. If this is correct, then the steepness of the gradients indicates that the elevated concentrations were first produced about 4000 yr ago, presumably by intrusion of the sill at 64 mbsf. This chronology is consistent with uplift of the hill sometime in the Holocene, as suggested by the lithostratigraphy and biostratigraphy.

The organic geochemistry at Site 856 is similar to that at Site 855. Methane concentrations are low and neither higher hydrocarbons nor hydrogen sulfide were detected. Concentrations of extractable organic matter are extremely low, but some thermally mature and overmature bitumen is present. Pristane and phytane are the major isoprenoid alkanes. Thermal maturation is evident in the carbon preference index, the isoprenoid to normal hydrocarbon ratio, and the pristane to phytane ratio, all of which decrease with depth in Holes 856A and 856B and are already low in the surficial sediment in Holes 856C, 856D, and 856E. All of these sediments have appar-

ently been heated to temperatures greater than 50°C, which is the beginning of the oil thermal window, at some time in their history. We do not believe, however, that the hydrocarbons at this site have migrated to any significant extent, because the sediment is not rich enough in the appropriate type of organic matter to undergo primary oil expulsion. The total organic carbon content is only 0.2 to 0.6 wt%.

Physical properties in the sediment at Site 856 correlate well with each other. They reflect both variations within individual turbidites, and the overall increase in compaction and lithification with depth that resulted from hydrothermal alteration. Velocity and thermal conductivity increase with depth, while wet-bulk density, porosity, and water content decrease. Grain density and thermal conductivity remain relatively constant. Cores of massive sulfide have extremely high and variable thermal conductivity that correlates positively with velocity. They also have a very high grain density of about 4.5 g/cm<sup>3</sup>.

Wireline logs were run for the first time in a seafloor sulfide deposit in Hole 856H. Repeated temperature logs revealed a suppressed thermal gradient through the upper 60 m of the hole, with a measured maximum of only 3°C, indicating flow down the borehole and into the surrounding rock. The maximum bottom-hole temperature measured was 28°C. Simple analytical models suggest that seawater is flowing down the hole at about 20-30 m/hr. Such strong flow requires that the formation be underpressured relative to the cold column of water in the borehole and that there be significant permeability. Resistivity, natural gamma-ray, and geochemical logs suggest that there is little or no sediment interlayered within the massive sulfide; this interpretation is consistent with recovered core, which was sediment-free, and with chemical analyses of the sulfide, which suggests that the fluids that formed the deposit had minimal interaction with sediment. A formation microscanner log confirmed the presence of numerous filled and open fractures in the rock.

Measurements of sediment temperature in Holes 856A and 856B revealed thermal gradients of about  $0.50^{\circ}$  and  $1.27^{\circ}$ C/m, respectively, implying present-day temperatures of about  $60^{\circ}$  and  $157^{\circ}$ C at the maximum depths of these two holes. When combined with thermal conductivities measured shipboard, these gradients yield values of heat flow of about 650 mW/m<sup>2</sup> in Hole 856A and 1730 mW/m<sup>2</sup> in Hole 856B. Heat flow is uniform in the upper 70 mbsf in Hole 856A; nonuniform heat flow in the upper 40 mbsf of Hole 856B could reflect



Figure 97. Magnesium number vs. titanium contents of samples for Site 856. Note the lack of distinctive trend, indicating no systematic fractional crystallization history for these samples.



Figure 98. Zr vs. Ti content of samples from Site 856. Note the lack of distinctive curvilinear distribution for samples from Site 856 in contrast to samples from Site 855. Fields A, B, C, and D are as in Figure 96.

recent slumping, fluid flow through the sediments, or strong lateral and vertical contrasts in thermal conductivity in the vicinity of the massive sulfide deposit.

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Figure 99, CaO/Al<sub>2</sub>O<sub>3</sub> vs. Mg number. Field boundaries from Karsten et al. (1990). The compositions of samples from Site 856 form a linear trend that is at a much higher Mg number and somewhat lower CaO/Al<sub>2</sub>O<sub>3</sub> ratio than all Juan de Fuca samples, including those from Site 855.

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Figure 100. Volume magnetic susceptibility vs. depth in Hole 856A. The gaps in the data reflect low core recovery.

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Figure 101. Correlative plots of volume magnetic susceptibility and compressional wave velocity obtained with the PWL vs. depth for Hole 856A. Turbidite boundaries are shown by dotted lines.

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Figure 102. A. Volume magnetic susceptibility vs. depth in Hole 856B. The gaps in the data reflect low core recovery. B. Expanded-scale plot of volume magnetic susceptibility vs. depth in Hole 856B.

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Figure 104. Compressional wave velocity obtained by PWL vs. depth. Thin line = Hole 856A; thick line = Hole 856B. Plotted data are values smoothed over 50 cm, after eliminating highly scattered data. The gaps in the data reflect limited core recovery.

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Figure 105. Compressional wave velocity, index properties, and thermal conductivity vs. depth in Hole 856A. Open diamonds = velocity obtained by DSV; solid diamonds = velocity obtained by HFV; open circles = porosity; and solid circles = water content. Properties from basalt samples are not shown except for thermal conductivity (open square).

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Figure 106. Correlative plot of compressional wave velocity, volume magnetic susceptibility, wet-bulk density, porosity, and thermal conductivity within turbidites at 58–64 mbsf in Hole 856A. Compressional wave velocity measured by PWL (solid line) and HFV (open circles). Volume magnetic susceptibility indicated by solid line and wet-bulk density by open circles. Dotted lines represent the boundaries of turbidites. Note that the two velocity data sets agree well.

NOTE: For all sites drilled, core description forms ("barrel sheets") and core photographs have been printed on coated paper and bound as Section 3, near the back of the book, beginning on page 573. Forms containing smear slide data are bound as Section 4, beginning on page 933. Thin-section data are given in Section 5, beginning on page 949.

Formation microscanner images for this site are presented on microfiche in the back of this book.



Figure 107. Correlation of thermal conductivity with porosity in Holes 856A (solid squares) and 856B (open squares). Dashed lines are the calculated geometric-mean thermal conductivities for two different grain thermal conductivities. The solid line represents a best-fit geometric mean with a calculated best-fitting grain thermal conductivity of 3.64 W/(m·K). The thermal conductivity of seawater was assumed to be 0.6 W/(m·K).



Figure 108. Compressional wave velocity, index properties, and thermal conductivity vs. depth in Hole 856B. Symbols as in Figure 105.



Figure 109. Compressional wave velocity, index properties, and thermal conductivity vs. depth in Holes 856G and 856H. Open symbols are for Hole 856G and solid symbols for Hole 856H. Porosity = circles and water content = squares. All thermal conductivity values repeatedly measured from the same piece are connected by lines.



Figure 110. Porosity vs. depth plot in Holes 856A (solid circles) and 856B (linked open circles).



Figure 111. Temperature profiles recorded in Hole 856H. See Table 38 for details.



Figure 112. A. Data from pass 4 compared with model temperature profiles for drawdown into a borehole. The values of parameters used in the model are as follows: initial geothermal gradient =  $0.5^{\circ}$ C/m, thermal diffusivity = 0.048 cm<sup>2</sup>/s, hole radius = 15 cm. B. Caliper log for reference.



Figure 113. Comparison of different logs of Hole 856H. The column at the far left shows core recovery. **A.** Variation of resistivity with depth. The curve labeled SFLU is recorded by the spherically focused induction tool, which senses the resistivity at shallow depth in the borehole wall. The IMPH curve corresponds to the resistivity at intermediate depth (about 1.8 m). The predominance of iron sulfide in the formation results in very low resistivities. **B.** Contribution of uranium to the total natural gamma spectrum. The data are uncorrected for hole diameter variations. **C.** Downhole variations in the yields of iron and sulfur measured by the gamma-ray spectrometer tool.



Figure 114. Temperature-time records for the four deployments of the APC temperature recorder and the single deployment of the WSTP in Hole 856A.



Figure 115. Temperature-time records for the three deployments of the APC temperature recorder and the single successful deployment of the WSTP tool in Hole 856B.



Figure 116. A–D. Temperatures measured in Hole 856A with the APC tool during Cores 139-856A-3H, -5H, -7H, and -9H, showing the best-fit theoretical decay curves and extrapolated *in-situ* temperatures. E. Temperatures measured in Hole 856A with the WSTP tool after Core 139-856A-11X, showing the best-fit theoretical decay curves and extrapolated *in-situ* temperature. In each case, the solid line shows measured temperatures, circled points are those that were fit to the theoretical decay curves, and the dashed line represents the extrapolated *in-situ* temperature.



Figure 117. A–C. Temperatures measured with the APC tool in Hole 856B during Cores 139-856B-3H, -5H, -7H, respectively, showing the best-fit theoretical decay curves and extrapolated *in-situ* temperatures. **D.** Temperatures measured with the WSTP tool in Hole 856B after recovery of Core 139-856B-9X, showing the best-fit theoretical decay curve and extrapolated *in-situ* temperature. Symbols as in Figure 116.



Figure 118. A. Temperatures measured in Hole 856A vs. the appropriate theoretical function that describes the approach with time of the annular APC cutting shoe or cylindrical WSTP to *in-situ* temperature. The theoretical function is proportional to reciprocal time and therefore, the estimated *in-situ* temperatures are given by the intercepts of the extrapolations of the linear trends of the measured data. **B.** Same for temperatures measured in Hole 856B.



Figure 119. Estimated formation temperatures in Holes 856A and 856B vs. depth (A) and thermal resistance (B). Solid symbols are WSTP measurements; open symbols are APC measurements. The linear gradients shown in (A) and the conductive heat flows shown in (B) were obtained by least squares fit to the data under the constraint that the lines pass through the known bottom-water temperature at the seafloor. The circled point is the unreliable value obtained with the WSTP deep in Hole 856B, which was excluded from the gradient calculation.



Hole 856H: Geochemical Log Summary

## Hole 856H: Resistivity-Natural Gamma Ray Log Summary

