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1. INTRODUCTION: INVESTIGATION OF HYDROTHERMAL CIRCULATION AND GENESIS OF MASSIVE SULFIDE DEPOSITS AT SEDIMENT-COVERED SPREADING CENTERS AT MIDDLE VALLEY AND ESCANABA TROUGH[1]

Shipboard Scientific Party[2]

INTRODUCTION

Leg 169 was the second leg of a planned two-leg program to investigate the geological, geophysical, geochemical, and biological processes at sediment-covered spreading centers in the northeast Pacific Ocean (Fig. 1). The major emphasis of the leg was to investigate the genesis of massive sulfide deposits.

The highly successful drilling completed during Leg 139 (Davis, Mottl, Fisher, et al., 1992) addressed a wide range of problems, but focused primarily on establishing broad-scale constraints on the hydrothermal circulation of seawater through the upper oceanic crust at a sediment-covered spreading center. Leg 139 results confirmed that the uppermost part of the oceanic crust in this regime is composed of interlayered basaltic sills and metasediments. An active hydrothermal upflow zone was safely drilled and cored, and geophysical logs from rock at in situ temperatures near 300°C were successfully recovered. Drilling on the flanks of the ridge established that relatively unaltered seawater is recharging into oceanic basement near one of the rift-bounding normal faults. The presence of an extensive seafloor mineral deposit south of Bent Hill was confirmed by penetrating 94 m of massive sulfide.

SCIENTIFIC OBJECTIVES

The primary objective of Ocean Drilling Program (ODP) Leg 169 was to investigate the genesis of massive sulfide deposits by drilling two deposits with different styles of mineralization; Middle Valley at the northern end of the Juan de Fuca Ridge and Escanaba Trough at the southern end of the Gorda Ridge (Fig. 1A). Three other objectives investigated on the cruise were (1) the tectonics of sedimented rifts and controls on fluid flow, (2) sedimentation history and diagenesis at sedimented rifts, and (3) the extent and importance of microbial activity in these environments. A series of holes was drilled across deposits at both of these sites to determine the sedimentary record of hydrothermal products adjacent to the deposits and to constrain the timing and duration of hydrothermal activity. Alteration and stockwork zones beneath the deposits were drilled to constrain the geochemical reactions that control mineralization and the parameters that controlled the fluid flow.

Both Middle Valley and Escanaba Trough (Fig. 1) are ideal natural laboratories for systematically determining the factors that control the location, size, and composition of massive sulfide deposits. The individual deposits in these two areas are considered to be potentially larger than most ore bodies discovered thus far on bare-rock ridges. Differences in both the maturity and composition of the massive sulfide deposits at the two ridge segments indicate that comparison of samples from the different deposits should provide more information on the processes controlling massive sulfide generation than could be obtained by more extensive drilling of only one of the deposits. For example, the chemical and isotopic compositions of hydrothermal deposits in Escanaba Trough indicate a dominantly sedimentary source for metals, whereas those in Middle Valley appear to be intermediate between basaltic and sedimentary sources (Figs. 2, 3; Goodfellow and Franklin, 1993; Zierenberg et al., 1993).

Middle Valley: Geology of the Hydrothermal Field

Middle Valley forms one branch of a ridge-transform-transform unstable triple junction with the Sovanco Fracture Zone and the Nootka Fault (Fig. 1A; Davis and Villinger, 1992). Middle Valley is a medium-rate spreading center (58 mm/yr), but the proximity to the cold Explorer plate results in a reduced magma supply and a slow-spreading ridge morphology with a deep and wide axial trough. A ridge jump is in progress, and current magmatic activity is mostly confined to the West Valley spreading center. Proximity of the Middle Valley spreading center to an abundant supply of terrigenous sediment during the Pleistocene lowstand of sea level has resulted in burial of the spreading center by 200 to >1000 m of turbiditic and hemipelagic sediment, with sediment thickness increasing to the north. The main areas in Middle Valley drilled during Leg 169 (Fig. 1B) are the Dead Dog Vent Field (DDVF) in the Area of Active Venting (AAV; Sites 858 and 1036) and the Bent Hill area (Sites 856 and 1035; Davis, Mottl, Fisher, et al., 1992).

Dead Dog Vent Field

The principal center of hydrothermal activity in Middle Valley is the DDVF (Fig. 4). Contoured heat-flow values show a concentric high coincident with a side-scan acoustic anomaly that outlines the 800-m-long and 400-m-wide vent field. Seismic profiles across the vent field show it is located ~2 km east of a prominent basement fault (Fig. 5; Rohr and Schmidt, 1994). Sediment thickness over the fault block in the area surrounding the vent field is ~450 m, which overlies a sill-sediment complex that forms the transition to oceanic crust (Davis, Mottl, Fisher, et al., 1992). However, hard acoustic reflectors that occur only immediately beneath the vent field were confirmed by drilling to be the top of a volcanic edifice at only 250 m depth (Fig. 6). The presence of more permeable volcanic basement penetrating up into the sediment cover acts as a conduit to focus flow of hydrothermal fluid to the seafloor (Davis and Fisher, 1994).

The vent field contains at least 20 active vents with exhalative fluid temperatures ranging up to 276°C (Ames et al., 1993). Active vents occur predominantly on top of 5- to 15-m-high, sediment-covered mounds a few tens of meters in diameter. The vent fluids have slightly elevated salinity with respect to normal seawater (Butterfield et al., 1994), and the composition indicates a significant interaction of hydrothermal fluid with sediment. The resultant chimneys are predominantly composed of anhydrite with only minor Mg-rich phyllo-

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[2]Shipboard Scientific Party is given in the list preceding the Table of Contents.

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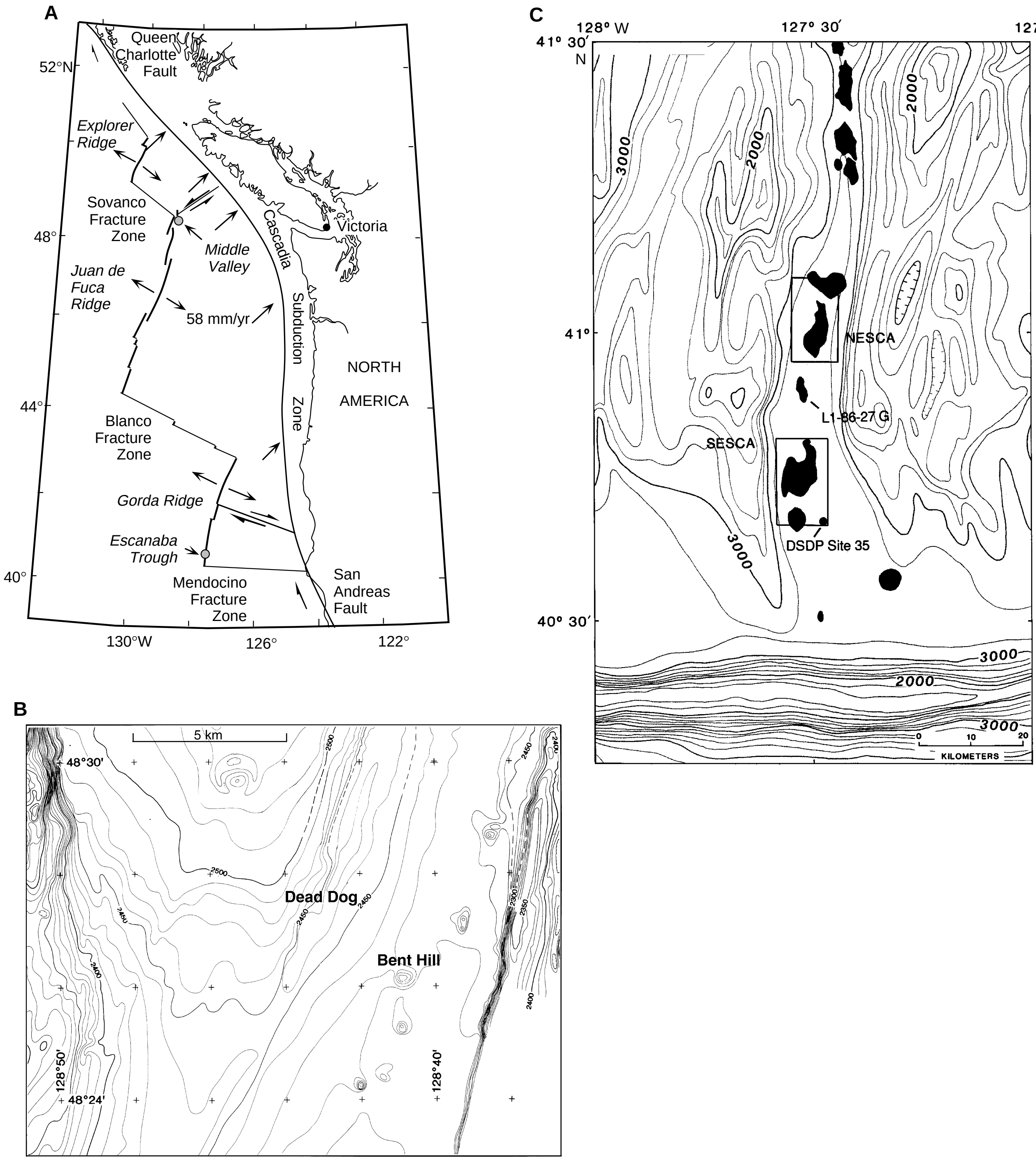

Figure 1. **A.** Location map showing the tectonic setting of the sediment-covered spreading centers at Middle Valley and Escanaba Trough on the Juan de Fuca-Gorda spreading system (modified from Davis, Mottl, Fisher, et al., 1992). **B.** Bathymetry of Middle Valley (Davis and Villinger, 1992) shown as contours drawn at 50-m intervals. Areas of drilling sites are the Dead Dog Vent Field (DDVF) in the Area of Active Venting (AAV) and Bent Hill. West Valley spreading center is just west of Middle Valley (modified from Mottl, Davis, Fisher, and Slack, 1994). **C.** Bathymetry of Escanaba Trough shown as 200-m intervals. Black areas are the igneous centers (modified from Zierenberg and Shanks, 1994).

silicates and sulfide minerals. Available data from piston cores and ODP Hole 858B suggest that subsurface deposition of anhydrite, Mg-rich smectite, and sulfide minerals may contribute to the growth of the mounds (Davis, Mottl, Fisher, et al., 1992; Goodfellow and Peter, 1994). Surface deposition of collapsed chimney debris may also contribute to the growth of the mounds, but prior to Leg 169 drilling, this growth mechanism was thought to be of relatively minor importance. Following the collapse of unstable chimney structures, anhydrite dissolves in cold seawater. The uppermost sediment recovered from Hole 858B appears to have formed in this manner; however, this layer is only a few meters thick and does not account for the bulk of the anhydrite, Mg-smectite, and sulfide that occurs at greater depth with-

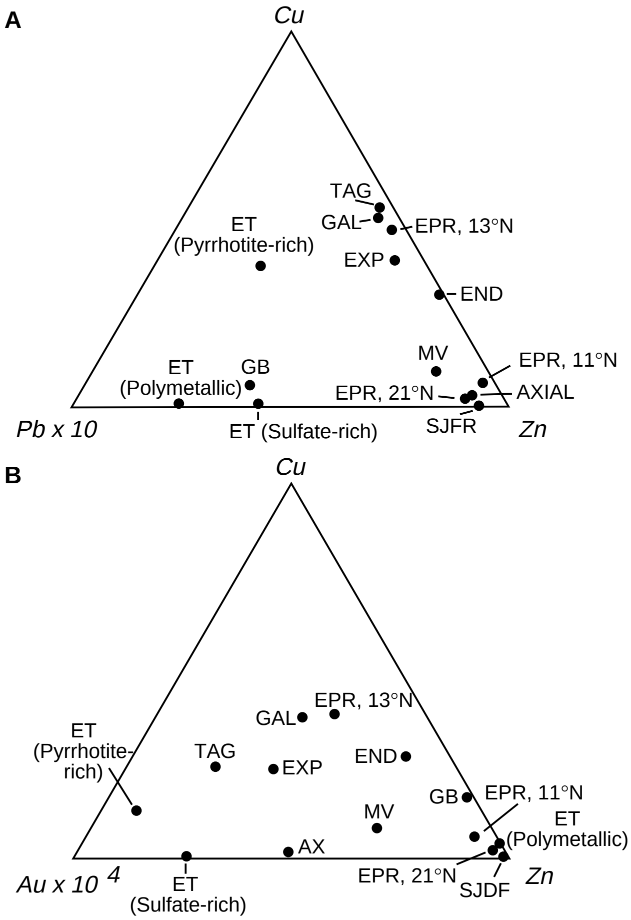

Figure 2. Triangular diagrams illustrating the (**A**) Pb-rich and (**B**) Au-rich nature of the Escanaba Trough (ET) massive sulfides relative to samples from Middle Valley (MV) or bare-rock hydrothermal systems. Other abbreviations used: TAG = Trans-Atlantic Geotraverse site; GAL = Galapagos spreading center; EXP = Explorer segment, Juan de Fuca Ridge; END = Endeavour segment, Juan de Fuca Ridge; AX = axial seamount, Juan de Fuca Ridge; SJDF = southern Juan de Fuca Ridge; GB = Guaymas Basin; EPR = East Pacific Rise. Modified from Koski et al. (1994).

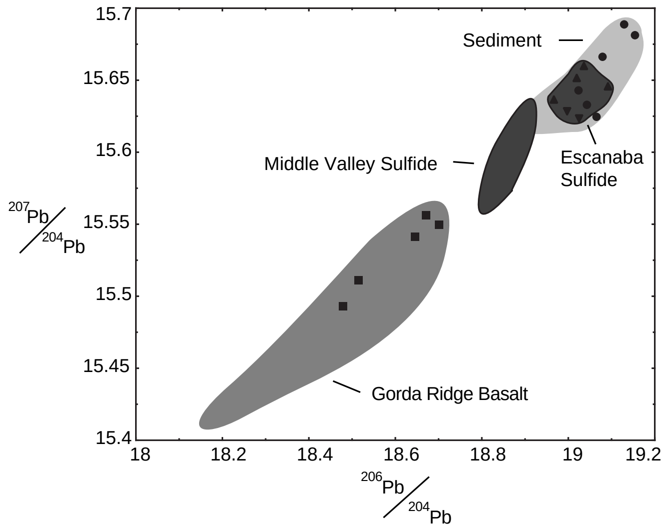

Figure 3. Pb isotope composition of sulfide, sediment, and basalt samples for Escanaba Trough and Middle Valley. Escanaba Trough sulfide composition indicates a large contribution of sediment-derived lead to the hydrothermal deposit. The Middle Valley sulfides are intermediate between basalt and sediment fields. Isotopic data are from Zierenberg et al. (1993) and Goodfellow and Franklin (1993).

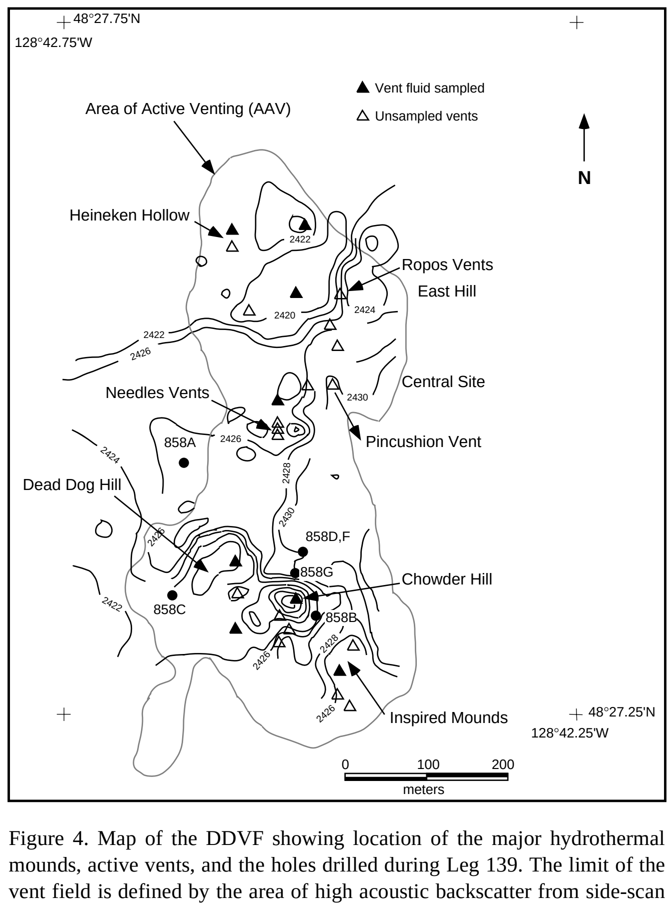

Figure 4. Map of the DDVF showing location of the major hydrothermal mounds, active vents, and the holes drilled during Leg 139. The limit of the vent field is defined by the area of high acoustic backscatter from side-scan sonar. Modified from Butterfield et al. (1994).

in the mound. Because the high-temperature hydrothermal fluid is strongly depleted in both Mg and SO_4, the abundance of these minerals in the subsurface requires that bottom seawater (with abundant Mg and SO_4) is drawn into the subsurface zone by the vigorous upflow at the active vent sites.

Bent Hill

Bent Hill is one of a string of small mounds that runs parallel to the eastern rift bounding normal fault scarp (Fig. 1B). These bathymetric highs are uplifted sediment hills to the north and volcanic cones to the south, where sediment cover thins. These features lie close to a normal fault that offsets basement reflectors (referred to as the Site 856 fault), but near the surface, sediment layering imaged in seismic reflection profiles appears to be continuous across this fault (Davis and Villinger, 1992; Davis, Mottl, Fisher, et al., 1992). The transition from essentially nonmagnetic oceanic crust that typifies the center of Middle Valley to crust with normal levels of magnetization passes through this area and probably marks the boundary between normal extrusive basalt and the sill-sediment complex that forms the

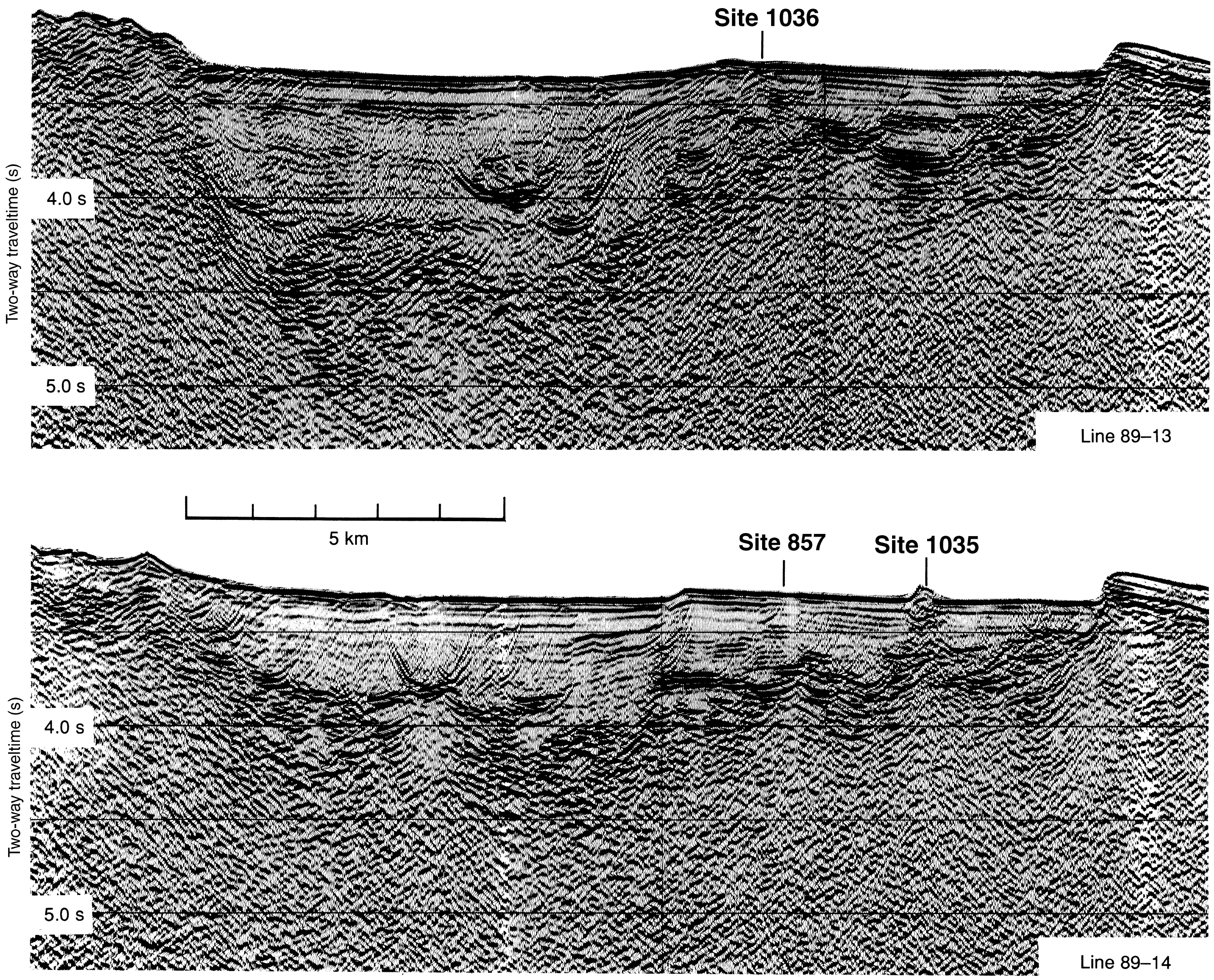

Figure 5. East-west multichannel seismic reflection profiles crossing the Leg 139 and the Leg 169 drilling sites (DD = Dead Dog; BH = Bent Hill). Modified from Davis, Mottl, Fisher, et al. (1992).

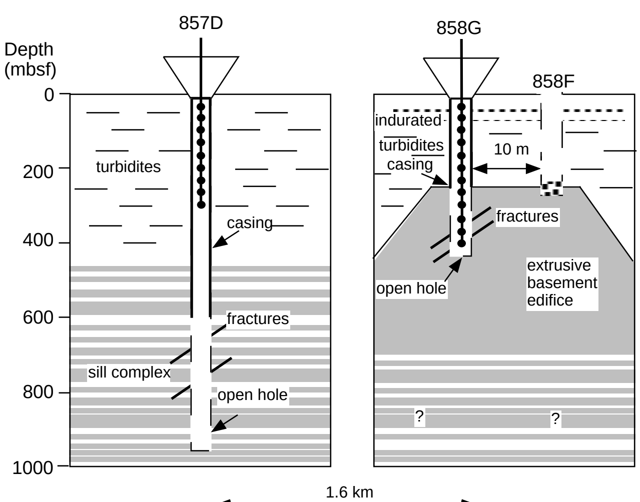

Figure 6. Diagram showing the depth to the basement in the two holes that have been instrumented with CORKs. Basement (shaded) at Site 857 is defined as the top of a sill-sediment complex at 470 mbsf. Basement under Site 858 rises to 250 mbsf and is extrusive basalt (from Davis and Becker, 1994a).

upper oceanic crust in the center of Middle Valley (Currie and Davis, 1994).

Bent Hill is a roughly circular feature 400 m in diameter that recently has been uplifted ~50 m (Fig. 7). It is bounded on the west by a steep scarp that parallels the rift bounding faults and exposes semi-consolidated turbiditic sediment. A very primitive, olivine-rich sill, which is petrogenetically distinct from the diabase and basalt recovered by drilling elsewhere in Middle Valley, was recovered at the base (~120 mbsf) of the two drill holes that penetrated Bent Hill (Fig. 8). Bright, reverse-polarity seismic reflections that are limited in extent to the area under Bent Hill are interpreted as the interface between the base of these sills and the underlying sediments (Rohr and Schmidt, 1994).

The 35-m-high Bent Hill inactive sulfide mound is located 100 m south of Bent Hill (Fig. 7). The Bent Hill Massive Sulfide deposit (BHMS) is extensively weathered to iron oxyhydroxides and is partially buried by sediment. Prior to Leg 169, massive sulfide was known to extend a minimum distance of 60 m north-south and 90 m east-west. During Leg 139, Hole 856H penetrated 94 m of massive sulfide (Fig. 8) before the hole had to be abandoned as a result of the inflow of heavy sulfide sand from the upper weathered section of the borehole wall. A strong magnetic anomaly across this mound is related to the occurrence of magnetite and has been modeled to suggest that mineralization continues at least another 30 m below the level drilled and possibly much deeper (Tivey, 1994).

The Ore Drilling Program (ODP) Mound massive sulfide deposit, consisting of two adjacent 12-m-high sulfide mounds, is located 330 m south of the Bent Hill sulfide deposit along the trend of the north-south scarp that bounds the western side of Bent Hill (Fig. 7). The morphology, degree of oxidation, and the lack of sediment cover of the ODP Mound deposit indicate that it is younger than the Bent Hill deposit. A single 264°C hydrothermal vent was known to be present on the northern flank of this deposit, but the southern part of the deposit was not explored. Contoured heat-flow values for the Bent Hill area show high values centered around this active vent (Davis and Villinger, 1992). The composition of the vent fluid is similar to those from the DDVF, but this vent has lower salinity and only half as much dissolved Ca (Butterfield et al., 1994).

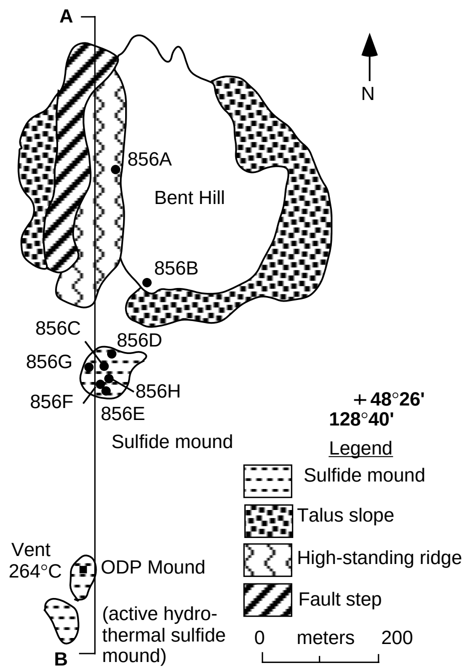

Figure 7. Map of Site 856 area showing the location of the Bent Hill and the two sulfide mounds to the south. A ridge-parallel normal fault underlies the west side of the sulfide deposits, Bent Hill, and similar uplifted sediment hills that occur south of the map area. Cross section along Line A–B is shown in Figure 8. Modified from Goodfellow and Peter (1994).

Previous studies of sulfides recovered in shallow cores from the BHMS deposit have demonstrated that the upper part of the deposit comprises clastic sulfide layers interbedded with hydrothermally altered and unaltered sediments (Goodfellow et al., 1993). Sulfide clasts display textures commonly observed in chimneys and consist of pyrrhotite, wurtzite, isocubanite, and chalcopyrite with later cementation and veining by sphalerite, pyrite, marcasite, magnetite, hematite, amorphous silica, hydrothermal clays, and barite. Textures indicate that the upper part of the mound was formed by buildup caused by the accumulation of sulfide chimney rubble (Goodfellow et al., 1993). The 94-m section of massive sulfides drilled on Leg 139 showed that the central part of the mound was made primarily of pyrrhotite, much of which has been replaced by a pyrite or pyrite + magnetite assemblage resulting from the late-stage circulation of relatively low-temperature hydrothermal fluid. Hydrothermal reworking has resulted in some zone refining with sphalerite enriched near the top and chalcopyrite more common at deeper levels (Duckworth et al., 1994).

Escanaba Trough: Geology of the Hydrothermal Field

The Gorda Ridge spreading center is located offshore of Oregon and northern California and is bounded by the Mendocino Fracture Zone on the south and the Blanco Fracture Zone on the north (Fig. 1C). A small offset in the spreading axis at 41°40′N latitude marks the northern boundary of Escanaba Trough, which forms the southernmost part of Gorda Ridge. Escanaba Trough is opening at a total rate of ~24 mm/yr and has a morphology consistent with the slow-spreading rate. The axial valley, which is at a depth of 3300 m, increases in width from ~5 km at the north end to more than 15 km near the intersection with the Mendocino Fracture Zone.

South of 41°17′N latitude, the axial valley of Escanaba Trough is filled with several hundred meters of turbiditic sediment (Figs. 9, 10). The sedimentary cover thickens southward and is a kilometer or more in thickness near the Mendocino Fracture Zone. Turbidites enter the southern end of the trough and are channeled northward by the axial valley walls (Vallier et al., 1973; Normark et al., 1994).

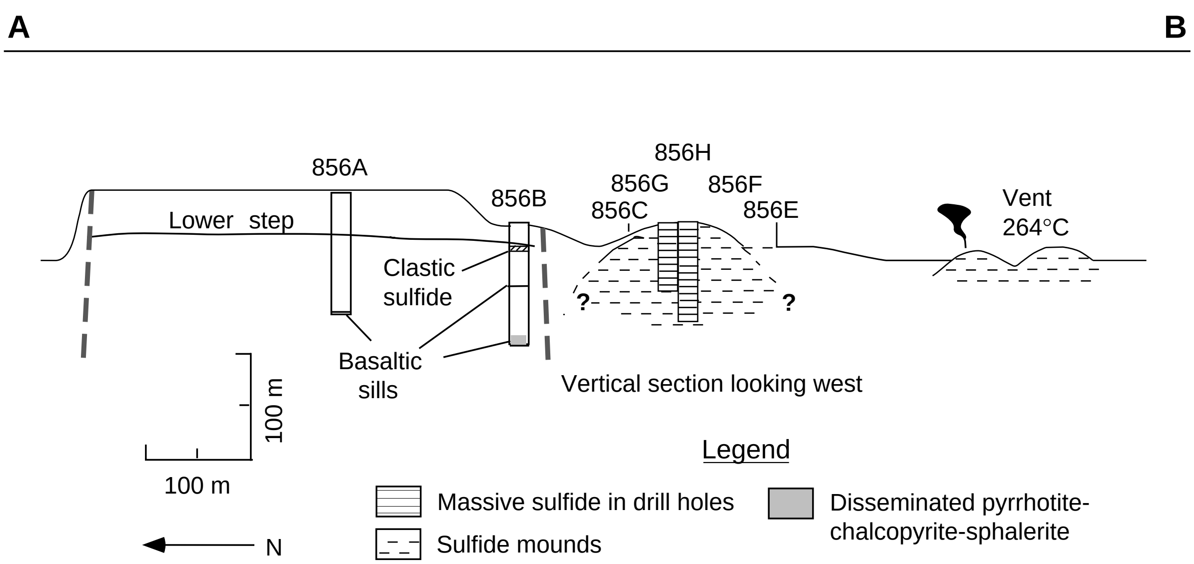

Figure 8. North-south cross section along Line A–B in Figure 7 of Site 856 area showing the extent of penetration of massive sulfide deposit south of Bent Hill during Leg 139 drilling and the location of basaltic sills beneath Bent Hill. Modified from Davis, Mottl, Fisher, et al. (1992).

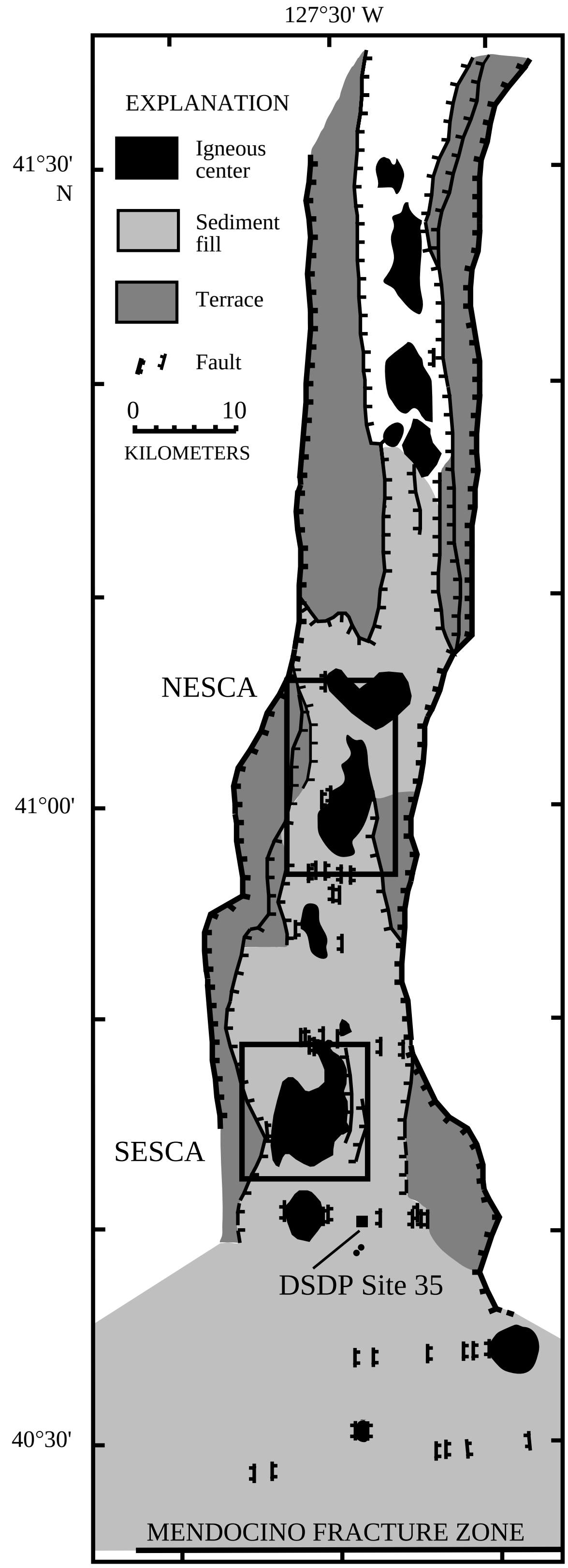

Figure 9. Map of the southern portion of the Gorda Ridge spreading center showing the sediment-filled portion of the Escanaba Trough (light shading), intra-trough terraces (intermediate shading), and the volcanic centers (dark shading) that rise through and locally pierce the sediment cover.

During sea-level lowstands in the Pleistocene, sedimentation was relatively rapid (up to 5 m/k.y.), and the entire sediment fill of the trough probably was deposited within the last 100 k.y. (Normark et al., 1994; Davis and Becker, 1994b).

Seismic reflection surveys show that the floor of Escanaba Trough is generally a smooth, flat plain underlain by continuous and relatively undisturbed turbidites (Fig. 11; Davis and Becker; 1994b; Morton and Fox, 1994). However, local areas along the axis of spreading have irregular seafloor topography characterized by circular hills 0.5−1.2 km in diameter that are uplifted 50−120 m above the surrounding seafloor. The sediment cover in these areas is described as moderately to highly disturbed, based on the discontinuity or absence of seismic reflectors (Fig. 10; Morton and Fox, 1994). Morton et al. (1994) mapped the distribution of the topographically rough, seismically disturbed zones, which typically are 3−6 km wide, oval-shaped areas aligned along the spreading axis. The strongly disturbed zones also are areas of high heat flow (Fig. 11; Davis and Becker, 1994b).

The areas of sediment disruption are sites of recent axial rift igneous activity. The geologic and geophysical evidence suggests that axial rift igneous activity at these sites is manifested by the intrusion of dikes, sills, and laccoliths into the sediment with less abundant volcanic flows (Morton and Fox, 1994; Zierenberg et al., 1993, 1994). Sulfide mineralization has been sampled by dredging, sediment coring, or submersible at four igneous centers within the sediment-covered part of Escanaba Trough. The Northern Escanaba Trough study area (NESCA; Figs. 10, 12) contains several large massive sulfide deposits, including an area of active hydrothermal venting. The dominant morphologic features in the NESCA area are the Southwest Hill and the Central Hill (Figs. 10, 12). The Southwest Hill is an elongated sediment hill that has been uplifted by 120 m above the surrounding turbidite plain. The steep sides of the hill have formed by mass wasting exposing semiconsolidated turbiditic sediment. Massive sulfide deposits occur at the base of the scarp that bounds the uplifted sediment hill. Southwest Hill is interpreted to have formed by uplift of sediment over a laccolithic sill; high-permeability fault zones that accommodated the uplift provided pathways for the flow of hydrothermal fluid to the seafloor (Denlinger and Holmes, 1994).

A large exposure of volcanic rock occurs east of the crest of the Central Hill (Fig. 12). The elevated area east of the Central Hill is covered by glassy basalt pillows 1−2 m in diameter. Lava tubes drape the north flank of the hill indicating flow to the north. These lava tubes fed sheet-flow basalts that ponded within the central depression of the spreading center. The area of Central Hill west of the outcropping pillow basalt is interpreted to have been uplifted by the intrusion of basalt into the sediment. The western, sediment-covered part of Central Hill contains the most extensive sulfide deposits observed in Escanaba Trough. The massive sulfide deposits on the western and southeastern flanks of the Central Hill are actively venting hydrothermal fluid, and the area on the northern flank shows indications of very recent hydrothermal activity, suggesting that these deposits are all part of the same hydrothermal system. An extensive area of massive sulfide is exposed on the northern slope of Central Hill. Massive sulfide extends more than 270 m from north to south and more than 100 m from east to west, but the western edge of the deposit has not been defined with certainty. Within this area there is nearly continuous outcrop of massive sulfide with few sediment-covered areas. The best explored and most hydrothermally active area of sulfide mineralization on Central Hill extends west from the northern end of the sediment-covered hill top (Fig. 12). This is not an area of continuous sulfide outcrop, but rather a region of abundant, closely spaced sulfide mounds. The mounds are typically 20 to 60 m in diameter and 5 to 10 m high. In 1988, two mounds were observed to be discharging high-temperature hydrothermal fluid; one near the eastern margin of the sulfide area was venting 217°C fluid, and one on the western edge of the explored area was venting 108°C fluid (Fig. 12). Even though

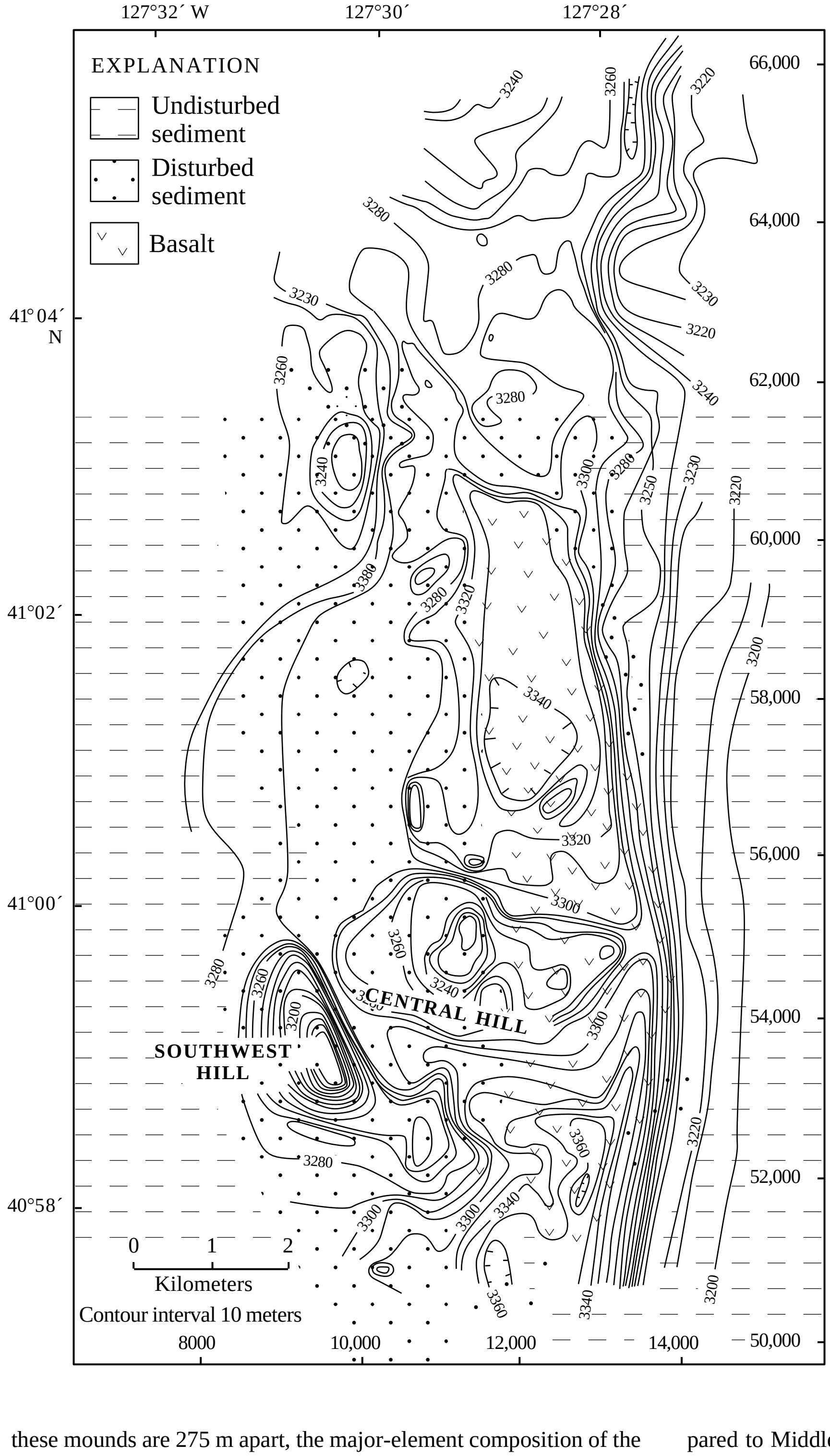

Figure 10. Bathymetric map of the NESCA area showing the location of the Southwest Hill, Central Hill, and on-axis volcanic rocks. The location of faults is constrained by the seismic profiles and camera and submersible observations of scarps. Modified from Zierenberg et al. (1994).

these mounds are 275 m apart, the major-element composition of the end-member fluid at both vents is identical (Campbell et al., 1994), a result that is consistent with the hypothesis that this large mineralized area is a single hydrothermal system hydrologically interconnected at depth. When the 217°C vent was revisited by the *Alvin* in 1994, the maximum temperature measured was 65°C (R. Lutz, pers. comm., 1994).

Sulfide samples collected at the surface of the deposit are dominantly pyrrhotite with variable amounts of isocubanite and chalcopyrite and minor sphalerite, galena, löllingite, arsenopyrite, and boulangerite. Sulfate occurs as barite crusts and chimneys on massive sulfide and intergrown barite-anhydrite in active vents. When compared to Middle Valley, the abundance of barite and enrichment of metals such as lead, arsenic, antimony, and bismuth indicate extensive contribution from sedimentary source rocks (Koski et al., 1994). Precious metals were significantly higher than in Middle Valley massive sulfide. Sediment alteration associated with the formation of massive sulfides is dominated by talc, chlorite, or smectite (Zierenberg and Shanks, 1994).

CORK Experiment

A major step toward establishing seafloor observatories was taken on Leg 139 by instrumentation of a sealed borehole using the Circulation Obviation Retrofit Kit (CORK) system. Geophysical logging,

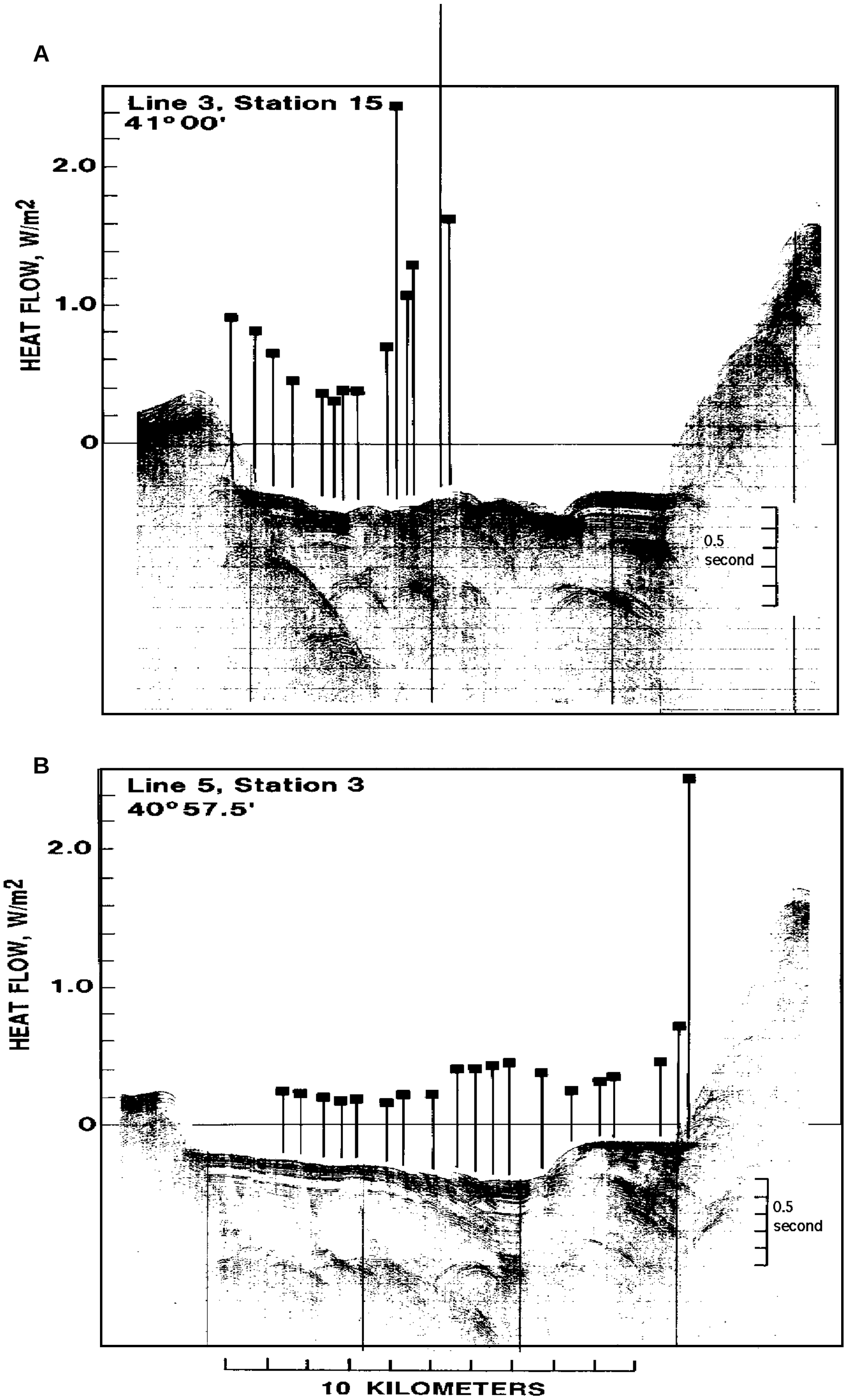

Figure 11. Heat-flow profile along (**A**) seismic Line 3, which crosses Escanaba Trough near Site 1038, and (**B**) Line 5, which crosses Escanaba Trough near Site 1037. Modified from Davis and Becker (1994b).

downhole experimentation, and borehole instrumentation provided the first direct constraints on the physical properties of an active submarine hydrothermal system (Davis, Mottl, Fisher, et al., 1992).

One of the objectives of Leg 169 was opening the two sealed, instrumented boreholes (Holes 857D and 858G) in the Middle Valley hydrothermal field to allow the first subsurface sampling of hydrothermal fluids from an ODP borehole. Reinstrumentation of these holes was planned to allow active experimentation on induced seismicity in a seafloor hydrothermal system and hole-to-hole hydrologic experimentation designed to constrain, for the first time, the physical and hydrologic properties that control hydrothermal flow on the scale of an entire vent field.

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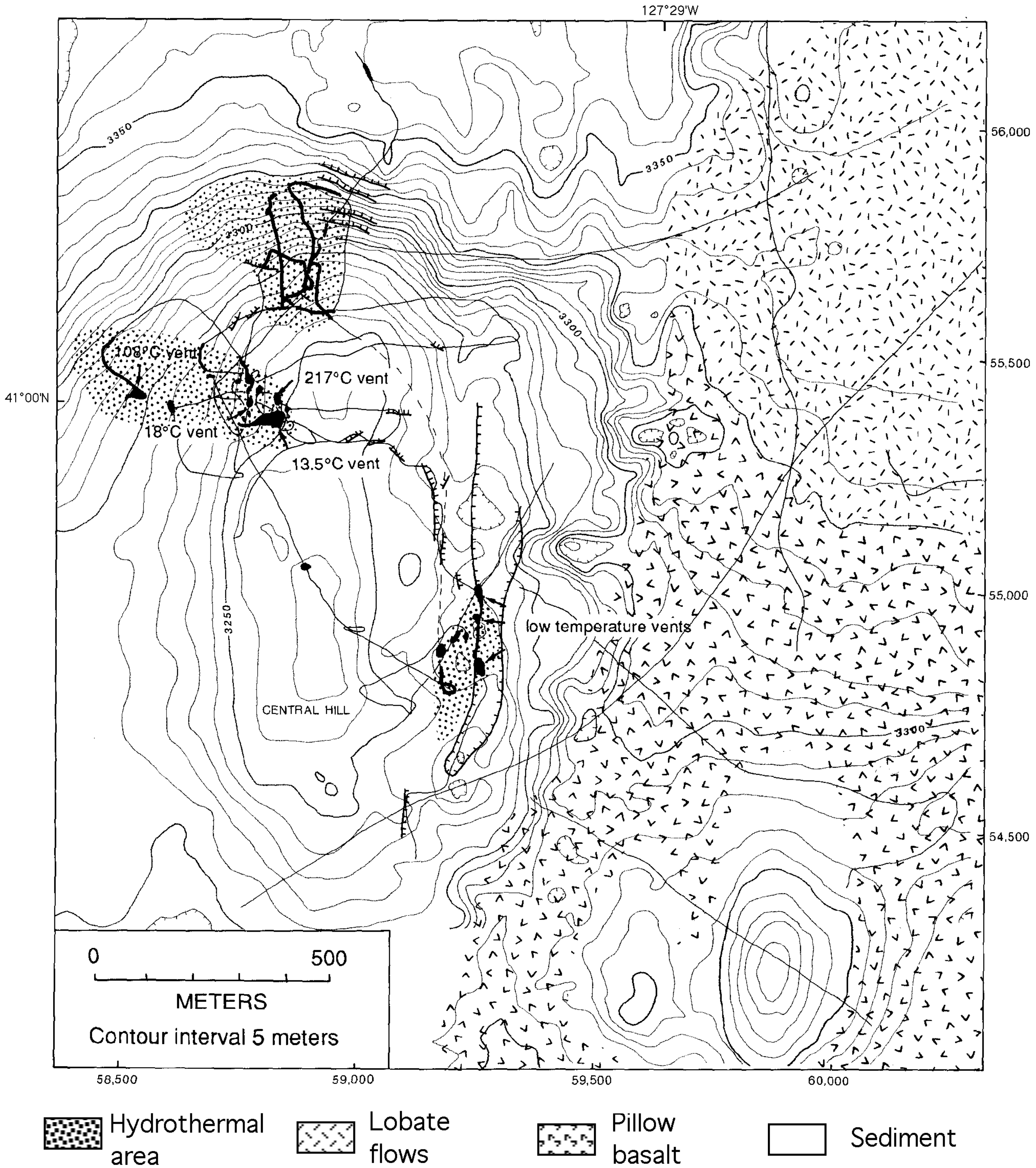

Figure 12. Detailed map of the Central Hill area of the NESCA site showing hydrothermal areas and known outcropping massive sulfide deposit (black). Location of active vents, fault scarps, and exposed volcanic rock are based on camera tows and submersible tracks shown as thin lines. Modified from Zierenberg et al. (1994).