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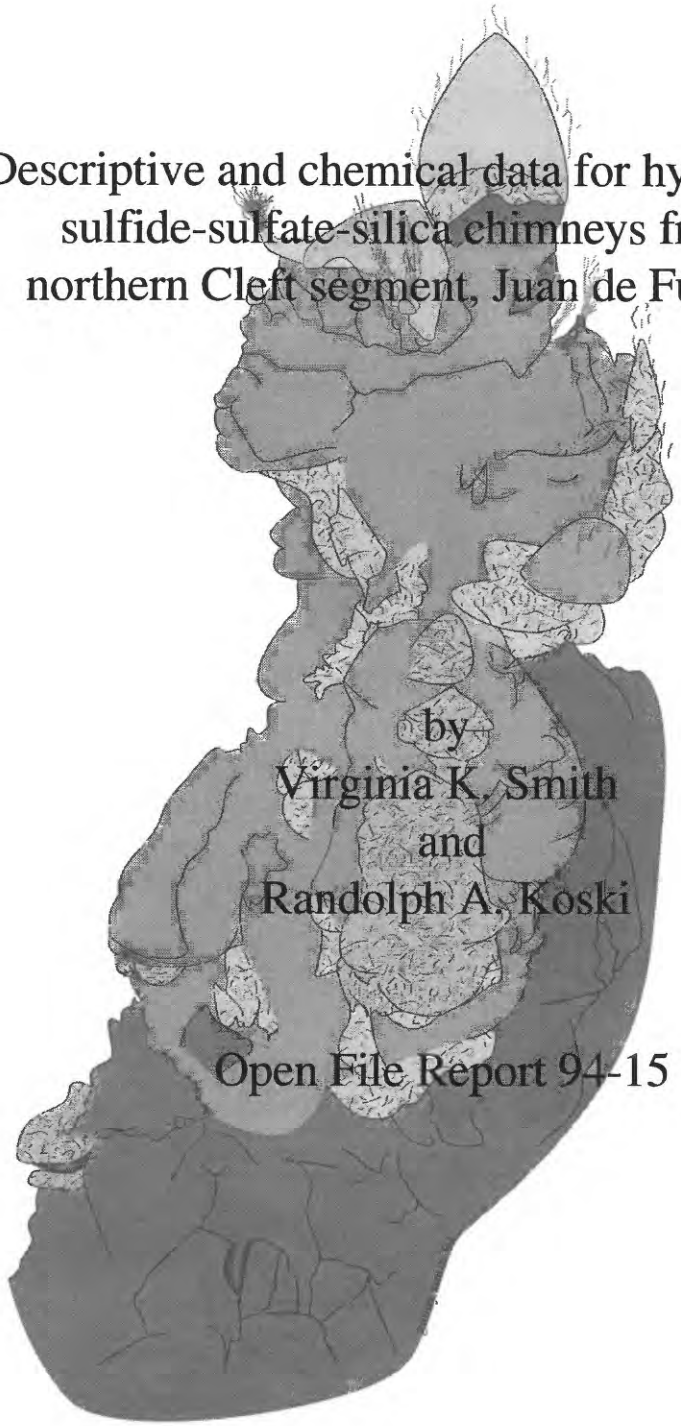
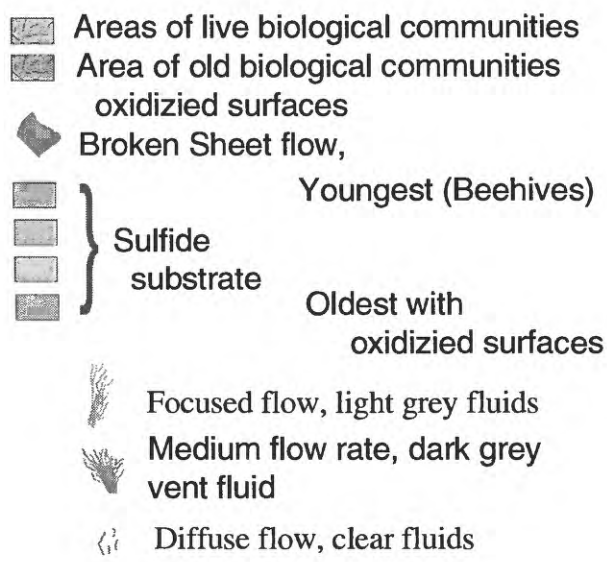
Descriptive and chemical data for hydrothermal sulfide-sulfate-silica chimneys from the northern Cleft segment, Juan de Fuca Ridge



by
Virginia K. Smith
and
Randolph A. Koski

Open File Report 94-15

Monolith Vent; Southern Edifice, 1994



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Descriptive and chemical data for hydrothermal sulfide-sulfate-silica chimneys from the northern Cleft segment, Juan de Fuca Ridge

by

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INTRODUCTION

During dive programs in 1988, 1990, and 1991, 37 hydrothermal chimney samples were collected by the submersible *Alvin* between latitudes 44°54' N and 45°01'N on the northern Cleft segment of the Juan de Fuca Ridge, northeast Pacific Ocean (fig. 1). Recent volcanic eruptions from a fissure system at the ridge axis has produced a 7.5-km-long sheet flow and a series of pillow mounds (fig. 2, Chadwick and others, 1991; Embley and others, 1991). In 1986 and 1987, thermal and chemical "megaplumes" produced by large exhalations of hydrothermal fluid were detected on the same ridge segment (Baker and others, 1987; 1989). Active hydrothermal discharge in the northern Cleft segment consists of (1) diffuse low-temperature (<60°C) flow through the young sheet flows and along the fissure system within a few kilometers north and south of the sheet flow area, and (2) focused high-temperature (to 328°C) flow from sulfide mounds and chimneys at three principal sites (the Monolith, Fountain, and Pipe Organ vents) along the fissured terrain (fig. 2).

In this report, we present macroscopic descriptions and all available bulk chemical data for the chimney samples. More comprehensive descriptions of the geologic setting and the hydrothermal deposits are presented by Embley and Chadwick (1994) and Koski and others (1994).

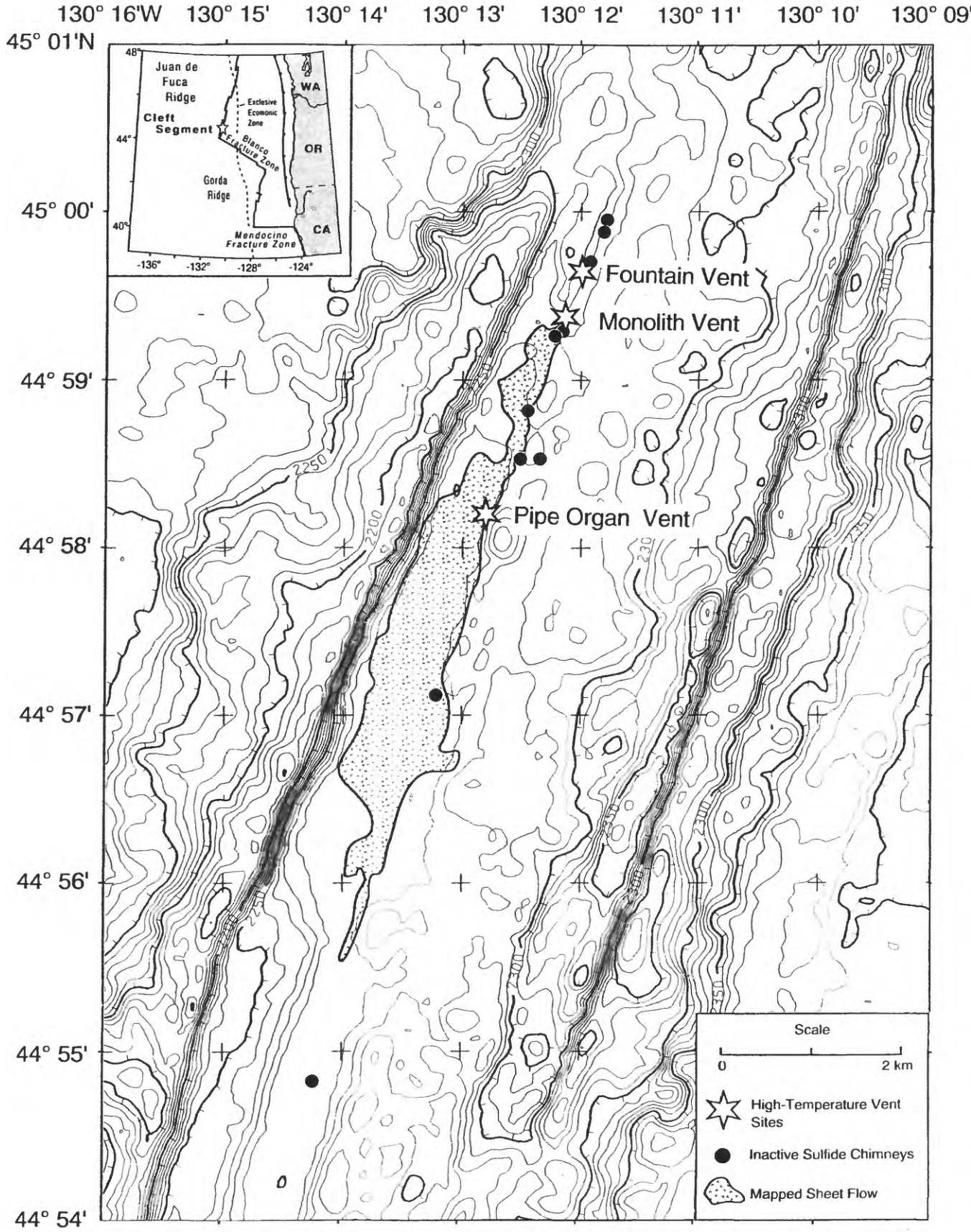

FIGURE 1. SeaBeam map of the northern Cleft Segment showing area of recent sheet flow, high-temperature vent sites, and other inactive chimney samples. Contour interval is 10 m. Bathymetry and location of sheet flow provided by R. Embley.

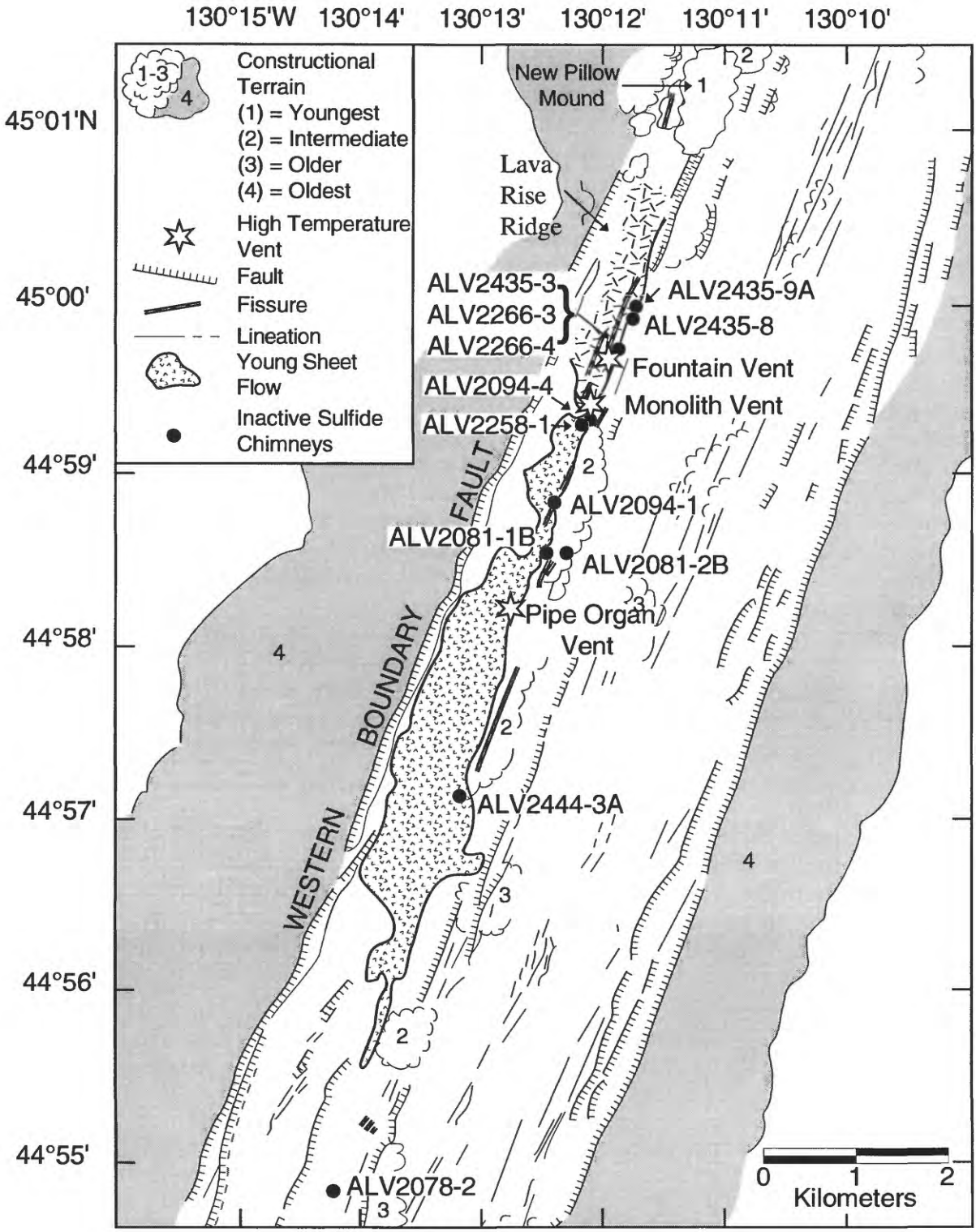

FIGURE 2. Interpretive geologic map of the northern Cleft segment showing bathymetry, area of young sheet flow lava, constructional terrains (pillow-lava mounds), linear features, high-temperature vent sites, and inactive sulfide deposits. The pillow-lava mounds are subdivided into four separate ages based on reflectivity and the amount of sediment cover (Embley and Chadwick, 1994). Samples from high-temperature vent sites are designated in Table 1. Table and Brigadoon vent sites (not shown) are located 5 and 20 m north of Monolith Vent, respectively. Modified from Embley and Chadwick (1994).

VENT SITES

The Monolith Vent, constructed on the eastern edge of a fissure, consists of a basal mound topped by diverse active chimneys (figs. 3*A* and *B)*. The basal dimensions in 1991 were approximately 8 m by 5 m; the total height of the structure including chimneys was about 5 m. The hottest fluid temperatures in both 1990 and 1991, approximately 328°C, were measured at small side spouts near the lower western flank of the mound. Two smaller sulfide edifices, the Table and Brigadoon vents with maximum fluid temperatures between 275°C and 283°C, are located 5 and 20 m north of the Monolith edifice, respectively (figs. 2 and 3*C*).

The Fountain Vent, located approximately 560 m north-northeast of the Monolith Vent (fig. 2), consists of two active sulfide mounds on the east side of a fissure. In 1991 the larger edifice was approximately 5 m in diameter at the base and 4 m in height, and much of the upper part was covered by robust tube-worm colonies (fig. 4*A*). The maximum hydrothermal fluid temperatures measured at Fountain Vent is 312°C.

The Pipe Organ vent field occurs in a fissure along the eastern margin of the sheet flow (fig. 2). In 1991, approximately 20 active sulfide chimneys were present in a cluster trending north-northeast parallel to the ridge axis. The sulfide structures consisted of spindly columns to 0.1 m in diameter and coalesced chimneys to 0.5 m in diameter (fig. 4*B*); the maximum chimney heights were 12 m. The maximum temperature of 261°C was measured in fluid discharging from a 4-m-tall chimney.

Inactive sulfide pinnacles up to 14 m in height are present along the northern and eastern edge of the sheet flow and in fissured terrain north of the Monolith Vent (figs. 2 and 4*C*). Field relations and Pb-210 analyses indicate that these sulfide structures represent an earlier hydrothermal episode that predated the sheet flow eruption (Koski and others, 1994).

DESCRIPTION OF CHIMNEY SAMPLES

The chimney samples can be classified into four categories based on their morphology, composition, texture, and fluid temperatures. Type I, Type II, and Type III chimneys formed at high-temperature vent sites whereas Type IV chimneys represent the earlier lower-temperature hydrothermal event. Table 1 is a summary of chimney characteristics. The location, classification, fluid temperatures, and descriptions of the chimney samples are presented in Table 2. Sample locations are shown in Figure 2.

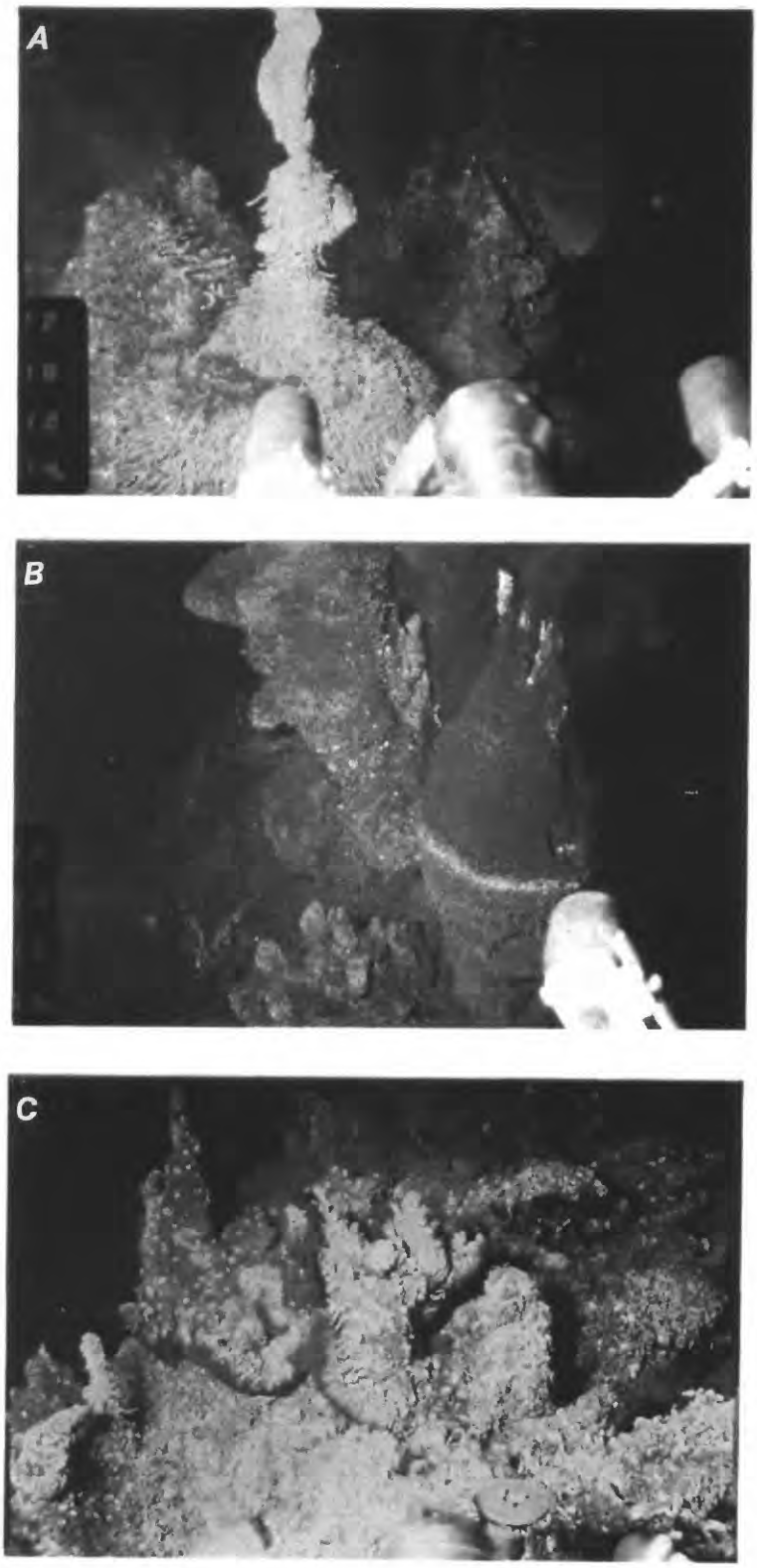

FIGURE 3. *Alvin* photographs of high-temperature vent sites and inactive sulfide chimney. *A.* View of south side of Monolith Vent, in 1990, showing active 1-m-high Type I chimney in foreground and cluster of chimneys including active Type II chimney on east side of mound. *B.* A large, bulbous Type II beehive chimney (about 1m in height) as seen in 1991, venting diffusely at the base of the northern edifice at Monolith Vent. *C.* Diffuse venting from small (0.5-m-high) Type III chimneys at Table Vent, 5 m north of the Monolith edifice.

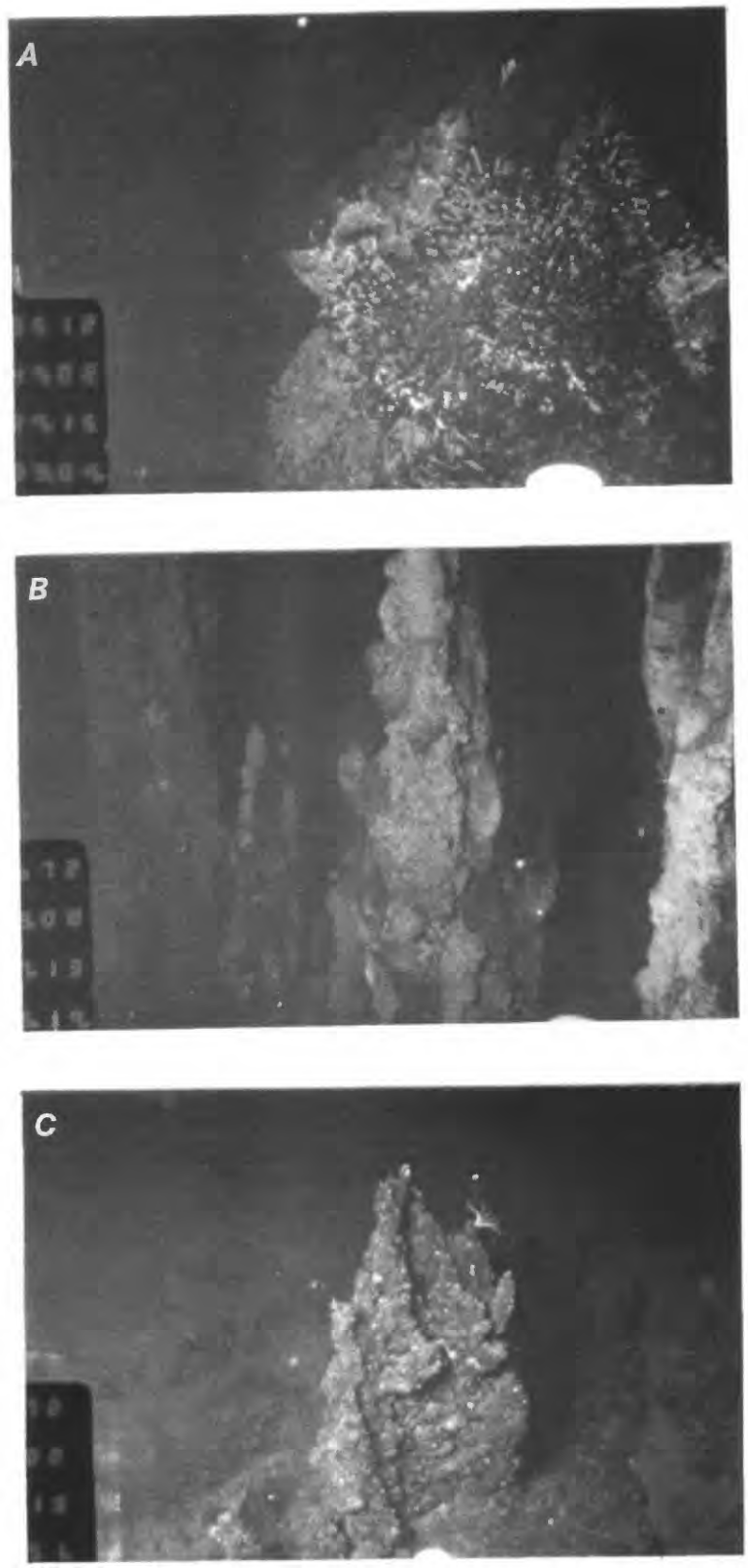

FIGURE 4. *A.* View of north side of Fountain Vent with dense covering of tube worms and small active beehive chimneys near the top. Width of mound approximately 5 m. *B.* Coalesced chimneys at Pipe Organ Vent coated with Fe oxyhydroxides and bacteria. Maximum width of coalesced chimney at right center is about 0.5 m. *C.* Inactive Type IV sulfide pinnacle, 1 m in height, with a few sessile organisms.

TABLE 1. Characteristics of Four Chimney Types

Characteristics	Type I	Type II	Type III	Type IV
Form	Columnar-cylindrical	Bulbous ("Beehive")	Columnar-spindly	Pinnacle
Substrate	Sulfide mound	Sulfide mound or chimney	Basalt	Basalt
Temperature (°C)	310 - 328	293 - 312	261 - 276	< 250 (est.)
Fluid Flow	Focused, rapid	Diffuse, slower than Type I	Focused, slow	Diffuse (?), slow

Type I Chimneys

Type I chimneys are tubular structures that vent focused high-temperature fluid at the Monolith Vent. Two samples were collected one year apart from the same orifice: the central part of a 1-m-tall chimney in 1990 (ALV2259-1, fig. 3*A*) and a 0.2-m-tall chimney (ALV2429-1) in 1991. Both samples display a tubular structure and a smooth-walled open channelway (figs. 5*A* and *B*). In cross section, the chimneys are concentrically zoned with an inner wall of massive chalcopyrite with minor pyrite and bornite, a wide middle wall of sphalerite, wurtzite, chalcopyrite, pyrite, and anhydrite, and a relatively narrow outer wall of marcasite, pyrite, sphalerite, and barite. The measured temperature of fluids venting from these chimneys was 310° in 1990 and 1991 (Koski and others, 1994).

Type II Chimneys (Beehive Structures)

Chimneys with a bulbous form and circumferential ribbing pattern are referred to as Type II or "beehive" structures. They occur on the Monolith and Fountain sulfide mounds (figs. 3*A*, *B*, and 4*A*) and on top of some of the chimneys at the Pipe Organ Vent. Type II chimneys vent fluid at temperatures between 293° and 312°C through their porous tops and side walls. The active chimneys consist of a fragile anhydrite-rich shell containing minor pyrite, sphalerite, wurtzite, and chalcopyrite (fig. 5*C*). Porosity of shell fragments are about 30%. A beehive structure at the north end of the Monolith Vent is topped by small columnar anhydrite chimneys (fig. 3*B*). Fossil Type II chimneys (e.g. sample ALV2442-7) are plugged by concentric layers of massive Zn sulfides, mostly sphalerite exhibiting a range of dendritic, colloform, and subhedral-granular textures.

A large high-temperature (314°C) chimney from Monolith Vent (sample ALV2433-3D) has a composite morphology with both Type I and Type II features. The chimney has the external shape and ribbing of a beehive structure, but the massive layers of chalcopyrite and anhydrite surrounding the large open channelway are more characteristic of Type I chimneys (fig. 6*A*). This hybrid chimney probably formed during a transition from Type II to Type I conditions at the vent (Koski and others, 1994).

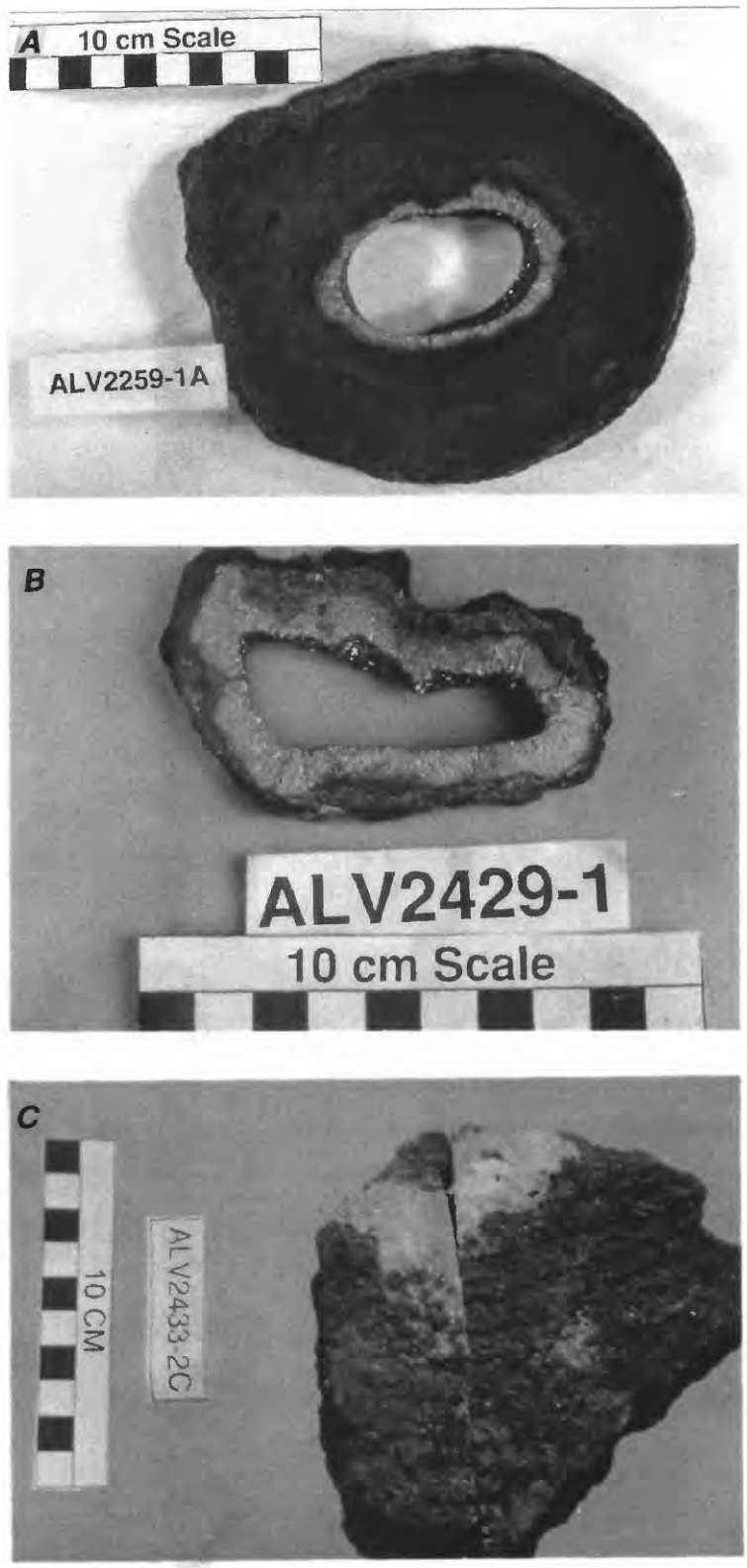

FIGURE 5. Photographs of chimney samples. *A, B.* Cross sections of Type I chimneys sampled from the same orifice at Monolith Vent (fig. 3*A.*). ALV2259-1A sampled in 1990 has a central channelway enclosed by a thin layer of chalcopyrite (light gray), wide Zn-sulfide-rich zone (gray), and a thin crust of partially oxidized pyrite and marcasite. ALV2429-1 sampled in 1991 has a thick inner layer of chalcopyrite (light gray) with a narrow outer layer of anhydrite+sphalerite. *C.* ALV2433-2C is a Type II anhydrite rich wall fragment with rib structures sampled in 1991. White patches are pure anhydrite.

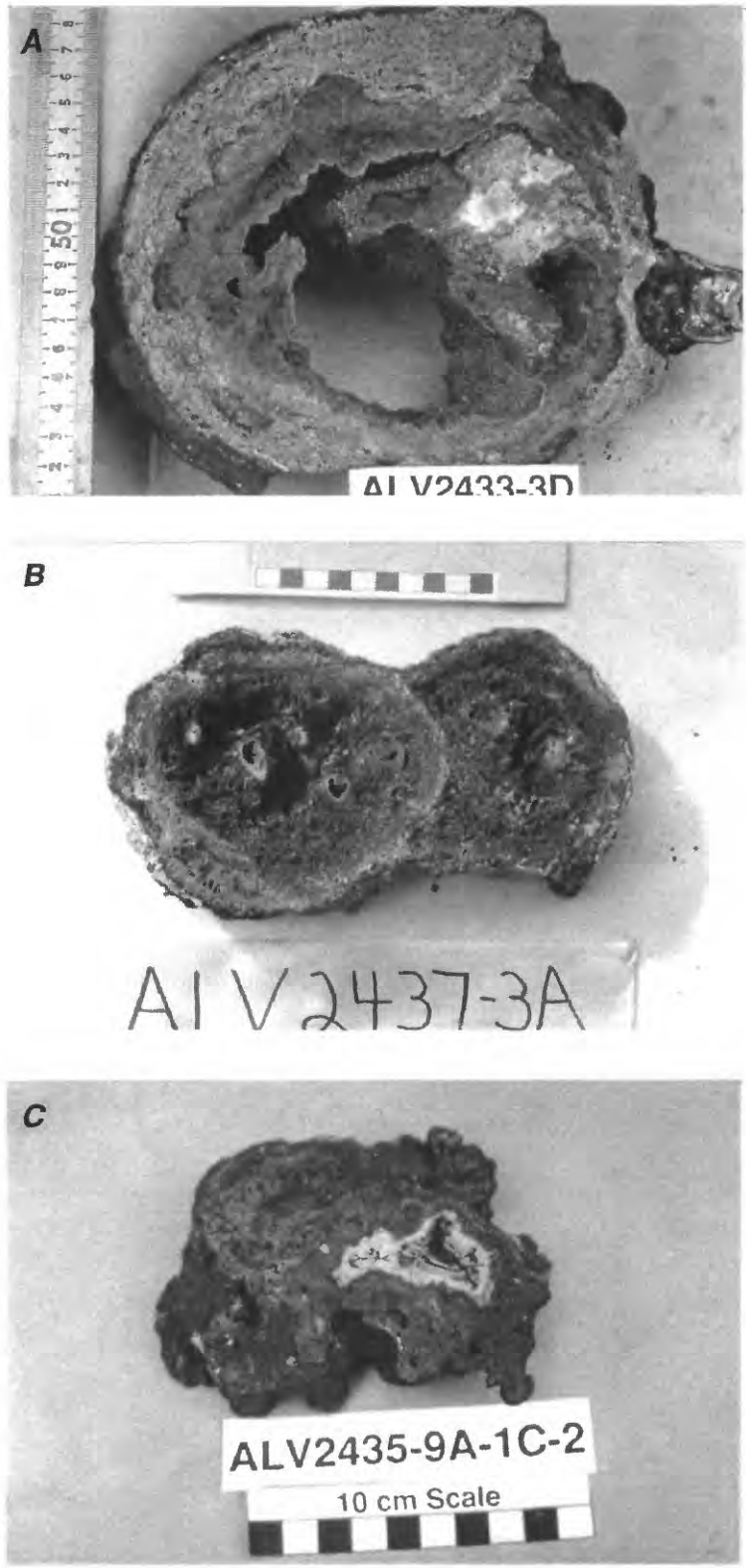

FIGURE 6. *A.* Cross section of sample ALV2433-3D with both Type I and Type II characteristics. The central channelway is enclosed, in sequence, by a layer of chalcopyrite and pyrite (medium gray), a wide anhydrite-rich layer (light gray), and a Zn-sulfide-rich shell (dark gray). *D.* Sample ALV2437-3A is an inactive Type III coalesced chimney structure from Pipe Organ Vent that is predominantly Zn sulfides with numerous small channelways and outer, partly oxidized crust of marcasite and pyrite Scale units are 1 cm. *C.* ALV2435-9A-1C is a Type IV chimney in which the central channelway and smaller conduits are infilled by colloform amorphous silica (white).

TABLE 2. Descriptions of Chimney Samples

Sample Number	Latitude °N	Longitude °W	Chimney type and activity[1]	Measured Water Temperature (°C)	Wt. (kg)	Mineralogy[2]	General Descriptions
ALV2078-2A2	44°54'49"	130° 14'15"	IV (i)	-----	0.75	py, mc, si, wt, sp, gl, ba, Fe ox.	Top of 50-cm-tall, chimney with knobby protuberances; predominantly Fe sulfides in concentric rings around conduits filled with amorphous silica. Orange Fe-oxyhydroxide coating and fossilized worm tubes are found on the surface of the Fe-sulfide crust. Chimney located on jumbled sheet flows. Length = 26 cm, diameter = 8 cm.
ALV2078-2B2	44°54'49"	130° 14'15"	IV (i)	-----	0.1	py, mc, si, ba, sp, clay, sul, Fe ox.	Top 0.3 m of a 7-m-tall chimney with knobby protuberances; similar to 2A but with a thicker Fe-oxyhydroxide coating. Interior consists of dense, colloform Fe sulfides with amorphous silica lining numerous conduits and old worm tube structures. Chimney located near ALV2078-2A2. Length = 27 cm, diameter = 8 cm.
ALV2081-1B	44°58'33"	130° 12'30"	IV (i)	-----	3	py, mc, si, sp, wt, cp, ba, Fe ox.	Wall fragment from top of 8-m-tall chimney. Interior is predominantly dendritic Fe sulfides with numerous ring-like structures around channelways. Black coating (Mn oxide?) on the exterior. Chimney located on older sediment covered, pillow lavas. Dimensions: 25 cm x 20 cm x 8 cm.
ALV2081-2B	44°58'33"	130° 12'20"	IV (i)	-----	0.5	py, mc, si, wt, sp, Fe ox.	15 cm tall spire of a small knobby chimney. Interior has a dense, crystalline pyrite+marcasite rim (1 to 4 cm) surrounding botryoidal sulfides lining numerous small central conduits. Fe-sulfide crust coated with Fe oxyhydroxides, worm tubes, and sponge attachments. Sample located in a field of 10 to 12 chimneys each < 1 m high rising out of sediment covered pillow lavas. Length = 15 cm, diameter = 5 cm.
ALV2093-2B	unknown	unknown	IV (i)	-----	25 (est.)	py, mc, si, sp, wt, Fe ox.	Uppermost 0.3 m of 5-m-tall, knobby chimney topped by multiple spires. Interior predominantly Fe sulfide in concentric rings around multiple conduits filled with amorphous silica and coarse crystalline sulfides. Fe oxyhydroxides and sparse worm casings on exterior. Spires are located on pillow lavas, but exact location unknown. Dimensions: 64 cm x 20.5 cm x 29 cm.

TABLE 2. Descriptions of Chimney Samples (Continued)

Sample Number	Latitude °N	Longitude °W	Chimney type and activity[1]	Measured Water Temperature (°C)	Wt. (kg)	Mineralogy[2]	General Description
ALV2094-1A1	44°58'50"	130° 12'21"	IV (i)	-----	30 (est.)	py, wt, si, mc, sp, cp, Fe ox.	Knobby chimney, 50-cm-high, that terminates in multiple spires. Interior is dendritic Fe sulfides in concentric rings. Conduits are lined with amorphous silica. Fe-oxyhydroxides coating and worm tubes on exterior. Chimney is located along a fracture in lobate flows. Length = 50 cm, diameter = 15 cm.
ALV2094-1B	44°58'50"	130° 12'21"	IV (i)	-----	0.1	mc, wt, sp, Fe ox.	Fragments of small chimney. Composed of fine crystalline Fe sulfides. Coarser-grained Fe sulfides in conduit. Patchy Fe-oxyhydroxides coating on exterior. Sampled from a 2-to 3-m-tall chimney adjacent to AVL2094-1A. Dimensions: 6 cm x 3 cm x 3 cm.
ALV2094-4A1 and ALV2094-4B1	44°59'19"	130° 12'08"	III (i)	----	4A - 7 4B - 3.72 (est.)	sp, wt, py, mc, si, ba, anh, gal, Mn ox.	Weathered, arcuate fragments of an old, hollow chimney. Fragments composed of dense, alternating layers of dendritic Zn sulfides. Exterior is coated with Mn oxide with scattered worm tubes, sponge attachments, and foraminifera. Chimneys located at the contact between old and new pillow lavas. Dimensions: 4A1 = 30 cm x 23 cm x 2 cm, 4B1 = 30 cm x 10 cm x 3 cm.
ALV2258-1	44°59'05"	130° 12'28"	IV (i)	-----	2.58	py, mc, si, wt, sp, Fe ox.	Columnar chimney, 30-cm high, with protuberances. Interior predominantly dense Fe sulfides in concentric rings around conduits that are lined with botryoidal Zn sulfides. Black oxyhydroxide coating on exterior surface. Worm tubes and sponge attachments present. Located on a sediment-covered sheet flow. Length = 12.5 cm, diameter = 7 cm.
ALV2259-1 Monolith Vent	44°59'24"	130° 12'05"	I (a)	310 - 320	10.53	cp, sp, wt, py, mc, anh, bn, cv, clay, ba, gl, Fe ox.	Middle part of tubular chimney. Zoned interior has 4-cm-wide layer of dense, anhydrite and Zn sulfides enclosing 1 cm thick layer of coarse, grained Cu-Fe sulfide. Central channelway is 5.5 cm x 3.5 cm. Partly oxidized Fe-sulfide crust has abundant embedded worm casings. Sampled from the top of southern end of sulfide mound. Dimensions: 45 cm x 11 cm x 8 cm.
ALV2259-2 Monolith Vent[3]	44°59'24"	130° 12'05"	II (i)	-----	0.91	sp, mc, py, wt, anh.	Arcuate fragments of outer chimney wall composed of dense, coarse-grained Zn sulfides. Remnant crust of Fe sulfide present within fragments. Thin crust of black botryoidal sulfide with patches of sulfur on exterior. Sampled at base of the edifice on eastern side. Dimensions of largest fragments: 19 cm x 12 cm x 3 cm.

TABLE 2. Descriptions of Chimney Samples (Continued)

Sample Number	Latitude °N	Longitude °W	Chimney type and activity[1]	Measured Water Temperature (°C)	Wt. (kg)	Mineralogy[2]	General Description
ALV2261-2 Table Vent	44°59'24"	130° 12'08"	III (a)	276	0.59	sp, wt, anh, py, mc, icb-cp, Fe ox.	Outer-wall fragment of chimney. Interior grades from fine-grained to coarse crystalline Zn sulfides and anhydrite toward the center. Exterior Fe sulfide crust has embedded worm casings. Chimney located between crevices of jumbled sheet flows. Dimensions: 11 cm x 7.5 cm x 4 cm.
ALV2265-1 Monolith Vent[3]	44°59'24"	130° 12'05"	III (i)	-----	2.5	sp, mc, py, wt, icb-cp, Fe ox.	Fragment of inactive chimney wall. Interior predominantly coarse-grained Zn sulfides with elliptical cavities in subparallel rows. Orange 2-mm-thick Fe-oxyhydroxide coating with worm casings on exterior. Fe sulfide layer, 1-cm-thick, between the Zn sulfide interior and the weathered exterior. Sampled from the base of Monolith Vent. Dimensions: 19 cm x 13 cm x 11 cm.
ALV2266-3	44°59'43"	130° 11'51"	IV (i)	-----	16.94	py, mc, sp, ba, si, ang, Fe ox.	Knobby, 60-cm-high, chimney terminating in one spire with numerous side flanges. Interior is dense, finely crystalline Fe sulfide. Numerous conduits lined with amorphous silica. Exterior coated with orange Fe oxyhydroxides and worm casings. Sample located in a field of 10 to 12 chimneys. Dimensions: 60 cm x 32 cm x 20 cm.
ALV2266-4	44°59'43"	130° 11'51"	IV (i)	-----	0.96	py, mc, wt, si, ang, clay, Fe ox.	Chimney fragment similar to ALV2265-1, but has Fe oxyhydroxide coating on silica within the central conduit. Also patchy Fe oxyhydroxide coating on exterior. Same location as ALV2266-3. Dimensions: 7 cm x 13 cm x 13 cm.
ALV2269-7 Monolith Vent[3]	44°58'24"	130° 12'05"	II (?) (a)	310	0.87	sp, wt, cp, py, anh.	Arcuate wall fragments from a high-temperature chimney. Wall has rib structure and consists of intergrown dendritic Zn sulfide and anhydrite. Coarse-grained wurtzite lining cavities. No exterior crust present. Dimensions of largest fragment: 15 cm x 15 cm x 4 cm.
ALV2429-1 Monolith Vent[3]	44°58'24"	130° 12'05"	I (a)	310	0.71	cp, sp, wt, anh, py, si, mc, clay, ba, cv, ap, Fe ox.	Tubular chimney, 20 cm in height, with zoned interior. A 1-cm-wide layer of anhydrite and Zn sulfide grades inward to a 1 to 2 cm wide layer of coarse-crystalline, chalcopyrite layer that surrounds the 5.5 cm x 2.5 cm open channelway. Sampled on the same orifice as ALV2259-1. Dimensions: 18 cm x 8 cm x 4 cm.
ALV2429-2 Fountain Vent[3]	44°59'40"	130° 11'56"	II (a)	-----	1.41 (est.)	sp, wt, py, mc, cp, ba.	Arcuate slabs from an active beehive chimney. One-cm-thick wall fragment with ribs of dense Zn sulfides. Two-mm-thick crust of botryoidal Fe sulfide with encased worm tubes. Sampled from the northeastern edifice. Dimensions: 11 cm x 8 cm x 1 cm.

TABLE 2. Descriptions of Chimney Samples (Continued)

Sample Number	Latitude °N	Longitude °W	Chimney type and activity[1]	Measured Water Temperature (°C)	Wt. (kg)	Mineralogy[2]	General Description
ALV2431-3A-1 Pipe Organ Vent[3]	44°58'13"	130° 12'45"	III (i)	-----	2.1 (est.)	sp, py, mc, wt, si, anh.	The top of coalesced 4-m-tall, columnar chimney structure. Interior is fine-grained Zn sulfides increasing in porosity toward center. Fe oxyhydroxides, worm casings, and foraminifera occur on outer wall of Fe sulfides. Sample located in old pillow lavas. Dimensions: 13.8 cm x 5.5 cm x 7.4 cm.
ALV2431-3A-2 Pipe Organ Vent[3]	44°58'13"	130° 12'45"	III (i)	-----	1.73 (est.)	sp, py, mc, wt, si, anh.	Sections of coalesced columnar chimney structure. The 1-cm-thick outer wall is dense, coarse-grained, Fe sulfides. This grades inward into fine-grained Zn sulfides. The center has 1 to 5 mm wide fluid channelways. Fe-oxyhydroxides and worm casings on the exterior surface of Fe sulfides. Dimensions: 10 cm x 20 cm x 11.5 cm.
ALV2433-2C Monolith Vent[3]	44°59'24"	130° 12'05"	II (a)	293 - 296	1.52	anh, py, sp, cp, wt, po.	Arcuate 2-cm-thick slabs from an active beehive chimney. Rib structure related to Zn sulfides alternating with anhydrite. Sample located on the southern end of Monolith Vent. Dimensions of largest fragment: 12.2 cm x 15.5 cm x 2 cm.
ALV2433-3C Monolith Vent[3]	44°59'24"	130° 12'05"	II (a)	303.4	0.5	anh, sp, py, wt, cp.	Arcuate slabs from an active beehive chimney similar to 2C. Minor chalcopyrite and pyrite lining cavities. Sampled at the base of a collapsed beehive chimney. Dimensions: 13 cm x 7.5 cm x 2 cm.
ALV2433-3D Monolith Vent[3]	44°59'24"	130° 12'05"	I, II (a)	314	10.65	cp, anh, sp, py, wt, gyp, si.	Beehive-shaped chimney with large orifice (5 cm wide) lined with Cu-Fe sulfides. The Cu-Fe-sulfide layer grades into a 2 cm thick, ring of dense, dendritic, anhydrite and Zn sulfide. There is a sharp boundary between layers. Outer wall surface has abundant Zn sulfide and ribbed morphology. Fe oxyhydroxide coating on exterior surface with worm tubes present. Sampled from cluster of active chimneys on southeast side. Dimensions: 44 cm x 17 cm x 22 cm.
ALV2433-4A Monolith Vent[3]	44°59'24"	130° 12'05"	II (a)	309	0.61	sp, py, anh, wt, cp, po.	Three spires, approximately 10 cm in height from top of an active beehive chimney. Walls are anhydrite and Zn sulfide. Sampled from the northern side of mound. Average dimensions: 10 cm x 7 cm x 3 cm.
ALV2434-1-20 Table Vent	44°59'24"	130° 12'08"	III (i)	-----	0.85	sp, wt, mc, py, cp.	Fragments of a chimney that grades inward from dendritic Zn sulfides to finely crystalline Fe sulfides lining channelways. Two-mm-thick crust of Fe sulfide encrusted with worm tubes and bacterial mats. Average dimensions: 8 cm x 6 cm x 5 cm.

TABLE 2. Descriptions of Chimney Samples (Continued)

Sample Number	Latitude °N	Longitude °W	Chimney type and activity[1]	Measured Water Temperature (°C)	Wt. (kg)	Mineralogy[2]	General Description
ALV2435-3	44°59'43"	130° 11'51"	IV (i)	-----	5 (est.)	py, sp, wt, si, mc, ang, Fe ox.	Top of 25-cm-tall knobby chimney. Interior is predominantly Fe sulfides forming concentric layers around channelways lined with amorphous silica. Patchy reddish-brown Fe oxyhydroxides on surface has worm tubes and foraminifera. Sample located in jumbled sheet flows. Length = 13 cm, diameter = 15 cm.
ALV2435-8	44°59'55"	130° 11'48"	IV (i)	-----	0.1	py, mc, sp, wt, si, ba, Fe ox.	Fragments from the tip of a 2-m-tall chimney, largely composed of Fe sulfide. Amorphous silica in central channelway is coated with red, Fe-oxyhydroxides. One-mm-thick botryoidal Fe-sulfide crust has worm casings and foraminifera. Isolated chimney located in jumbled sheet flow. Sponges, starfish, and other attached organisms were restricted to the north side of this chimney. Dimensions: 4 cm x 4 cm x 2 cm.
ALV2435-9A	45°00'00"	130° 11'39"	IV (i)	-----	11.69	py, mc, si, sp, wt, ang, Fe ox.	Knobby, 45-cm-high, chimney with colloform Fe sulfides in concentric layers around numerous conduits infilled with amorphous silica. Surface has crust of Fe sulfide with worm casings and foraminifera. Sample is from top of a 11-m-high chimney located on the edge of a fracture and surrounded by jumbled sheet flow. Dimensions: 45 cm x 19 cm x 13 cm.
ALV2436-1E Fountain Vent[3]	44°59'40"	130° 11'56"	III (i)	----	0.15 (est.)	sp, wt, py, mc, icb-cp.	A 17-cm-high chimney spire with a 1-cm-thick wall of dense, finely crystalline Zn sulfides that partially fill a 1-to 2-cm-wide central channelway. Patchy, botryoidal, oxidized, Fe-sulfide crust. Spire is located at the top of the north side of the large mound. Dimensions: 17 cm x 4 cm x 4 cm.
ALV2436-1F Fountain Vent[3]	44°59'40"	130° 11'56"	II (a)	304 - 311.5	0.25	sp, anh, py, mc, wt, icb-cp.	Three arcuate fragments from an active beehive chimney composed predominantly of dense, finely-grained Zn sulfides and anhydrite. Outer wall is a thin layer of Fe sulfides. Sampled from north side of large mound. Dimension of largest fragment: 13 cm x 6 cm x 6 cm.
ALV2436-2F Fountain Vent[3]	44°59'40"	130° 11'56"	III (i)	----	1.32 (est.)	sp, py, mc, wt, icb-cp, Fe ox.	Wall fragments from a beehive chimney composed of Zn, Fe, and Cu-Fe sulfides. Worm tubes incorporated in oxidized Fe-sulfide crust. Sampled from the south side of large mound. Dimensions of largest fragment: 12 cm x 6 cm x 2 cm.

TABLE 2. Descriptions of Chimney Samples (Continued)

Sample Number	Latitude °N	Longitude °W	Chimney type and activity[1]	Measured Water Temperature (°C)	Wt. (kg)	Mineralogy[2]	General Description
ALV2437-3A Pipe Organ Vent[3]	44°58'13"	130° 12'45"	III (i)	-----	8.02	sp, py, mc, si, po, icb-cp, cv, Fe ox.	Section of a 4-m-high columnar structure formed by 2 coalesced chimneys. Composed predominantly of Zn sulfides where porosity increases from rim to the center. Fe sulfide form concentric layers around narrow conduits. A thin coating of Fe oxyhydroxides with worm casing on outer Fe-sulfide wall. Dimensions: 41 cm x 12 cm x 20 cm.
ALV2442-7 Monolith Vent[3]	44°59'24"	130° 12'05"	II (i)	-----	64	sp, wt, py, mc.	Large fossil beehive chimney. Interior has variable porosity with concentric layers of Zn sulfide enclosing arcuate cavities. Exterior has 3-mm-thick crust of botryoidal Fe sulfides and worm casings. Chimney located near the base of the southern end of sulfide mound. Length: 65 cm, approximate diameter: 40 cm.
ALV2444-3A	44° 57'10"	130° 12'51"	III (i)	-----	5.27	sp, wt, mc, cp, po, si, Fe ox.	Weathered chimney fragments with multiple conduits. Largely composed of Zn-sulfide with minor amounts of Cu-Fe sulfides. Worm tubes, foraminifera, and bacterial filaments on surfaces of the Fe-sulfide crust. Chimney located in thin sheet flows. Dimension of largest fragment: 18 cm x 20 cm x 15 cm.

[1](a) = active chimney, (i) = inactive chimney.

[2]Key mineralogy determined by hand specimen examination and analysis of polished thin sections: ang = anglesite, ap = apatite, anh = anhydrite, ba = barite, clay = Mg- and Fe-rich clays, cp = chalcopyrite, cv = covellite, Fe ox = goethite and amorphous Fe oxyhydroxides, gl = galena, gyp = gypsum, icb-cp = inter-grown isocubanite and chalcopyrite, mc = marcasite, Mn ox = manganese oxide, po = pyrrhotite, py = pyrite, si = amorphous and opaline silica, sp = sphalerite, sul = sulfur, wt = wurtzite.

[3]Position of Monolith, Fountain, and Pipe Organ vents supplied by R. Embley, written communication, 1994.

Type III Chimneys

Type III chimneys are typical of the Pipe Organ and Table vents, and are also the most abundant chimney type in the southern Cleft segment of Juan de Fuca Ridge (Koski and others, 1984: Paradis and others, 1988). Type III chimneys located at Pipe Organ Vent are tall (to 12 m) columnar structures, often constructed of two or more coalesced chimneys. Chimneys present at Table Vent are small columnar structures up to one meter in height (fig. 3*C*and 4*B*).. Fluid venting through a Type III chimneys at Pipe Organ Vent has a measured temperature of 261°C .

The chimneys typically have a thick-walled construction with narrow tortuous fluid channelways. The mineralogy of the chimney walls is dominated by dendritic sphalerite intergrown with subhedral to euhedral sphalerite, wurtzite, and subhedral pyrite. The narrow (1 to 5 mm) channelways are lined with concentric layers of sphalerite, isocubanite, and pyrrhotite. The chimney surfaces consist of a 1- to 2-mm-thick layer of Fe oxyhydroxides covering a 1- to 5-mm-thick layer of marcasite and pyrite (fig. 6*B*). Worm tubes, sponge attachments, foraminifera, and bacterial mats have been found on the exterior of Type III samples.

Type IV Chimneys

Most of the inactive solitary chimneys located near the fissures and referred to as Type IV have a distinctive low-temperature sulfide-silica-sulfate mineral assemblage. The chimneys are typically thick walled with a knobby exterior and numerous small fluid channelways (fig. 4*C*). The most abundant sulfide minerals are colloform and subhedral pyrite and marcasite; coarse-grained euhedral wurtzite and sphalerite are less abundant but concentrated around fluid channelways. Small blebs of chalcopyrite occur along the margins of wurtzite crystals in a few samples. Anglesite is the most abundant sulfate mineral, and forms subhedral to euhedral crystals interstitial to sulfides, especially around fluid channelways. Barite is present in the outer wall of several chimneys.

Open spaces and, especially, the interior channelways of most Type IV chimneys are coated or infilled with amorphous silica (fig. 6*C*). Amorphous silica textures typically are colloform or fibrous; the latter morphology has resulted from precipitation on the surfaces of filamentous bacteria.

BULK CHEMISTRY OF CHIMNEYS

Table 3 presents bulk chemical data for 23 chimney samples determined at the laboratories of the Geological Survey of Canada (GSC) and Bondar-Clegg & Company (BCC) in Ottawa, Canada. Major element oxides, Ag, Ba, Be, Co, Cr, Cu, Mn, Ni, Pb, Sc, Sr, V, Y, Yb, and Zr were analyzed by inductively coupled plasma/atomic emission spectrometry at GSC; As, Bi, Sb, Se, Te, and Mo by atomic absorption spectrometry at GSC; Br, Cd, Ce, Cs, Eu, Hf, Ir, La, Lu, Rb, Sm, Sn, Ta, Tb, Th, U, and W by neutron activation (except Cd, Sn, and W in samples ALV2429-1 and ALV2437-3A-2 by inductively coupled plasma/atomic emission spectrometry) at BCC; Fe (as FeO) and CO_2 by wet-chemical methods at GSC; total S by a combustion/infra-red method at GSC; and Au by a fire assay/DC plasma technique at BCC.

The two Type I samples from Monolith Vent have high but variable CaO, Cu, and Zn contents that reflect different proportions of anhydrite, chalcopyrite, and Zn sulfides in the chimneys. Pb, Ag, As, Ba, Co, and Sb are higher in the thicker-walled chimney (ALV2259-1). The active, anhydrite-rich Type II chimneys (ALV2261-2C and ALV2433-2C) have high Ca and Sr contents whereas samples of fossil beehive structures (e.g. ALV2259-2, ALV2436-1F, and ALV2442-7) contain much lower Ca and Sr and higher metal contents, especially Zn and Cd.

TABLE 3. Chemical Data for Hydrothermal Sulfide Chimney Samples

Chimney Type	I	I	II	II	II	II	II	II	II	II	III
Sample number	ALV2259 - 1	ALV2429 - 1	ALV2259 - 2	ALV2261 - 2C	ALV2429 - 2	ALV2433 - 2C - 1B	ALV2436 - 1F	ALV2442 - 7A - 3A	ALV2442 - 7A - 3B	ALV2442 - 7A - 3C	ALV2094 - 4A
wt %											
SiO_2	3.1	5.0	2.5	0.15	<0.5	<0.5	0.6	1.3	<0.5	1.3	13.9
TiO_2	n.d.	<0.02	n.d.	n.d.	<0.02	<0.02	<0.02	0.02	<0.02	<0.02	n.d.
Al_2O_3	0.22	0.49	0.85	0.05	<0.2	<0.2	0.24	0.83	<0.2	0.39	0.15
MgO	0.04	0.46	0.01	0.04	0.05	0.34	<0.04	0.05	0.07	0.04	0.14
CaO	0.95	3.9	0.10	28.8	0.13	30.3	0.63	0.07	0.07	0.06	0.17
Na_2O	0.27	0.26	0.18	0.24	0.31	0.22	0.18	0.18	0.23	0.21	0.59
K_2O	0.13	0.08	0.05	0.08	0.11	0.08	0.05	0.06	0.09	0.07	0.15
CO_2	0.2	--	0.1	0.1	--	--	--	--	--	--	0.6
P_2O_5	0.05	--	0.04	0.04	0.04	0.04	0.04	0.03	0.05	0.04	0.22
Fe	13.7	21.6	7.8	4.9	11.3	7.2	12.9	40.1	2.5	6.9	9.0
Cu	8.60	20.4	0.55	0.12	0.44	0.69	0.59	0.0	0.3	1.2	0.35
Zn	34.1	12.1	51.2	11.7	49.7	5.0	46.7	3.2	60.7	55.3	40.4
Pb	0.06	0.01	0.11	0.02	0.09	0.01	0.06	0.07	0.18	0.03	0.22
S	34.0	31.0	32.8	27.3	33.5	27.8	34.7	48.7	32.7	29.8	28.1
ppm											
Ag	150	59	200	47	84	13	76	6	180	84	720
As	199	54	376	44	134	45	180	59	52	124	360
Au	0.18	0.06	0.28	0.12	0.17	0.03	0.19	0.01	0.04	0.23	0.25
Ba	1100	36	300	360	<30	60	<30	770	<30	<30	5100
Be	0.1	--	n.d.	0.3	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	n.d.
Bi	<0.2	<1	<0.2	<0.2	--	--	--	--	--	--	0.06
Br	--	--	--	--	22	14	5	15	18	3	--
Cd	--	549	--	--	1910	250	>2000	28	1040	>2000	--
Ce	--	--	--	--	<29	<16	<39	<34	<39	<40	--
Co	34	6	15	1	27	10	29	41	36	18	13
Cr	5	6	5	2	<10	10	<10	<10	<10	<10	24
Cs	--	--	--	--	<1.9	1	<2.5	2	<2.8	<2.7	--
Eu	--	--	--	--	<1	<1	<1	<1	<1	<1	--
Hf	--	--	--	--	<3	<1	<4	6	<4	<4	--
Ir	--	--	--	--	<0.05	<0.05	<0.11	<0.05	<0.12	<0.12	--
La	8	<5	10	9	<10	<10	<10	<10	<10	<10	1
Lu	--	--	--	--	<0.4	<0.2	<0.6	<0.4	<0.6	<0.6	--
Mn	120	110	120	60	180	<60	180	180	<60	60	1000
Mo	8	62	18	6	23	21	18	49	5	10	21
Ni	n.d.	2	4	n.d.	15	11	11	<10	13	12	n.d.
Rb	--	--	--	--	<17	<5	<23	<16	<25	<23	--
Sb	31	13	44	10	27	5	31	2	18	46	117
Sc	2	--	0.5	0.3	<0.5	1.1	<0.5	0.8	<0.5	<0.5	--
Se	19	--	3	4	1	7	1	1	0.28	5	n.d.
Sm	--	--	--	--	0.15	0.34	0.19	0.18	0.15	<0.10	--
Sn	--	60	--	--	<100	<100	<100	<100	<100	<100	--
Sr	42	252	2	1900	23	1700	33	52	<20	<20	43
Ta	--	<100	--	--	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	--
Tb	--	--	--	--	<1.0	<0.5	<1.3	<0.5	<1.5	<1.7	--
Te	--	67	--	--	16	<10	<10	<10	<20	<20	--
Th	--	--	--	--	<0.8	<0.2	<1.1	<0.8	<1.2	<1.2	--
U	--	--	--	--	<0.5	<0.2	<0.7	3.2	<0.7	<0.7	--
V	n.d.	11	5	n.d.	<5	<5	<5	<5	<5	<5	22
W	--	<20	--	--	41	43	62	233	67	43	--
Y	n.d.	<5	n.d.	1	<5	<5	<5	<5	<5	<5	--
Yb	0.8	--	n.d.	n.d.	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.2
Zr	n.d.	38	n.d.	n.d.	<10	<10	<10	19	<10	<10	--

n.d. = not detected; -- = no data

TABLE 3. Chemical Data for Hydrothermal Sulfide Chimney Samples (Continued)

Chimney Type	III	III	III	IV	IV	IV	IV	IV	IV	IV	IV	IV
Sample number	ALV2265 - 1	ALV2269 - 7	ALV2437 3A - 2	ALV2078 - 2A - 2	ALV2081 - 1B	ALV2081 - 2B	ALV2093 - 2B	ALV2258 - 1	ALV2266 - 3A	ALV2435 - 3 - 1	ALV2435 - 3 - 2	ALV2435 - 9A - 1F
wt %												
SiO_2	1.04	0.36	26.7	35.6	31.6	32.7	34.6	35.8	34	36.3	28.9	61.6
TiO_2	n.d.	n.d.	<0.02	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.02	<0.02	<0.02
Al_2O_3	0.12	0.12	0.04	1.4	0.80	1.2	0.90	0.92	1.7	0.89	0.51	0.99
MgO	0.07	0.02	0.10	0.85	0.03	0.04	0.16	0.02	0.09	0.04	0.06	0.20
CaO	0.10	0.08	0.36	0.30	0.21	0.23	0.24	0.18	0.34	0.21	0.18	0.22
Na_2O	0.31	0.18	0.94	0.46	0.27	0.37	0.85	0.28	0.54	0.42	0.44	0.53
K_2O	0.12	0.07	0.11	0.45	0.26	0.43	0.45	0.25	0.35	0.25	0.27	0.30
CO_2	0.5	0.1	--	0.6	0.5	0.4	0.5	0.2	0.6	--	--	--
P_2O_5	0.05	0.04	--	0.14	0.14	0.16	0.20	0.02	0.05	0.07	0.10	0.09
Fe	9.0	5.7	11.8	18.7	26.6	22.7	21.1	25.3	18.4	21.1	28.2	13.9
Cu	0.58	0.29	0.33	0.15	0.13	0.10	0.07	0.02	0.12	0.07	0.06	0.02
Zn	48.3	54.8	39.6	5.2	2.8	4.3	3.9	0.89	8.2	3.6	2.2	0.7
Pb	0.06	0.16	0.14	2.7	0.07	0.38	0.40	0.56	2.50	1.9	0.9	0.31
S	34.4	33.5	26.7	23.4	32.0	28.7	26.5	31.3	17.8	30.2	29.8	14.2
ppm												
Ag	99	280	203	860	210	310	180	550	590	340	320	77
As	136	375	239	195	204	288	267	127	327	78	96	162
Au	0.11	0.19	0.51	0.33	0.27	0.44	0.29	0.30	0.40	0.28	0.30	0.26
Ba	920	270	98	10000	30	490	660	40	170	<30	30	350
Be	n.d.	n.d.	--	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.5	<0.5	<0.5
Bi	<0.2	<0.2	<1	0.04	0.02	0.23	0.13	<0.2	<0.2	--	--	--
Br	--	--	--	--	--	--	--	--	--	25	23	17
Cd	--	--	765	--	--	--	--	--	--	<12	13	<5
Ce	--	--	--	--	--	--	--	--	--	<30	<30	<23
Co	28	13	1355	6	4	5	5	220	57	45	31	88
Cr	6	5	5	26	8	24	24	n.d.	7	15	19	13
Cs	--	--	--	--	--	--	--	--	--	<1.1	<1.1	<0.5
Eu	--	--	--	--	--	--	--	--	--	<2	<2	<1
Hf	--	--	--	--	--	--	--	--	--	<4	<4	5
Ir	--	--	--	--	--	--	--	--	--	<0.05	<0.05	<0.05
La	10	9	<5	--	--	--	--	6	7	<10	<10	<10
Lu	--	--	--	--	--	--	--	--	--	0.5	<0.4	<0.2
Mn	120	60	70	1100	1000	720	720	500	110	660	180	660
Mo	21	14	120	34	81	84	92	76	96	74	68	67
Ni	n.d.	5	8	n.d.	17	12	6	n.d.	5	20	23	<10
Rb	--	--	--	--	--	--	--	--	--	<17	<17	<13
Sb	23	56	34	134	30	47	35	113	218	73	75	83
Sc	0.3	n.d.	--	--	--	--	--	0.2	0.3	1.3	0.9	0.6
Se	3	2	--	6	3	12	8	9	32	5	4	8
Sm	--	--	--	--	--	--	--	--	--	0.18	<0.10	<0.22
Sn	--	--	133	--	--	--	--	--	--	<100	<100	<100
Sr	4	2	45	290	12	67	85	46	97	46	45	72
Ta	--	--	<100	--	--	--	--	--	--	<0.5	<0.5	<0.5
Tb	--	--	--	--	--	--	--	--	--	<0.5	<0.5	<0.5
Te	--	--	164	--	--	--	--	--	--	<10	<10	<10
Th	--	--	--	--	--	--	--	--	--	<0.9	<0.9	<0.8
U	--	--	--	--	--	--	--	--	--	0.9	2.2	6.5
V	n.d.	n.d.	<2	15	6	14	22	n.d.	5	<5	11	6
W	--	--	<20	--	--	--	--	--	--	216	217	465
Y	n.d.	n.d.	<5	--	--	--	--	n.d.	n.d.	<5	<5	<5
Yb	n.d.	n.d.	--	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.5	<0.5	<0.5
Zr	n.d.	n.d.	<5	--	--	--	--	n.d.	n.d.	<10	<10	<10

n.d. = not detected -- = no data

The four Type III chimneys have high Zn/Cu ratios (>80) and high Ag contents (average 325 ppm) similar to Zn-sulfide-rich chimneys recovered from the southern Cleft segment of Juan de Fuca Ridge (Koski and others, 1984; Bischoff and others, 1983). Type IV chimneys, characterized by the low-temperature mineral assemblage marcasite + pyrite + wurtzite + amorphous silica + anglesite, have high SiO_2 (maximum 61.6%, average 36.7%), Pb (2.7%, 1.1%), Ag (860 ppm, 382 ppm), Sb (218 ppm, 90 ppm), Mn (1100 ppm, 628 ppm), Mo (96 ppm, 75 ppm), and Cr (26 ppm, 15 ppm), and low Cu (0.15%, 0.08%). The relatively high Mn contents are probably related to thin surface coatings of Mn oxide.

SUMMARY

The four chimney types represent deposition of hydrothermal minerals in response to distinctly different fluid flow characteristics (Koski and others, 1994). Type I chimneys result from the rapid focused flow of high-temperature (>310°C) fluids through the Monolith sulfide mound. In contrast, Type II beehive structures form where slightly lower temperature (293° to 312°C) fluids are discharged more diffusely through mounds and chimneys. Type III chimneys form from focused flow of lower-temperature (261° C) Zn-rich fluids through basaltic substrates. Similarly, Type IV chimneys are built directly on volcanic substrates, but their mineral assemblages, textures, lack of mineral zonation, and fluid inclusion characteristics (K.-Y. Lee, unpublished data, 1993) indicate deposition from hydrothermal fluids at low temperatures (<250°C) and sluggish flow rates.

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