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Mineralogy and chemistry of hydrothermal chimneys from the northern Cleft segment, Juan de Fuca Ridge

by
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INTRODUCTION

The 70-km-long Cleft segment of the Juan de Fuca Ridge extends from the Blanco Fracture Zone northward to the slightly offset Vance segment at 45° 05′ N latitude (Johnson and Holmes, 1989; Embley and Chadwick, 1994) (Figure 1). A distinct axial valley displaying many fissures and volcanic eruptive features marks the ridge (Embley and others, 1991; Embley and Chadwick, 1994). Within the valley, sheet and lobate lava flows have erupted onto blocky lava flows from fissures that cut the west flank of several long pillow lava mounds between 44° 55.7′ N latitude and 44° 59.5′ N latitude (Figure 2). The sheet flows have fresh glassy surfaces with scarce sediment cover, indicating a very recent eruption (Embley and others, 1991; Embley and Chadwick, 1994). Bathymetric changes recorded by repeated multibeam sonar scans indicate eruption of pillow lava mounds at about 46° 01′ N latitude between 1983 and 1987 (Chadwick and others, 1991; Fox and others, 1992). The recent sheet flows, pillow lava mounds, and fissures are manifestations of continuing tectonic extension and volcanic eruptions at the axis of spreading (Koski and others, 1994). The detection in 1986 and 1987 of thermal and chemical "megaplumes" produced by enormous exhalations of hydrothermal fluid supports the hypothesis that the northern Cleft segment is currently in a stage of active volcanism (Baker and others, 1987, 1989). Recent submersible investigations of the northern Cleft segment have revealed the presence of sulfide mounds and chimneys at both active and inactive vent sites (Butterfield and Massoth, 1994; Embley and Chadwick, 1994; Koski and others, 1994) (Figure 2).

The hydrothermal activity of the northern Cleft segment includes: (1) diffuse low-temperature (to 60°C) fluid flow through sheet flow lava and (2) focused high-temperature (to 330°C) flow through sulfide chimneys at three sites known as the Pipe Organ, Monolith, and Fountain vents. An earlier period of hydrothermal activity along the fissure system is represented by inactive chimneys (Koski and others, 1994).

Four types of hydrothermal chimneys have been identified at the northern Cleft segment (Koski and others, 1994):

Type I chimneys on mounds grow from rapid, focused fluid flow at temperatures ranging from 310-328°C. Type I chimneys from the Monolith Vent have smooth-walled central channelways lined with chalcopyrite, a thick middle wall composed of anhydrite, sphalerite, wurtzite, chalcopyrite, and pyrite, and a narrow outer wall composed of marcasite, pyrite, and sphalerite. Small amounts of amorphous silica, barite, Mg-Fe silicates, galena, and apatite are present in the middle wall.

Type II chimneys, bulbous forms resembling beehives, are deposited from diffuse fluid flow through the tops of mounds at temperatures ranging from 293-312°C. Initially, Type II chimneys are shells composed of abundant anhydrite with minor sphalerite, pyrite, wurtzite, chalcopyrite, and traces of pyrrhotite. Continued hydrothermal discharge results in complete replacement and infilling of the anhydrite shell by sulfides, especially sphalerite, and the fragile structures are preserved.

Type III chimneys have a columnar or spindle shape and grow directly from fissures in basalt. Fluid flow through Type III chimneys at Pipe Organ Vent is slow but focused, and has a temperature of about 260°C. Type III chimneys are composed of abundant sphalerite, with lesser amounts of marcasite, pyrite, isocubanite, chalcopyrite, pyrrhotite, and anhydrite, and minor amounts of barite, amorphous silica, and galena. Type III chimneys are dominated by porous deposits of dendritic sphalerite containing small, tortuous channelways. Some chimneys display thin bands of colloform pyrite/marcasite which mark the location of the outer wall during earlier stages of chimney growth. The small, twisting channelways are lined with colloform sphalerite, subhedral isocubanite grains containing chalcopyrite lamellae, and thin tablets of pyrrhotite deposited with the basal pinacoid perpendicular to the flowline of the channelway. The chimneys have outer walls of pyrite/marcasite, amorphous iron oxyhydroxide, barite, and bacterial filaments.

Type IV chimneys are jagged pinnacles deposited directly on basalt. They are thought to have formed from diffuse, slow fluid flow with temperatures of less than 250°C (Koski and others, 1994). These chimneys are composed of pyrite, marcasite, and amorphous silica, with minor sphalerite, wurtzite, and Al-phyllosilicates, and trace amounts of anglesite, barite, chalcopyrite, and galena. Colloform and granular pyrite, marcasite, sphalerite, and wurtzite are thickly overgrown by amorphous silica that ultimately plugs channelways and fills interstices. Anglesite euhedra and skeletal microcrystals of galena are included in the silica overgrowth. Barite forms rosette-like sprays of microcrystals in the peripheries of some chimneys.

In this paper we present detailed petrography, mineralogy, and partial chemistry of selected chimney samples from 18 sites in the northern Cleft segment of the Juan de Fuca Ridge (Figure 2). Emphasis is placed on late-stage silicates, oxides, phosphates, and sulfates. The general chemistry of bulk samples, with emphasis on sulfides from this suite, was presented by Koski and others (1994).

METHODS

Thirty chimney samples recovered by *Alvin* were slabbed in cross-section and 150 overlapping uncovered doubly-polished thin sections were prepared from the slabs. The polished thin sections were examined in detail in both transmitted and reflected light (Heald-Wetlaufer and others, 1982) using a Leitz Orthoplan research microscope. Sample descriptions and thin section petrography are summarized in Table 1.

To better characterize the fine-grained late-stage hydrothermal and alteration phases, selected subsamples were analyzed by powder X-ray diffraction techniques. Nineteen 40 mg subsamples of silicate-, oxide-, phosphate-, and sulfate-bearing materials were powdered, affixed as water slurries to glass slides, and air dried (Oinuma and Kobayashi, 1961). Stripchart diffractograms covering a scanning range of 3-80°2θ were produced by analyzing the subsamples on a Rigaku Miniflex X-ray diffractometer using CuKα Ni-filtered radiation generated at 30 kV and 10 mA. Subsamples containing lattice-expandable phyllosilicates were further subjected to treatment with ethylene glycol vapor at 60° C for 4 hours and then X-rayed again to examine the lattice displacement (Brunton, 1955). X-ray diffraction analyses of the late-stage hydrothermal and alteration phases are summarized in Table 2.

The qualitative chemistry of the late-stage hydrothermal and alteration phases was determined by scanning electron microscopy (SEM) in conjunction with energy dispersive X-ray analysis (EDAX). Eighteen doubly-polished thin sections and 14 SEM mounts of corresponding material from the thin section sample wafers were selected for analysis. A total of 68 EDAX point analyses and 144 SEM photomicrographs were made. Chemical data for the late-stage hydrothermal and alteration phases are summarized in Table 2.

RESULTS

Examination of the samples revealed that the internal structure of many of the chimneys is commonly dominated by a very porous intergrowth of dendritic, colloform, and granular Zn and Fe sulfides. Smaller amounts of Pb sulfide, Cu-Fe sulfides, Ca, Ba, Pb, Fe, K-Fe, and Zn sulfates, Ca phosphates, Al and Mg-Fe silicates, Si, Fe, and Mn oxides, and native sulfur occur as accessory phases and in places major components. The mineral phases encountered in the chimney samples, with examples of occurrences and textures, are described below:

Sulfides

Sphalerite (ZnS) is the dominant zinc sulfide in all the chimney types. This phase composes the superstructure of many chimneys either by original deposition from hydrothermal fluids (e.g., sample ALV2437-3A, Table 1) or by replacement of pre-existing minerals (sample ALV2442-7A, Table 1). Dendritic crystallites and colloform overgrowths are the most common forms. The dendrites are commonly intergrown with smaller amounts of other sulfides such as wurtzite, pyrite, marcasite, pyrrhotite, and chalcopyrite. Euhedral crystals of sphalerite are deposited as an overgrowth on the less crystalline forms locally in interstices and along channelways, (e.g., sample ALV2444-3A-1, Table 1). The mineral commonly contains included microcrysts of pyrite and chalcopyrite and less commonly of isocubanite and galena.

Wurtzite (ZnS) is the next most abundant zinc sulfide in the chimneys. This phase mimics sphalerite in its occurrence except that it does not occur as dendritic crystallites. Wurtzite is most abundant as striking euhedra birefringent in bright red-orange hues under crossed nicols (e.g., sample ALV2434-1-20, Table 1). The birefringence of colloform wurtzite is not so obvious owing to the small size of the crystallites making up the bleb-like forms. Colloform wurtzite commonly overgrows colloform sphalerite. Euhedral wurtzite crystals typically occur as overgrowths on sphalerite and form aggregates lining cavities and channelways. In all its forms, wurtzite commonly contains included microcrysts of both pyrite and chalcopyrite, and less commonly of isocubanite and galena.

Pyrite (FeS_2) is generally the most abundant iron sulfide occurring in the chimneys. Particularly abundant in Type IV chimneys, pyrite is commonly intergrown with its polymorph marcasite in colloform aggregates of interlocking microcrystals. Some Type IV chimneys (e.g., sample ALV2078-2B, Table 1), are so rich in this intergrowth that the other phases present are minor in abundance. Like sphalerite, pyrite also forms dendrites and euhedra, though these are much less common than the colloform habit. These forms may occur as overgrowths on colloform pyrite/marcasite (e.g., sample ALV2078-2A, Table 1). Discrete microscopic pyrite euhedra are commonly intergrown with the other minerals in the interior of all the chimney types.

Marcasite (FeS_2), a striking birefringent contrast in polarized reflected light to its isotropic polymorph pyrite, stands out boldly in the intergrowths described above. The mineral commonly mimics pyrite in its occurrence in all the chimney types. Thin euhedral plates of the phase, commonly deposited with the basal pinacoid perpendicular to the substrate, occur as overgrowths on colloform and dendritic pyrite/marcasite (e.g., sample ALV2078-2A, Table 1). The phase is also encountered intergrown with other sulfides (e.g., sample ALV2258-1, Table 1).

Pyrrhotite ($Fe_{1-x}S$) is deposited locally in some Type III chimneys as tabular crystals commonly associated with chalcopyrite and isocubanite in a porous boxwork lining or infilling interior channelways. This boxwork may form the bulk of the interior of some Type III chimneys (e.g., sample ALV2444-3A, Table 1). Pyrrhotite is very susceptible to oxidation and is commonly replaced entirely or in part with iron oxyhydroxide. The mineral is locally intergrown with other sulfides of the groundmass (e.g., sample ALV2437-3A, Table 1).

Chalcopyrite ($CuFeS_2$) is a major component in Type I chimneys (e.g., sample ALV2429-1, Table 1). In this chimney type, the mineral commonly forms a dense, thick plating of interlocking crystals whose long axes are perpendicular to the vector of fluid flow along the large tubular central channelways. Chalcopyrite commonly replaces earlier-formed phases such as anhydrite in these chimneys. In other chimneys, chalcopyrite is intergrown with other sulfide phases as a minor component of the chimney wall and also is deposited as inclusions in Zn-sulfides.

Isocubanite ($CuFe_2S_3$) is locally intergrown with chalcopyrite in some Type III chimneys (e.g., sample ALV2436-1E, Table 1). The phase commonly includes exsolution lamellae of chalcopyrite and is in places overgrown by chalcopyrite (e.g., sample ALV2444-3A, Table 1).

Galena (PbS) occurs as a rare accessory phase in some chimneys. The phase commonly occurs as minute cubic crystals and skeletal crystals associated with and included in wurtzite and sphalerite (e.g., sample ALV2266-3, Table 1), in Type IV chimneys. The mineral also occurs as inclusions in amorphous silica deposits (e.g., sample ALV2078-2A, Table 1) in Type IV chimneys.

Sulfates

Anhydrite ($CaSO_4$) is a major component of Type I, Type II, and some Type III chimneys and is the first mineral to precipitate in Type I and Type II chimneys. Some youthful Type II chimneys are composed almost entirely of anhydrite (e.g., sample ALV2433-3C, Table 1), whereas mature Type II chimneys (e.g.) sample ALV2442-7 (Table 1) are porous Zn sulfide-rich structures in which the original anhydrite has been replaced. Anhydrite commonly remains as isolated relicts in these chimneys.

Barite ($BaSO_4$) occurs in all the chimney types as a minor accessory phase. The greatest abundance occurs in Type IV chimneys. In all its occurrences, barite is deposited as rosette-like sprays of minute bladed prismatic crystals. The rosettes are commonly concentrated in and just below the colloform pyrite/marcasite outer wall of the chimneys and less commonly on the walls of channelways.

Anglesite ($PbSO_4$) occurs as a minor accessory phase in Type IV chimneys. The mineral is commonly deposited as colorless transparent euhedra enclosed in opaline silica (e.g., sample ALV2266-3, Table 1). Anglesite also occurs less commonly in association with Al-phyllosilicates, opaline silica, and sulfur (e.g., sample ALV2258-1, Table 1).

Jarosite [$KFe_3(SO_4)_2(OH)_6$], a golden yellow alteration product of iron sulfides, occurs as thin coatings on colloform pyrite/marcasite in the outer wall of Type IV chimneys. Such deposits are commonly composed of (1) tabular or rhombic microcrystals of pure jarosite (e.g., sample ALV2435-3, Table 1, Figure 3), or (2) a mixture of jarosite and clay-like phyllosilicates or iron oxyhydroxide.

Bianchite ($ZnSO_4.6H_2O$) was identified by microscopy, SEM imagery (Figure 4), EDAX analysis (Figure 4), and (without certainty) by XRD analysis in sample ALV2094-4A1 (Table 1). The mineral occurs as rare efflorescences of microcrystals on sphalerite.

Gypsum ($CaSO_4.2H_2O$) occurs in small amounts in some of the chimneys as an alteration product of anhydrite. The mineral replaces anhydrite by hydration and occurs as elongate rhombic euhedra on the periphery of anhydrite deposits (e.g., sample ALV2094-1A, Table 1). Gypsum also occurs locally as single euhedra in interstices (e.g., sample ALV2094-4A1, Table 1).

Phosphates

EDAX analyses of some iron oxyhydroxide deposits on the outer walls of chimneys detected Ca and P. These elements were also detected in rare 1-10 micron thick interlayer deposits in Fe and Mg-Fe-silicate overgrowths on sphalerite crystals in sample ALV2429-1. XRD analyses of these deposits produced little evidence of any discrete phosphate mineral species. A single X-ray line for dahllite (carbonate-apatite) [$Ca_5(PO_4,CO_3)_3(OH)$] was encountered in the analyses of the outer walls of samples ALV2258-1 and ALV2435-3 (Table 2). A single X-ray line for hydroxylapatite [$Ca_5(PO_4)_3(OH)$] was encountered in the analysis of the outer wall of sample ALV2431-3A-1A-1 (Table 2). Neither of these mineral species were detected through transmitted light microscopy or SEM photomicrography.

Silicates

Several unidentified smectites or smectite-like phyllosilicates commonly occur in interstices of the chimneys as microspherules composed of radiating microcrystals. The microspherules are locally clustered in loose aggregates in sample ALV2434-1-20B-1A (Figure 5), a Type III chimney, and as layered overgrowths on sulfides in sample ALV2094-1A-8 to 9A (Figure 6), a Type IV chimney. Most of these phases yielded a single indistinct line-broadened basal (001) XRD reflection near 5°2θ, indicating poor crystallinity or very small crystal size (Klug and Alexander, 1962). On treatment with glycol, the basal XRD reflection of some of these phyllosilicates (e.g., sample ALV2094-1A-8 to 9A, Table 2), was shifted slightly and intensified. This reaction indicates that the phyllosilicates in these samples are probably true smectites. The phyllosilicates in some of the samples, even though displaying the 5°2θ line, were unchanged by treatment with glycol (e.g., sample ALV2442-7A-1B-5, Table 2). The phyllosilicates in some samples (e.g., ALV2434-1-20B-1A, Table 2) displayed two basal reflections in the 5-7°2θ range and may represent mixed-layer smectite/chlorite. Background in all the samples analyzed by XRD is high, which may indicate the presence of an amorphous component (Klug and Alexander, 1962).

EDAX analyses indicate that the cation composition of most of the phyllosilicates is predominantly Si+Al (Figure 5). Other elements detected in minor or trace amounts are Ca, Fe, Mn, K, Na, V, and Zn (Table 2).

The Al-phyllosilicates occur in greatest abundance in the interiors of Type II, III, and IV chimneys, especially in interstices around central channelways. Though generally minor in abundance, these phases may become major components in some chimneys (e.g., sample ALV2442-7A, Figure 8). In this chimney, the interstices are tightly packed with Al-phyllosilicate in a broad central aureole around the central channelway.

Mg-Fe silicate minerals with variable Mg and Fe content were observed in sample ALV2429-1, a Type I chimney (Figures 9 and 10, Table 2). In this sample, sphalerite crystals near the outer wall are overgrown with thin layers of fibrous Mg-Fe-silicates. The layer in contact with the sphalerite is high in Mg (Figure 9) and is colorless in transmitted light. The subsequent overgrowth is high in Fe (Figure 10) and is brown in transmitted light. One questionable broad, low intensity XRD line was detected near 12°2θ, but no response to glycolation was observed.

Amorphous silica is abundant in Type IV chimneys and is present in smaller amounts in other chimney types as both colloform overgrowths (e.g., sample ALV2094-1A, Figure 11, Table 1), and as porous networks of filaments, rods, and microspherules (e.g., sample ALV2266-3, Figure 12, Table 1). The latter forms resemble bacteria that are abundant at all active chimneys.

The amorphous silica deposits are typically isotropic and dark between crossed nicols. Some deposits, particularly those immediately overgrowing sulfides, display faint birefringence between crossed nicols. High magnification does not reveal crystallites or differences in refractive index. The birefringence may result from the presence of opaline silica, but X-ray diffraction analyses did not reveal the presence of crystalline silica phases in any of the samples.

Oxides

Amorphous iron oxyhydroxide occurs as an alteration product of iron sulfides in all of the chimney types. The substance may also be deposited by direct precipitation from hydrothermal fluid. The color is commonly brownish-orange or brownish-red and the form may be powdery and fragile or resinous and compact with a conchoidal fracture (e.g., sample ALV2435-3-2 TOP, Figure 13). Textural variations in the resinous form include banding (e.g., sample ALV2435-8A-1, Figure 14), and mottling (e.g., sample ALV2094-4A-3A, Figure 15). The variations are caused by inhomogeneities in chemical composition, particularly with regard to Fe/Si ratio. Inactive chimneys and inactive parts of active chimneys commonly have rusty exterior coatings of porous colloform iron oxyhydroxide (e.g., sample ALV2429-1, Figure 16).

The colloform pyrite/marcasite intergrowth of chimney outer walls is commonly altered in part to iron oxyhydroxide. Some of the iron oxyhydroxide deposits in the outer wall have branching stalks and beaded forms (e.g., sample ALV2431-3A-1B-1B-2, Figure 17). These structures may represent fossilized bacteria. Pyrrhotite in the chimney interiors and along channel walls is commonly altered to X-ray amorphous iron oxyhydroxide. No crystalline oxides or oxyhydroxides of iron were identified by XRD in any of the chimney samples. EDAX analyses commonly revealed the presence of Si and trace amounts of Al, Ca, Mg, Mn, P, K, Na, S, and Zn (Table 2).

Amorphous manganese oxyhydroxide occurs as soot-like deposits on the outer walls of some inactive chimneys (e.g., sample ALV2094-4A1, Table 1). No crystalline oxides or oxyhydroxides of manganese were detected in any of the samples analyzed by XRD. The element was detected by EDAX analysis in the iron oxyhydroxide crust on the outer wall of some samples (e.g., ALV 2435-3-2 TOP, Table 2).

Other minerals

Sulfur occurs as prismatic crystals in some Type III and Type IV chimneys (e.g., sample ALV2266-3), associated with sulfides, amorphous silica and phyllosilicates (Figure 18) or as granules intergrown with iron and zinc sulfides (e.g., sample ALV2444-3A, Table 1). The mineral also occurs as an overgrowth on sulfide grains or as single crystals lining interstices. Sulfur was positively identified by XRD only in sample ALV2094-1A-8 to 9 (Table 2) where it occurs with a smectite-like phyllosilicate, sphalerite, and wurtzite.

Iron sulfates were detected by SEM and EDAX analyses in several of the chimney samples but were not detected by XRD. Some of the sulfates are brightly birefringent in plane polarized light and occur as very thin crusts between underlying iron sulfide phases and overlying amorphous silica (e.g., sample ALV2258-1, Table 1).

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REFERENCES

Baker, E.T., Massoth, G.J., and Feely, R.A., 1987, Cataclysmic venting on the Juan de Fuca Ridge: Nature, v. 329, p. 149-151.

Baker, E.T., Lavelle, J.W., Feely, R.A., Massoth, G.J., and Walker, S.L., 1989, Episodic venting of hydrothermal fluids from the Juan de Fuca Ridge: Journal of Geophysical Research, v. 94, p. 9237-9250.

Berry, L.G., Post, B., Weissman, S., McMurdie, H., and McClune, W., eds., 1974, Selected powder diffraction data for minerals: Joint Commitee of Powder Diffraction Standards, Publication DBM-1-23, 1296 p.

Brunton, G., 1955, Vapor pressure glycolation of oriented clay minerals: American Mineralogist, v. 40, p. 124-126.

Butterfield, D.A., and Massoth, G.J., 1994, Geochemistry of North Cleft segment vent fluids: Temporal changes in chlorinity and their possible relations to recent volcanism, Journal of Geophysical Research: v. 99, p. 4951-4968.

Carroll, D., 1970, Clay minerals: a guide to their X-ray identification: Geological Society of America Special Paper 126, 80 p.

Embley, R.W., Chadwick, W.W., Perfit, M.R., and Baker, E.T., 1991, Geology of the northern Cleft segment, Juan de Fuca Ridge: Recent lava flows, seafloor spreading, and the formation of megaplumes: Geology, v. 19, p. 771-775.

Embley, R.W.and Chadwick, W.W., 1994, Volcanic and hydrothermal processes associated with a recent phase of seafloor spreading at the northern Cleft segment: Juan de Fuca Ridge: Journal of Geophysical Research, v. 99, p. 4741-4759.

Feely, R.A., Massoth, G.J., Baker, E.T., Cowen, J.P., Lamb, M.F., and Krogslund, K.A., 1990, The effect of hydrothermal processes on midwater phosphorus distribution in the northeast Pacific: Earth and Planetary Science Letters, v. 96, p. 305-318.

Fox, C.G., Chadwick, W.W., Jr., and Embley, R.W., 1992, Detection of changes in ridge-crest morphology using repeated multibeam sonar surveys: Journal of Geophysical Research, v. 97, p. 11149-11162.

Haymon, R.E., and Kastner, M., 1986, The formation of high temperature clay minerals from basalt alteration during hydrothermal discharge on the East Pacific Rise at 21°N: Geochimica et Cosmochimica Acta, v. 50, p. 1933-1939.

Heald-Wetlaufer, P., Foley, N.K., and Hayba, D.O., 1982, Applications of doubly-polished sections to the study of ore deposits, in Hagni, R.D., ed., Process mineralogy-II, Applications in metallurgy, ceramics, and geology: American Institute of Mining, Metalurgical, and Petroleum Engineers, p. 451-468.

Johnson, H.P., and Holmes, M.L., 1989, Evolution in plate tectonics: The Juan de Fuca Ridge, in: Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The Geology of North America, v. IV, The Eastern Pacific Ocean and Hawaii, Geological Society of America, p. 73-91.

Klug, H.P., and Alexander, L.E., 1962, X-ray diffraction procedures for polycrystalline and amorphous materials: John Wiley & Sons, Inc., New York, 716 p.

Koski, R.A., Jonasson, I.R., Kadko, D.C., Smith, V.K., and Wong, F.L.,1994, Compositions, growth mechanisms, and temporal relations of hydrothermal sulfide-sulfate-silica chimneys at the northern Cleft segment, Juan de Fuca Ridge: Journal of Geophysical Research, v. 99, p. 4813-4832.

Oinuma, K., and Kobayashi, K., 1961, Problems of rapid clay mineralogical analysis of sedimentary rocks: Clay Science, v. 1, p. 8-15.

Schoonen, M.A.A., and Barnes, H.L., 1991, Mechanisms of pyrite and marcasite formation from solution: III. Hydrothermal processes: Geochimica et Cosmoschimica Acta, v. 55, p. 3491-3504.

Seyfried, W.E., and Mottl, M.L., 1982, Hydrothermal alteration of basalt by seawater under seawater-dominated conditions: Geochimica et Cosmochimica Acta, v. 46, p. 985-1002.

Styrt, M.M., Brackmann, A.J., Holland, H.D., Clark, B.C., Pisutha-Arnond, V., Eldridge, C.S., and Ohmoto, H., 1981, The mineralogy and isotopic composition of sulfur in hydrothermal sulfide/sulfate deposits on the East Pacific Rise, 21°N latitude: Earth and Planetary Science Letters, v. 53, p. 382-390.

Von Damm, K.L., and Bischoff, J.L.,1987, Chemistry of hydrothermal solutions from the southern Juan de Fuca Ridge: Journal of Geophysical Research, v. 92, p. 11334-11346.

Zierenberg, R.A., Shanks, W.C., III, and Bischoff, J.L., 1984, Massive sulfide deposits at 21° N, East Pacific Rise: Chemical composition, stable isotopes, and phase equilibria: Geological Society of America Bulletin, v. 95, p. 922-929.

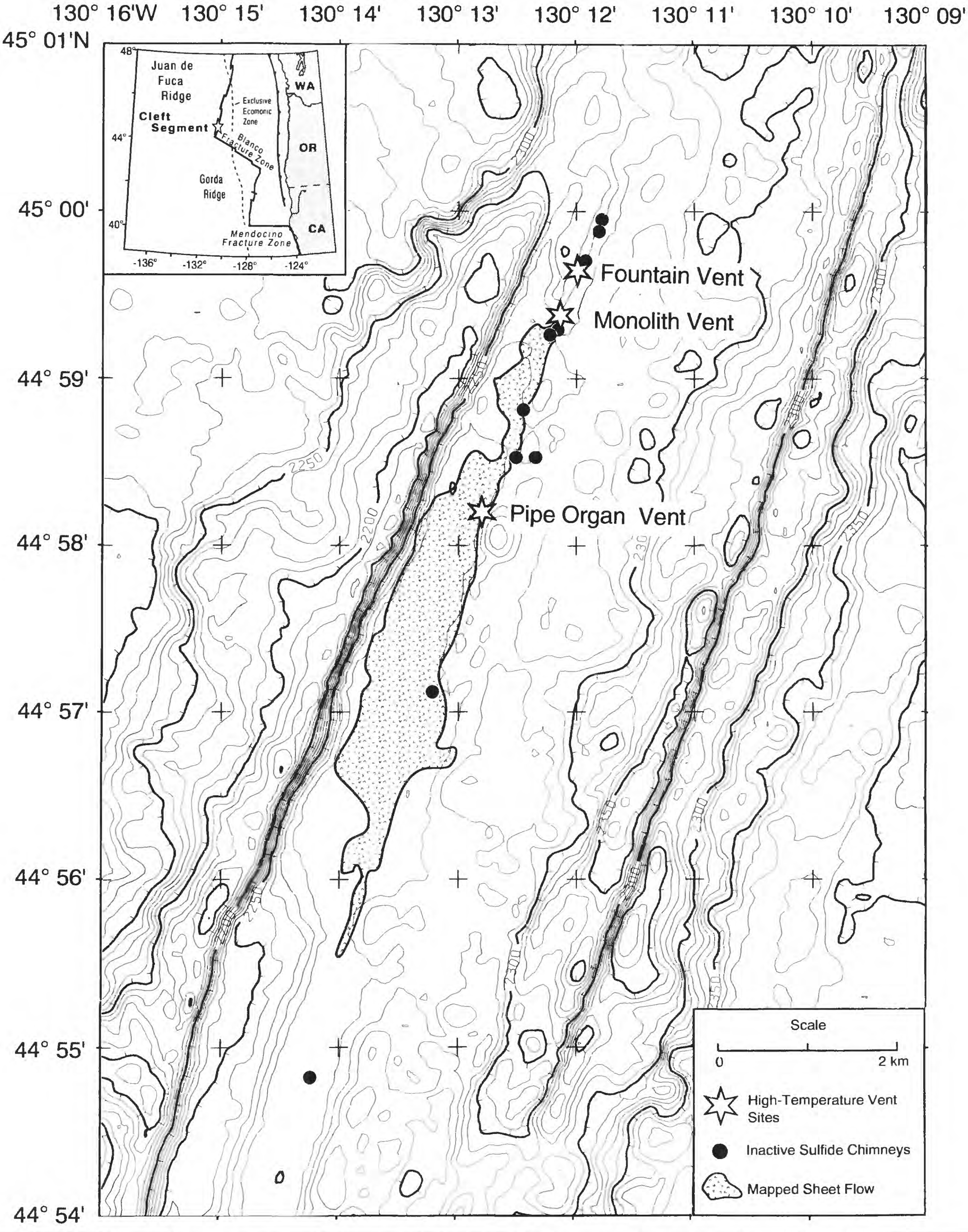

Figure 1. Location map and bathymetry of the northern Cleft segment showing area of recent sheet flow, high temperature vent sites, and locations of inactive chimney samples. Contour interval is 10m. Bathymetry and location of sheet flow provided by R. Embley.

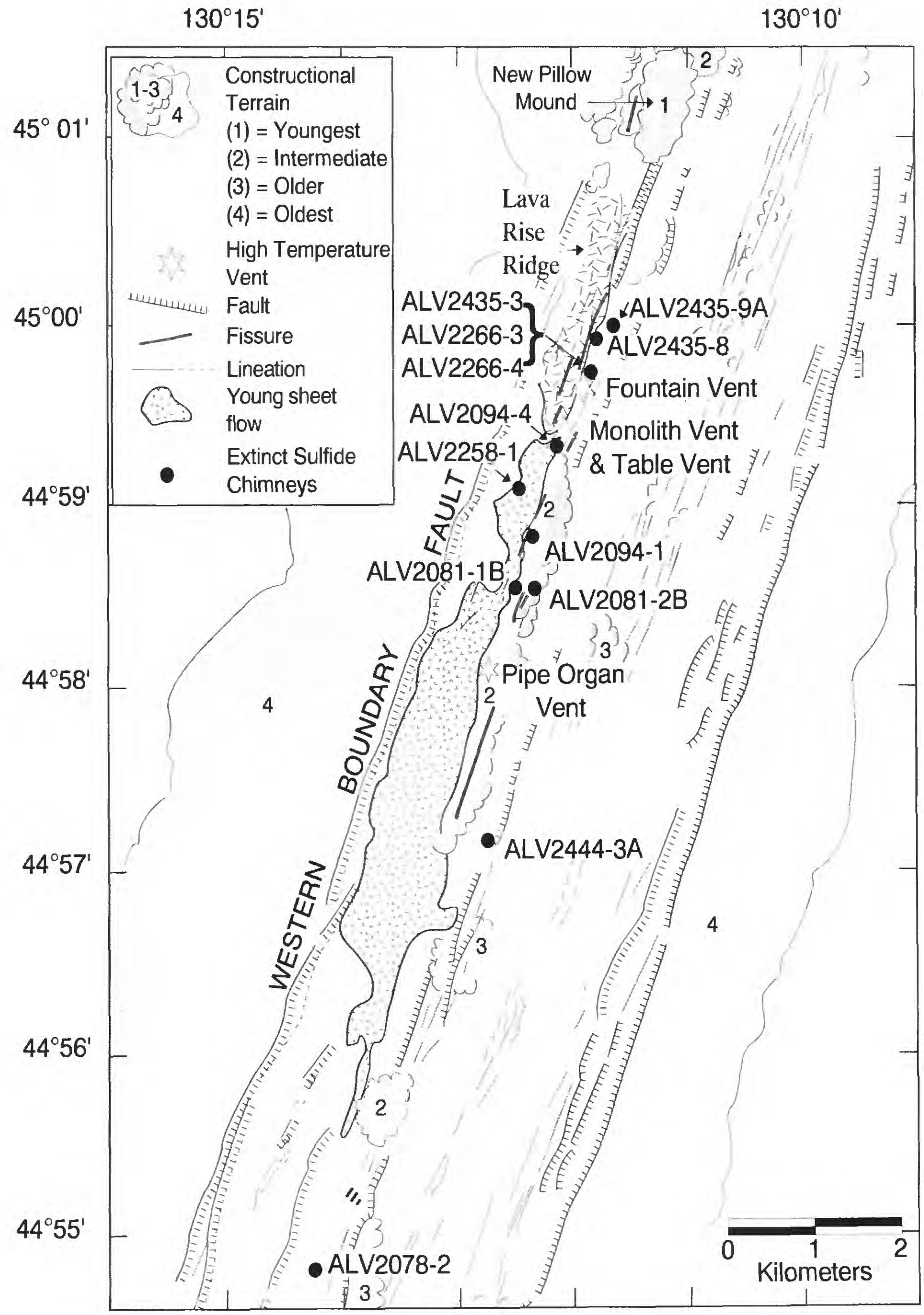

Figure 2. Interpretive geologic map of the northern Cleft segment showing bathymetry, area of young sheet flow lava, constructional terrains (pillow lava mounds), linear features, high-temperature vent sites, and inactive sulfide deposits. The pillow lava mounds are subdivided into four separate ages based on reflectivity and the amount of sediment cover (Embley and Chadwick, 1994). Samples are discussed in the report text and in Tables 1 and 2. Table and Brigadoon vent sites (not shown) are located 5 and 20m north of Monolith Vent, respectively. Sample numbers not shown on the map include: ALV2259, ALV2269, ALV2429-1, ALV2433, ALV2442 from Monolith Vent, ALV2261, ALV2265, and ALV2434 from Table Vent, ALV2429-2, ALV2431, ALV2436 from Fountain Vent, and ALV2437 from Pipe Organ Vent. Base map modified from Embley and Chadwick (1994).

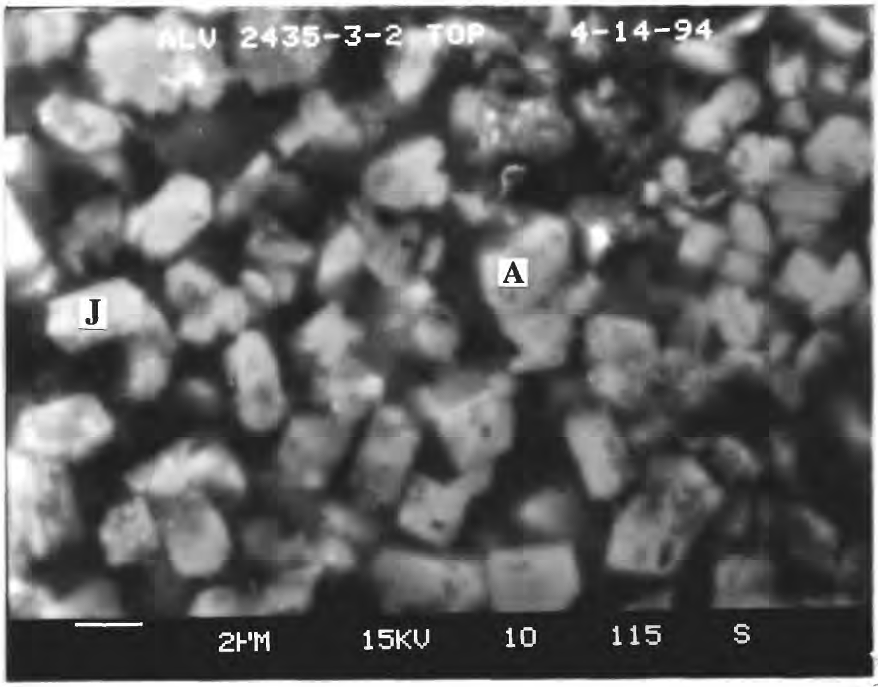

Figure 3a. ALV2435-3-2 TOP: secondary electron SEM photomicrograph of jarosite crystals coating X-ray amorphous iron oxyhydroxide crust (J=jarosite, A=point analyzed). Bar at lower left represents 2 microns.

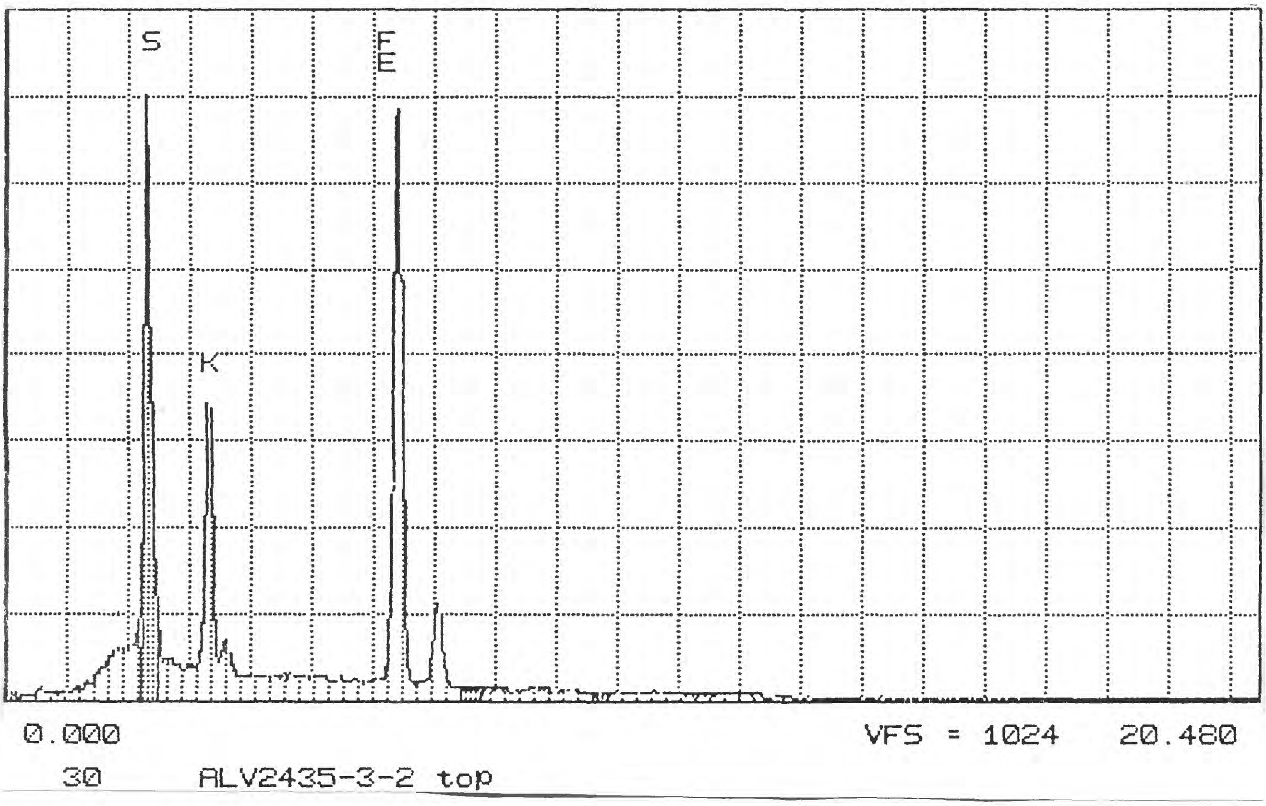

Figure 3b. EDAX spectrogram from point analysis of jarosite.

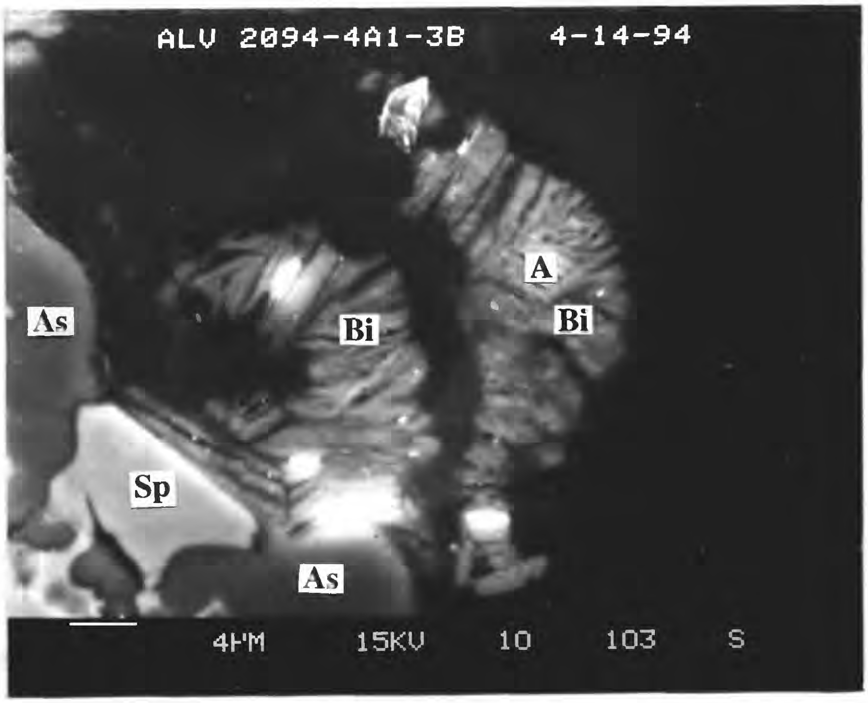

Figure 4a. ALV2094-4A1-3B: secondary electron SEM photomicrograph of bianchite ($ZnSO_4.6H_2O$) (?) on sphalerite (As=amorphous silica, Sp=sphalerite, Bi=bianchite (?), A=point analyzed). Bar at lower left represents 4 microns.

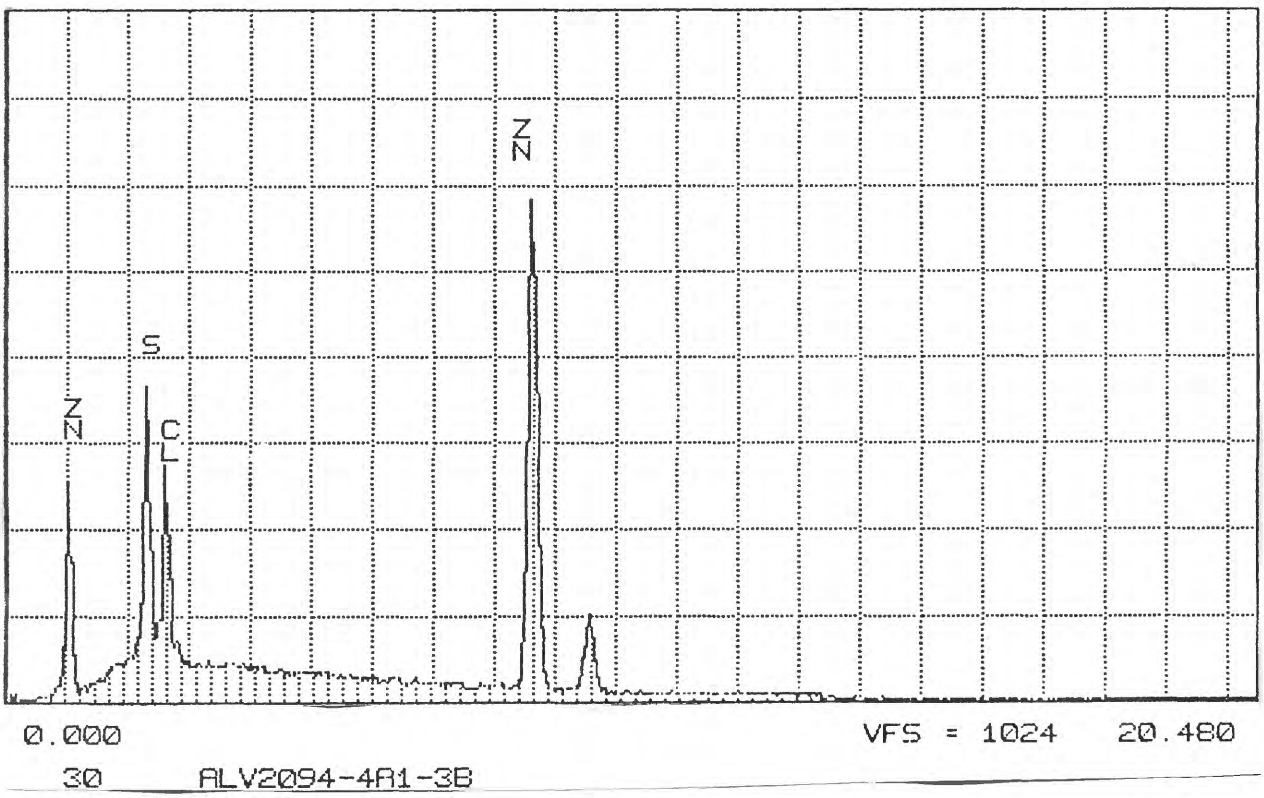

Figure 4b. EDAX spectrogram from point analysis of bianchite (?) overgrowth.

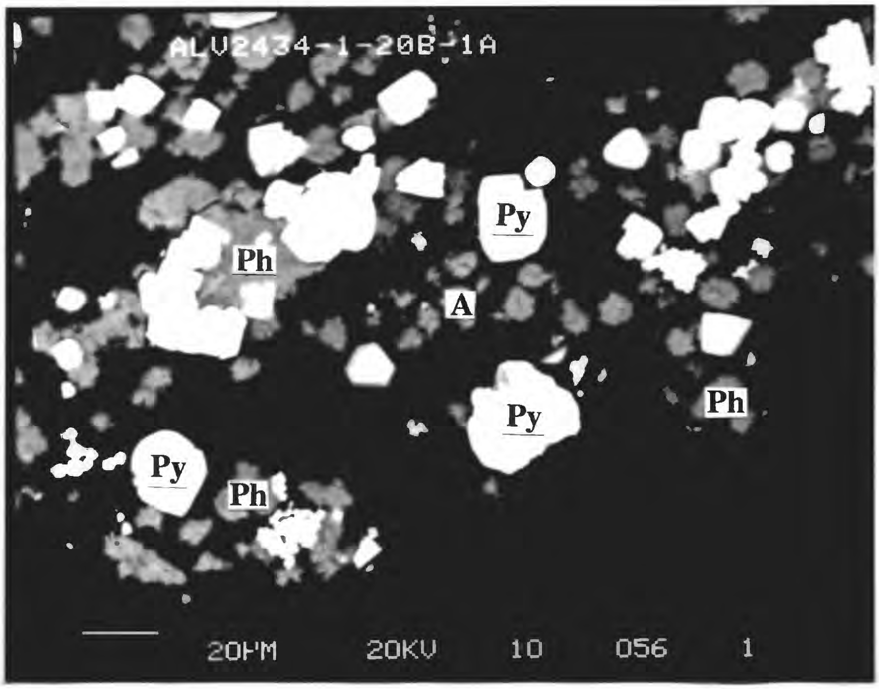

Figure 5a. ALV2434-1-20B-1A: backscatter electron SEM photomicrograph showing microspherules of Al-phyllosilicate with pyrite (Ph=phyllosilicate, Py=pyrite, A=point analyzed). Bar at lower left represents 20 microns.

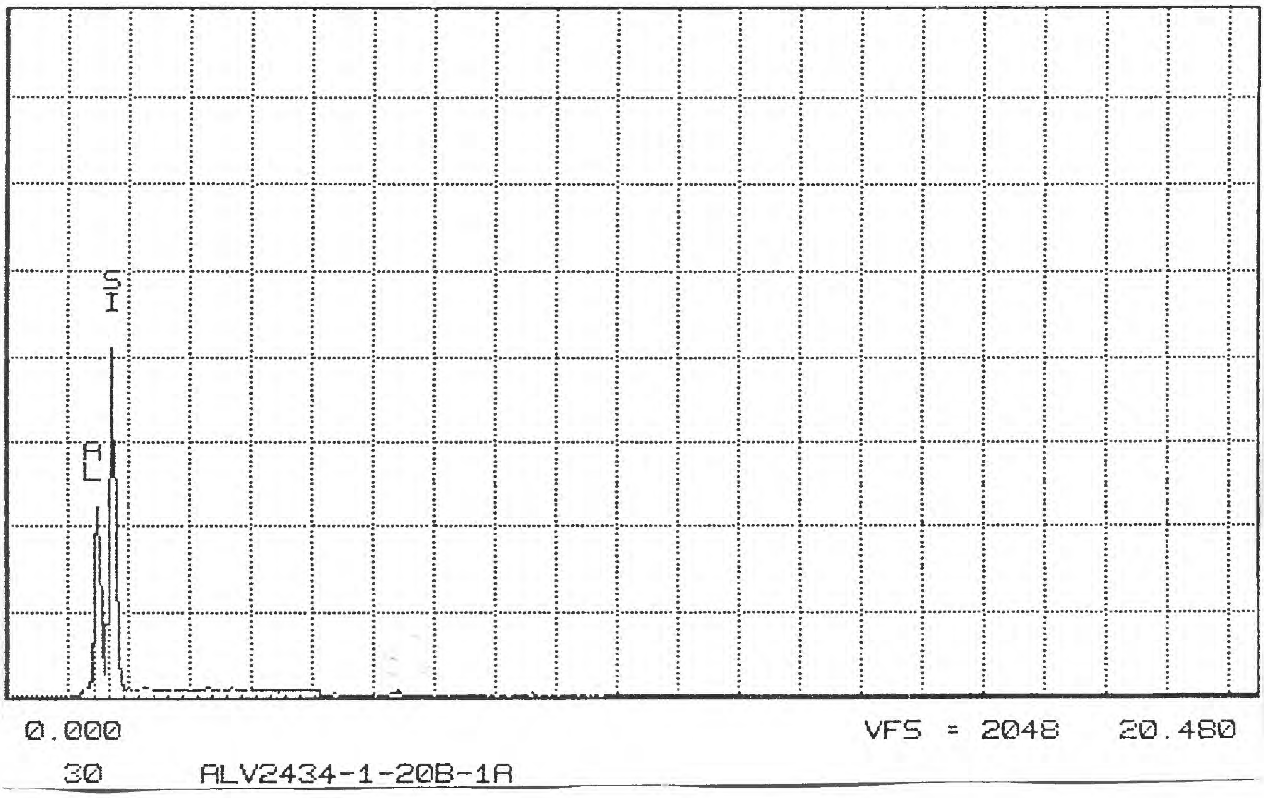

Figure 5b. EDAX spectrogram from point analysis of phyllosilicate microspherule.

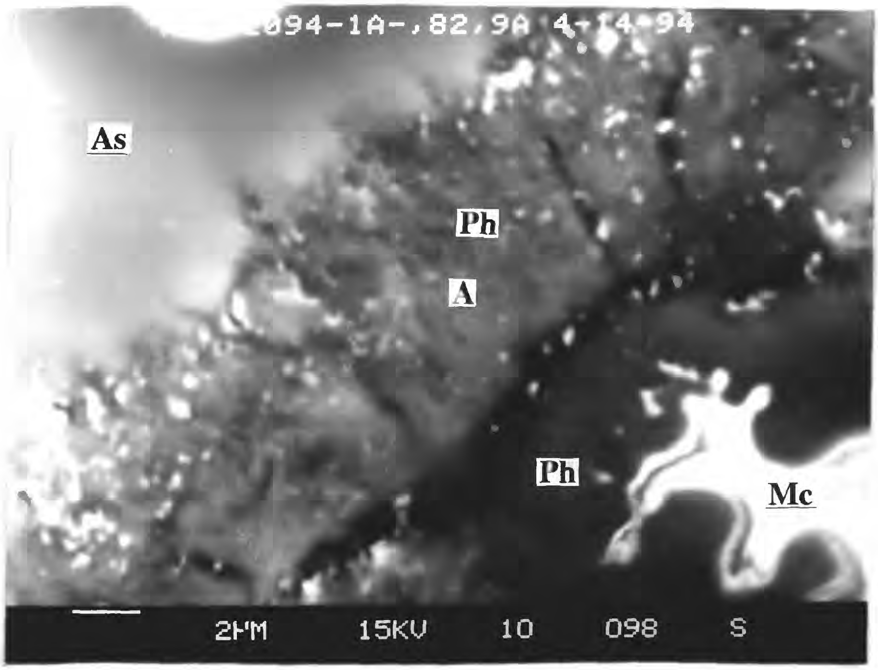

Figure 6a. ALV2094-8 to 9A: secondary electron SEM photomicrograph of Al-phyllosilicate overgrowth on marcasite which is overgrown by amorphous silica (As=amorphous silica, Mc=marcasite, Ph=phyllosilicate, A=point analyzed). Bar at lower left represents 2 microns.

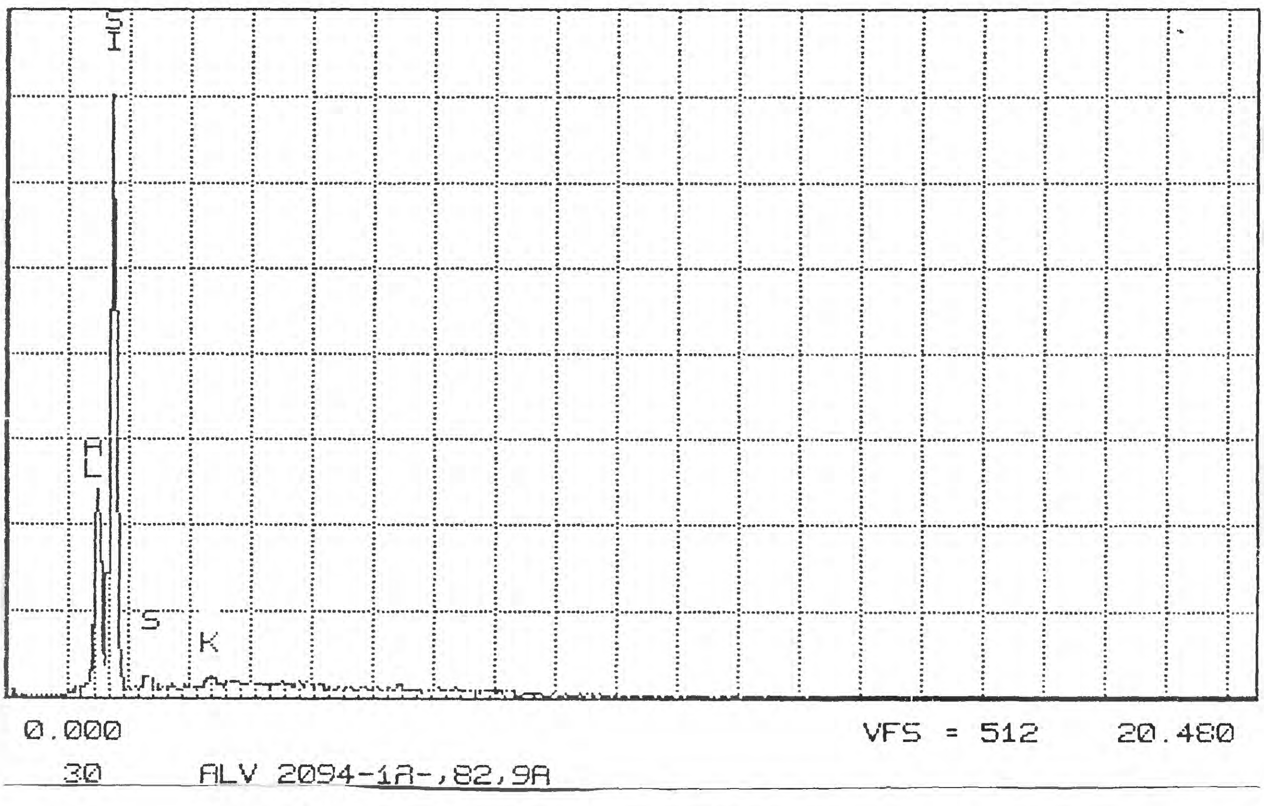

Figure 6b. EDAX spectrogram from point analysis of phyllosilicate overgrowth.

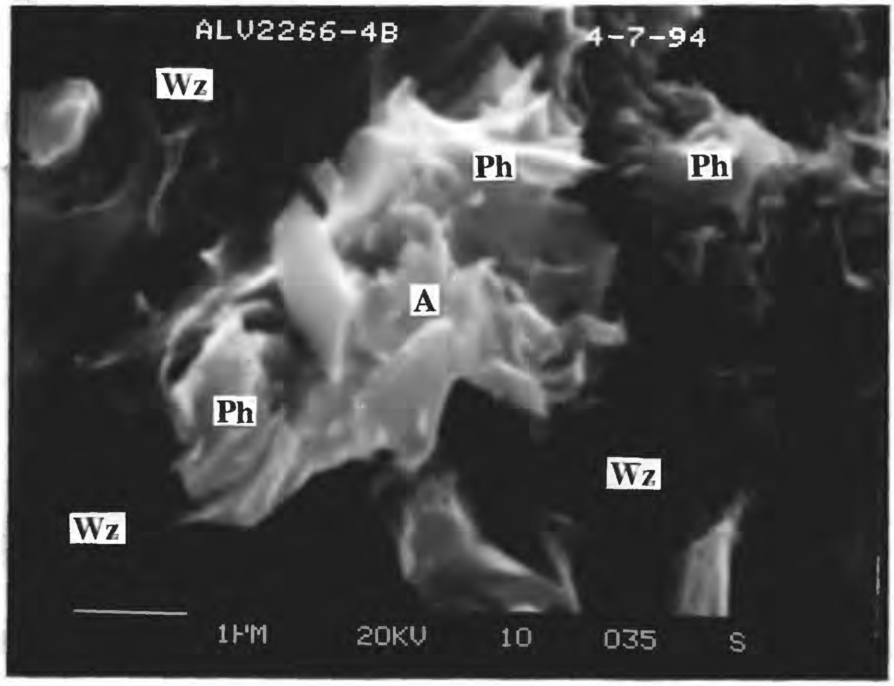

Figure 7a. ALV2266-4B:secondary electron SEM photomicrograph of aggregated platy Al-phyllosilicate crystals which contain minor V, K, Fe, and Zn. (Ph=phyllosilicate, Wz=wurtzite, A=point analyzed). Bar at lower left represents 1 micron.

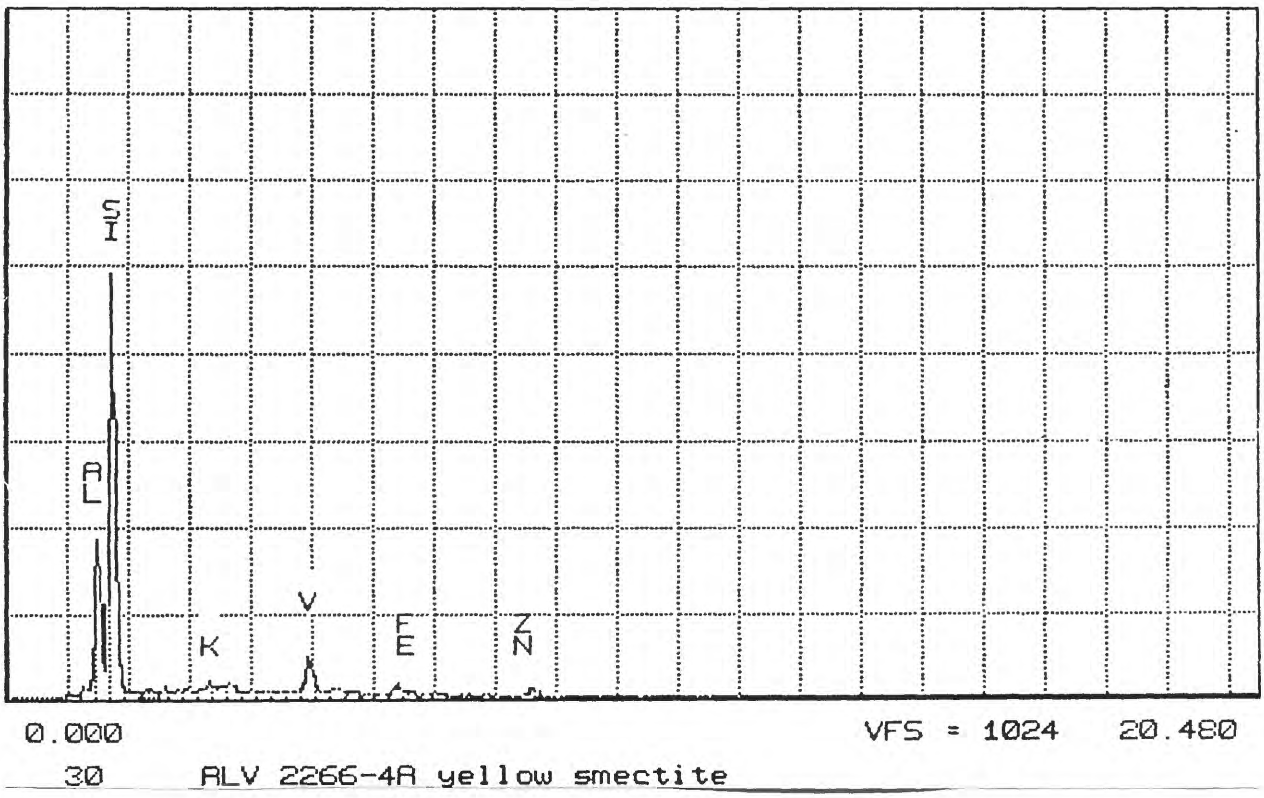

Figure 7b. EDAX spectrogram from point analysis of aggregated platy phyllosilicate crystals.

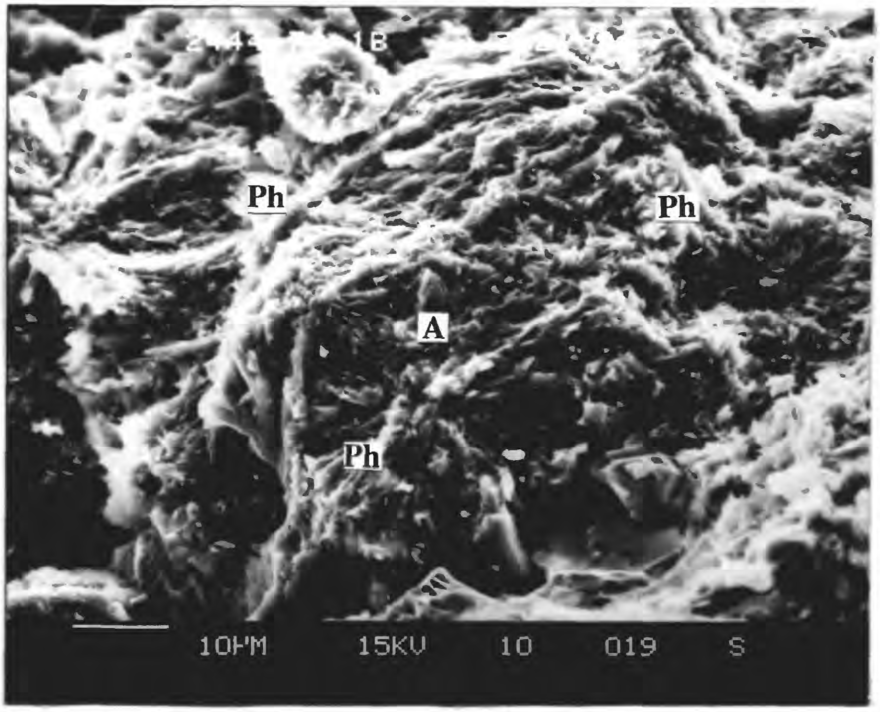

Figure 8a. ALV2442-7A-1B-5: secondary electron SEM photomicrograph of dense aggregate of Al-phyllosilicate microspherules. (Ph=phyllosilicate, A=point analyzed). Bar at lower left represents 10 microns.

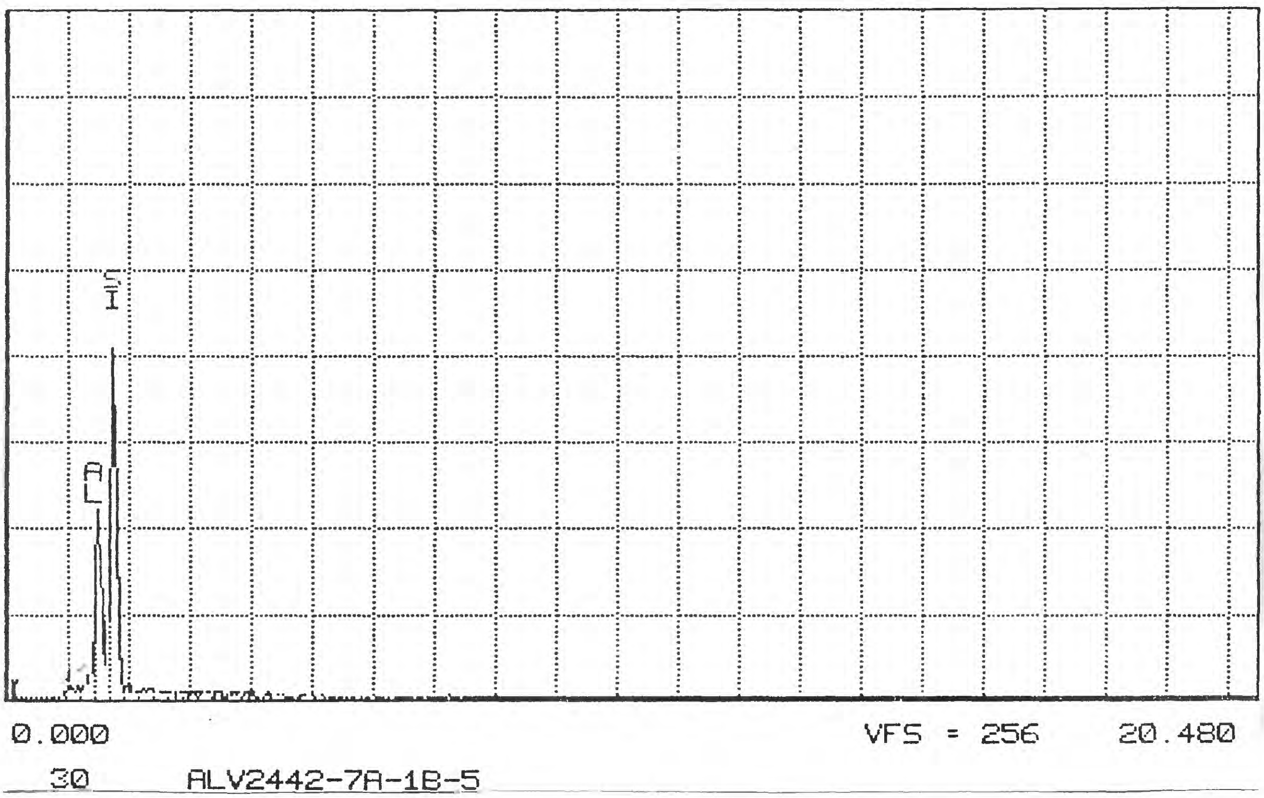

Figure 8b. EDAX spectrogram from point analysis of phyllosilicate microspherule.

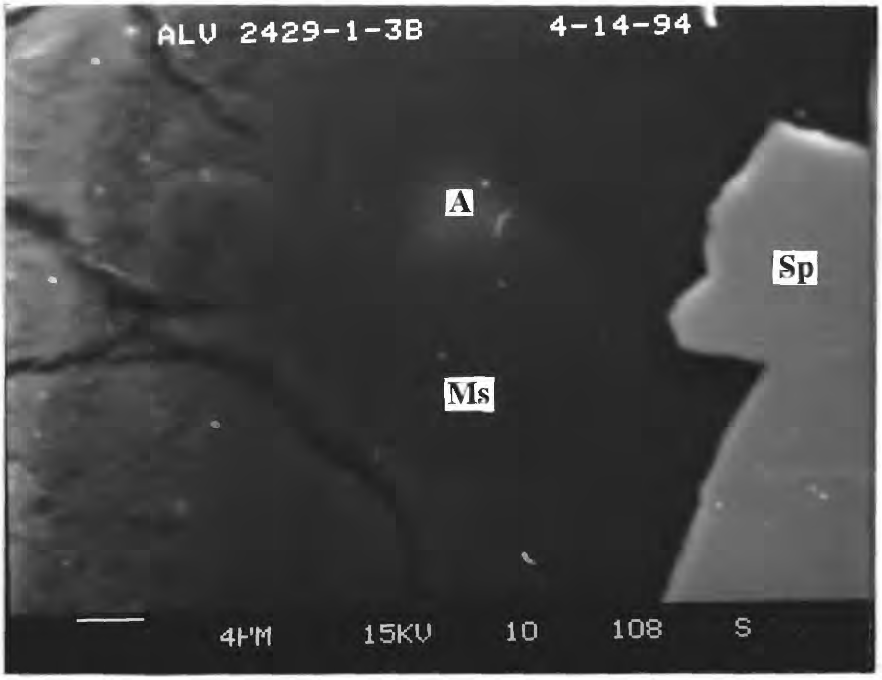

Figure 9a. ALV2429-1-3B: secondary electron SEM photomicrograph of fibrous Mg-silicate overgrowing sphalerite (Ms=Mg-silicate, Sp=sphalerite, A=point analyzed). Bar at lower left represents 4 microns.

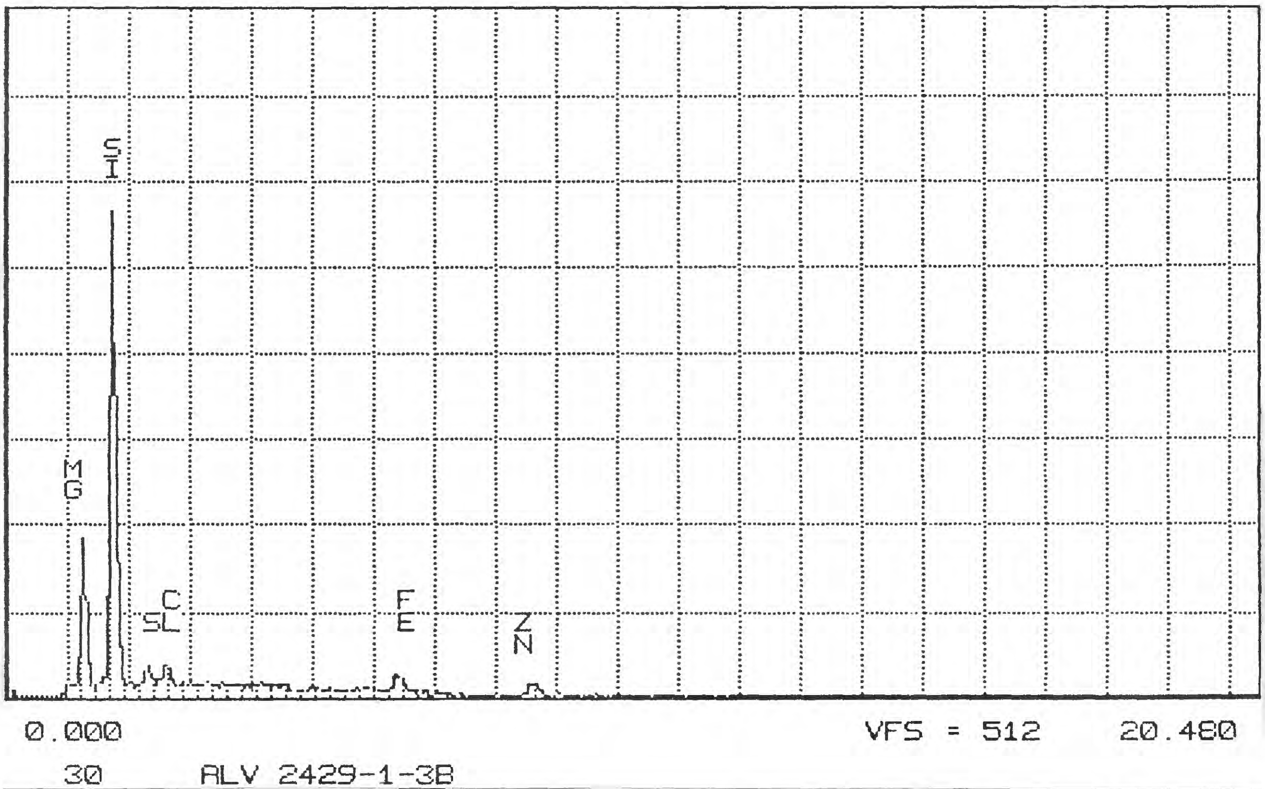

Figure 9b. EDAX spectrogram from point analysis of Mg-silicate overgrowth.

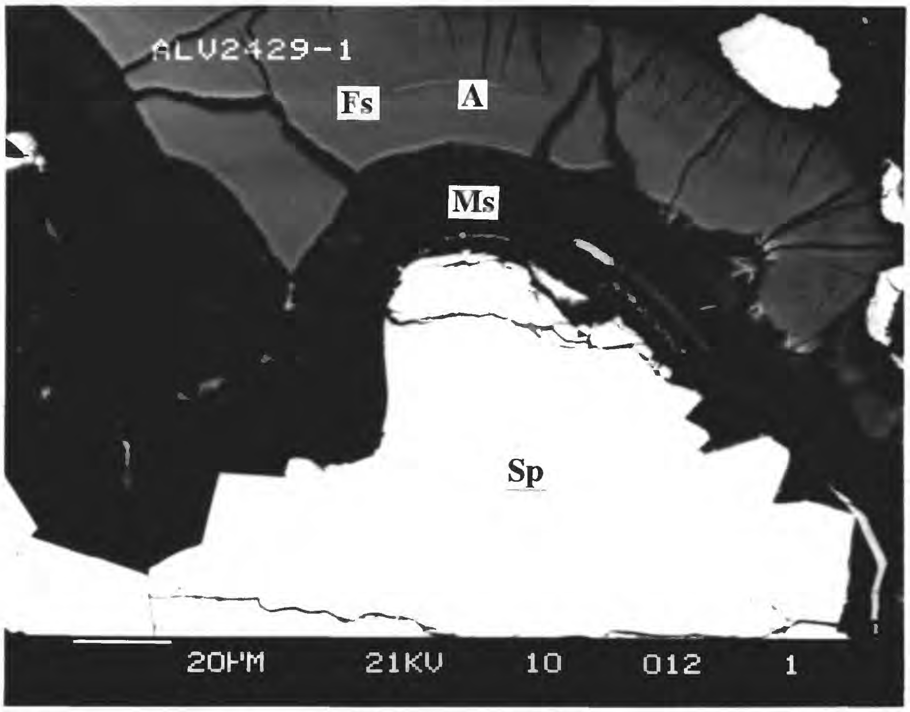

Figure 10a. ALV2429-1: backscatter electron SEM photomicrograph of fibrous Fe-silicate overgrowing Mg-silicate (Fs=Fe-silicate, Ms=Mg-silicate, Sp=sphalerite, A=point analyzed). Bar at lower left represents 20 microns.

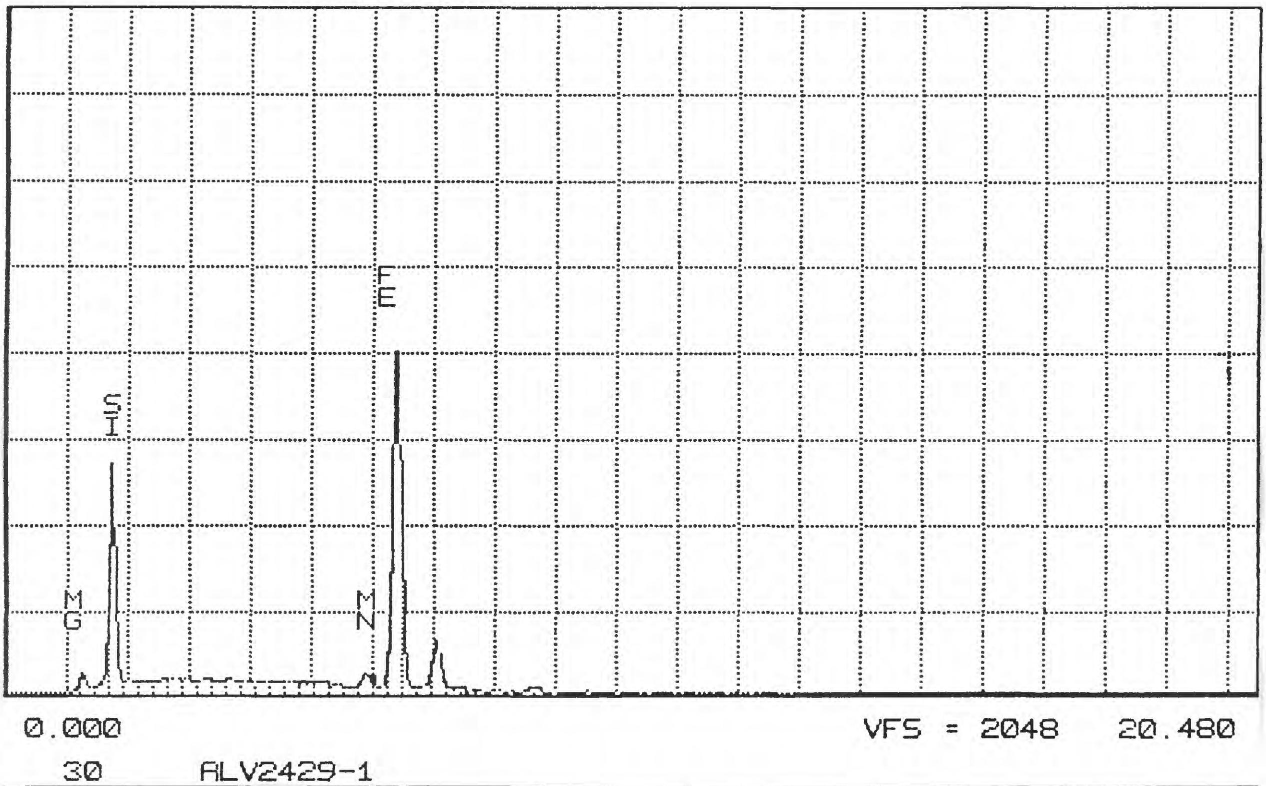

Figure 10b. EDAX spectrogram from point analysis of Fe-silicate overgrowth.

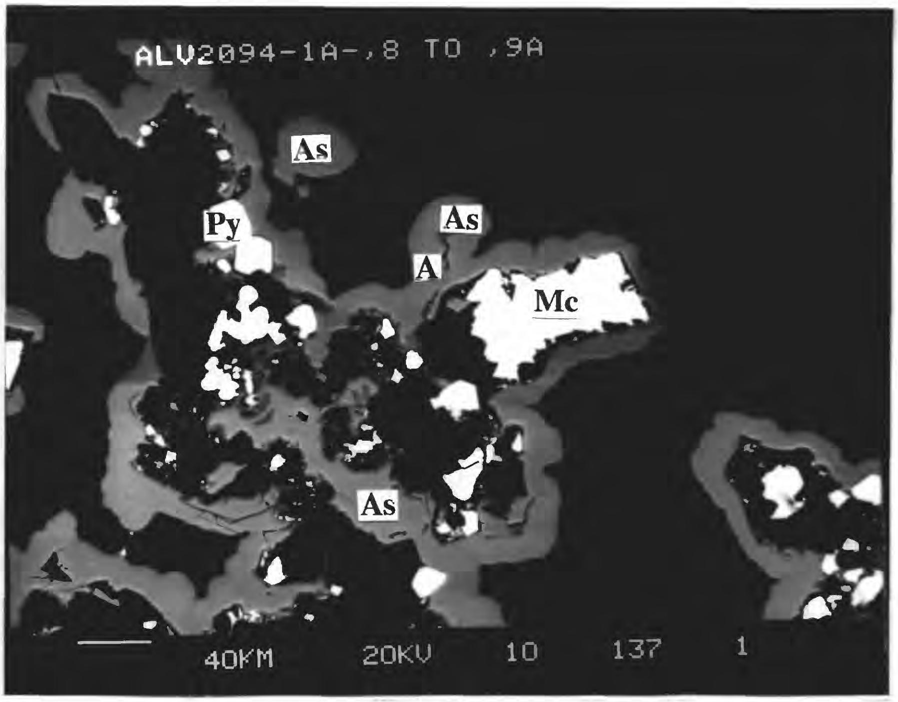

Figure 11a. ALV2094-8 to 9A: backscatter electron SEM photomicrograph of colloform amorphous silica overgrowth on crystalline marcasite and pyrite (Mc=marcasite, As=amorphous silica, Py=pyrite, A=point analyzed). Bar at lower left represents 40 microns.

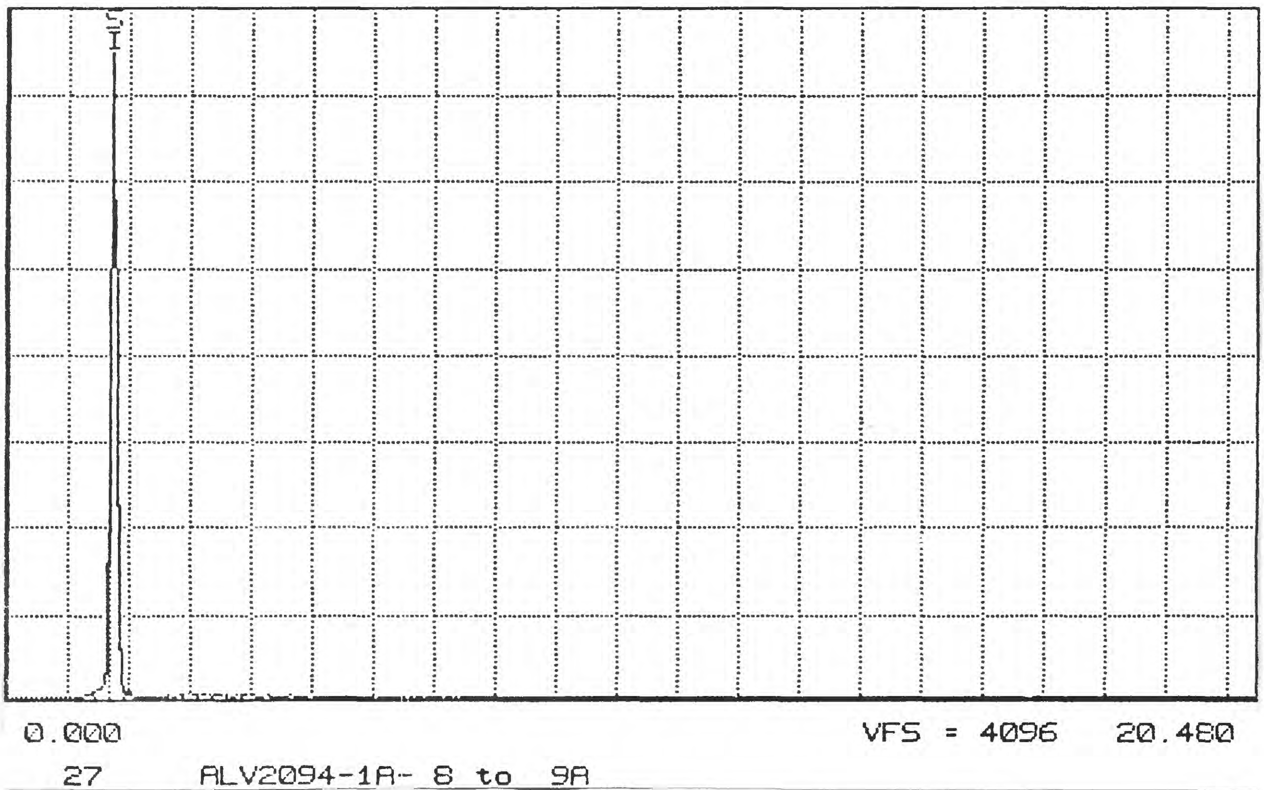

Figure 11b. EDAX spectrogram from point analysis of amorphous silica overgrowth on crystalline marcasite and pyrite.

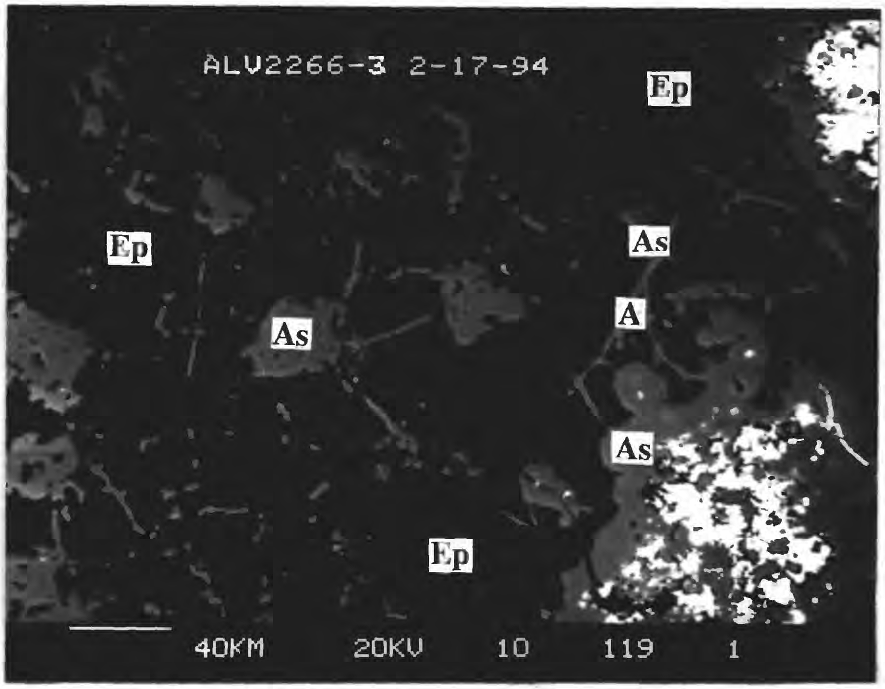

Figure 12a. ALV2266-3: back scatter electron SEM photomicrograph of amorphous silica filaments, spherules, and rods (As=amorphous silica, Ep=epoxy, A=point analyzed). Bar at lower left represents 40 microns.

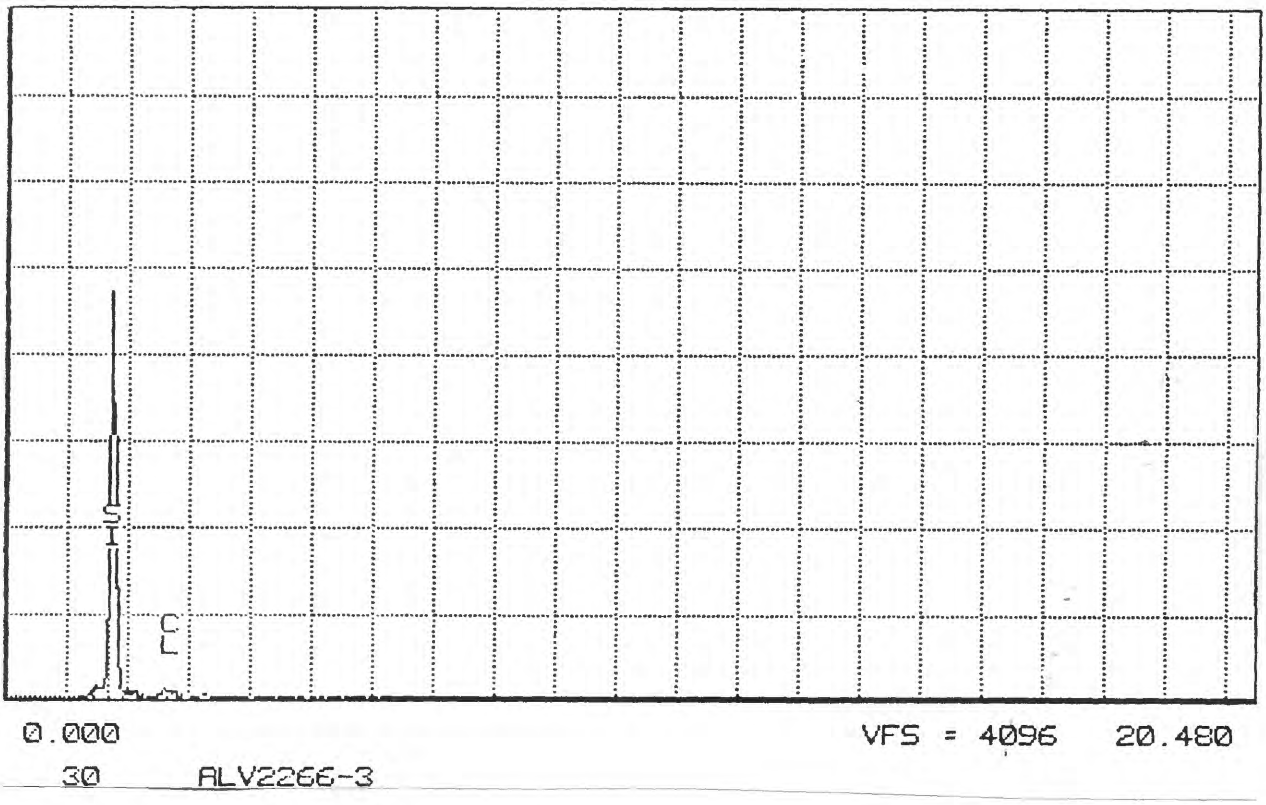

Figure 12b. EDAX spectrogram from point analysis of filamentous amorphous silica.

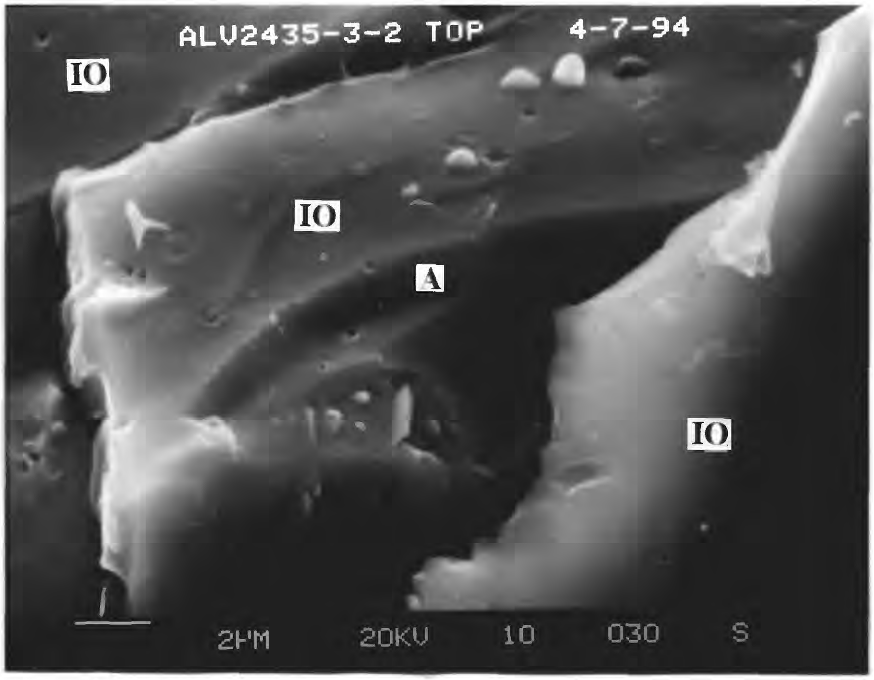

Figure 13a. ALV2435-3-2 TOP: secondary electron SEM photomicrograph of X-ray amorphous iron oxyhydroxide crust (IO=iron oxyhydroxide, A=point analyzed). Bar at lower left represents 2 microns.

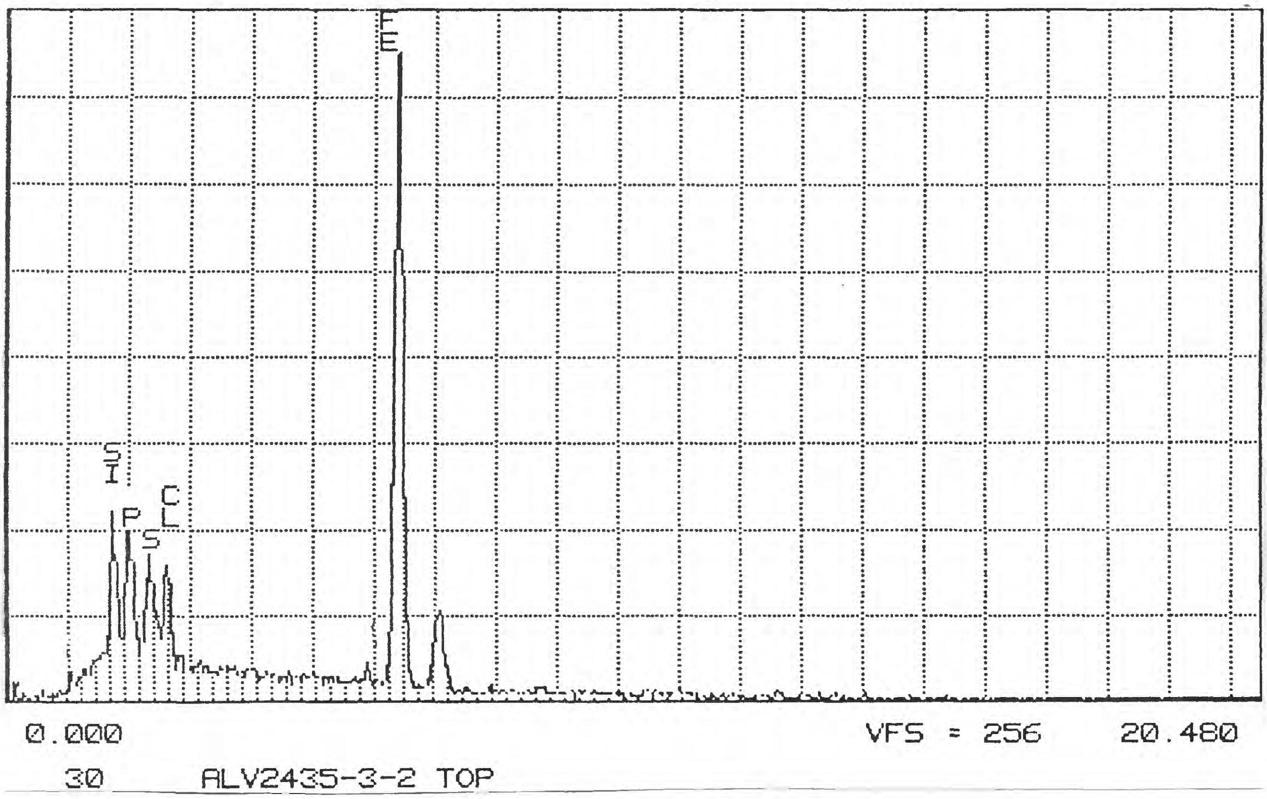

Figure 13b. EDAX spectrogram from point analysis of X-ray amorphous iron oxyhydroxide crust.

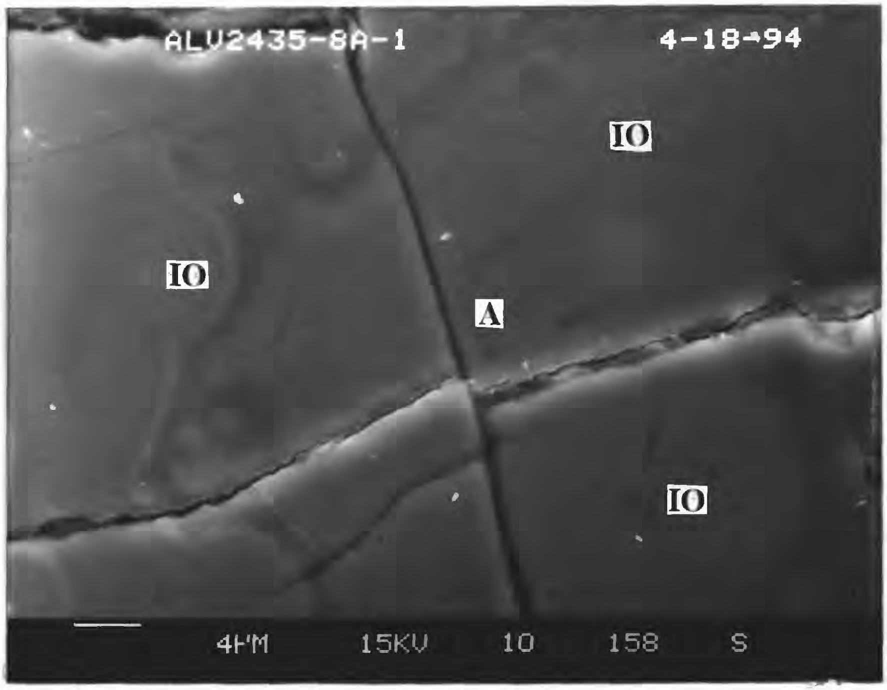

Figure 14a. ALV2435-8A-1: secondary electron SEM photomicrograph of dense banded X-ray amorphous iron oxyhydroxide crust (IO=iron oxyhydroxide, A=point analyzed). Bar at lower left represents 4 microns.

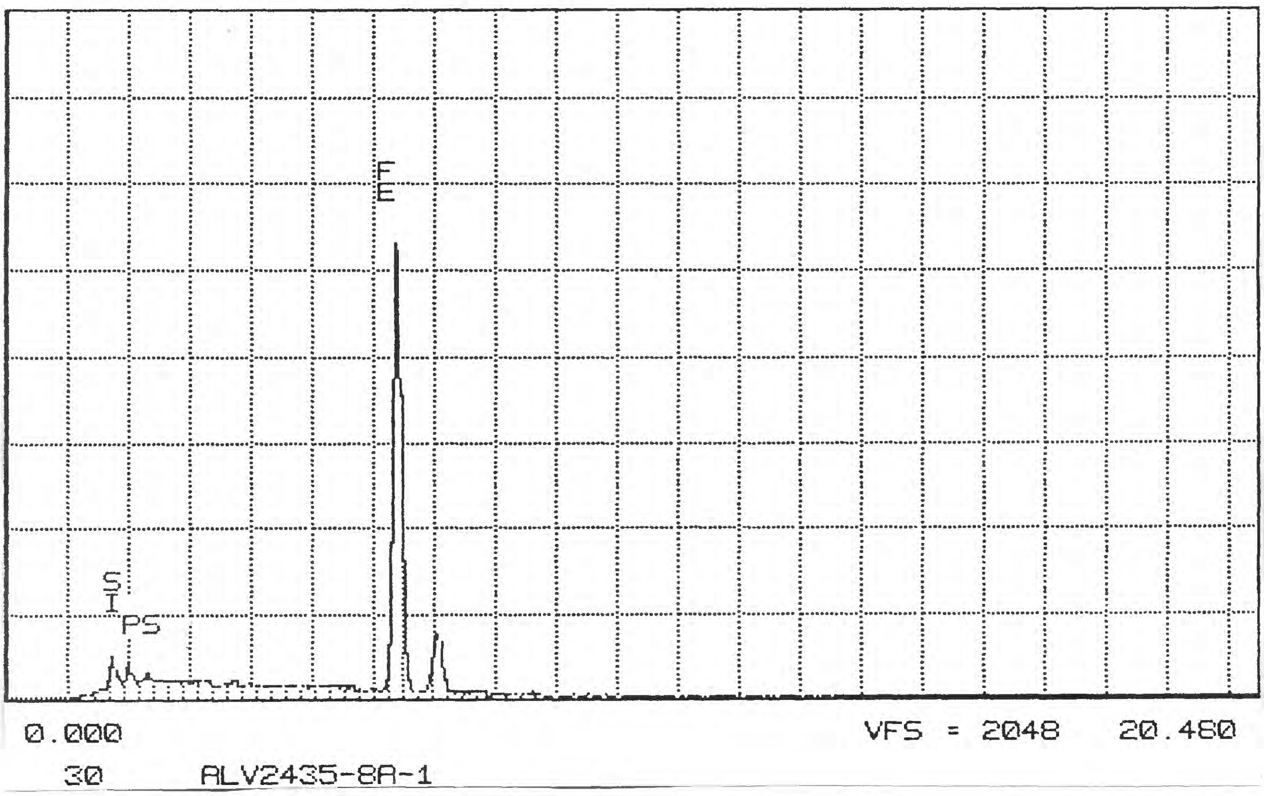

Figure 14b. EDAX spectrogram from point analysis of dense banded X-ray amorphous iron oxyhydroxide crust.

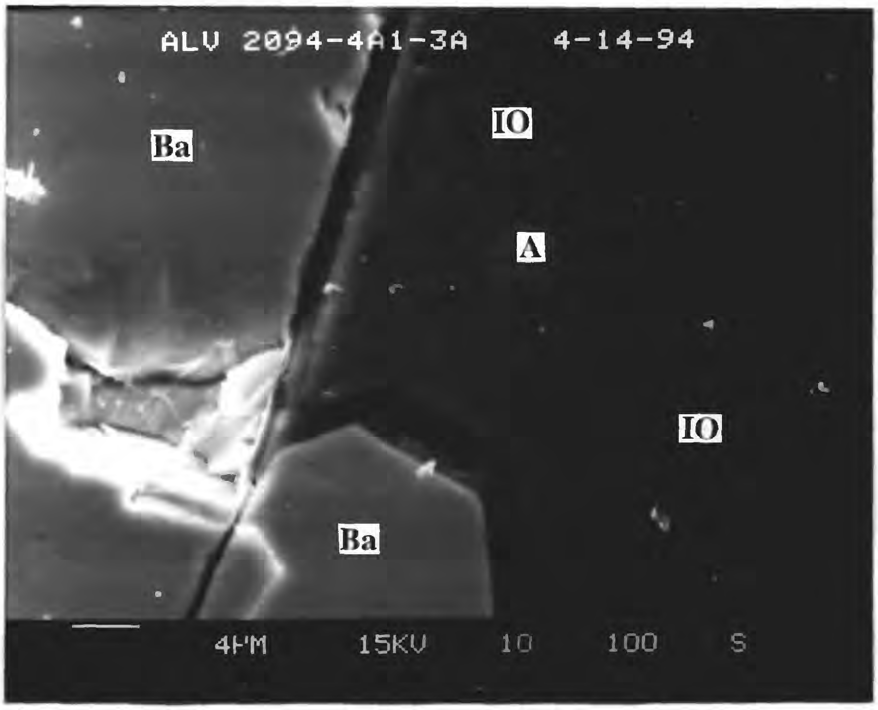

Figure 15a. ALV2094-4A-3A: secondary electron SEM photomicrograph of dense mottled siliceous X-ray amorphous iron oxyhydroxide crust with included barite (Ba=barite, IO=iron oxyhydroxide, A=point analyzed). Bar at lower left represents 4 microns.

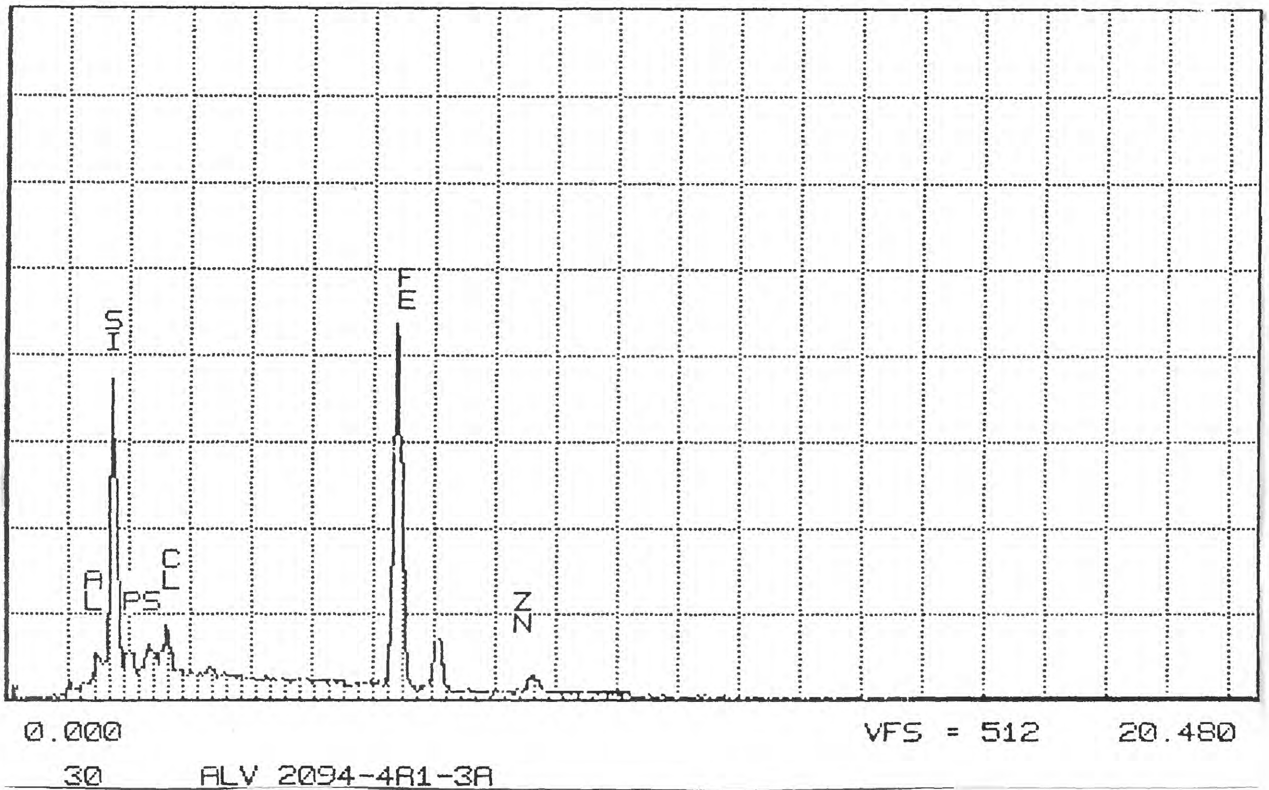

Figure 15b. EDAX spectrogram from point analysis of dense mottled siliceous X-ray amorphous iron oxyhydroxide crust.

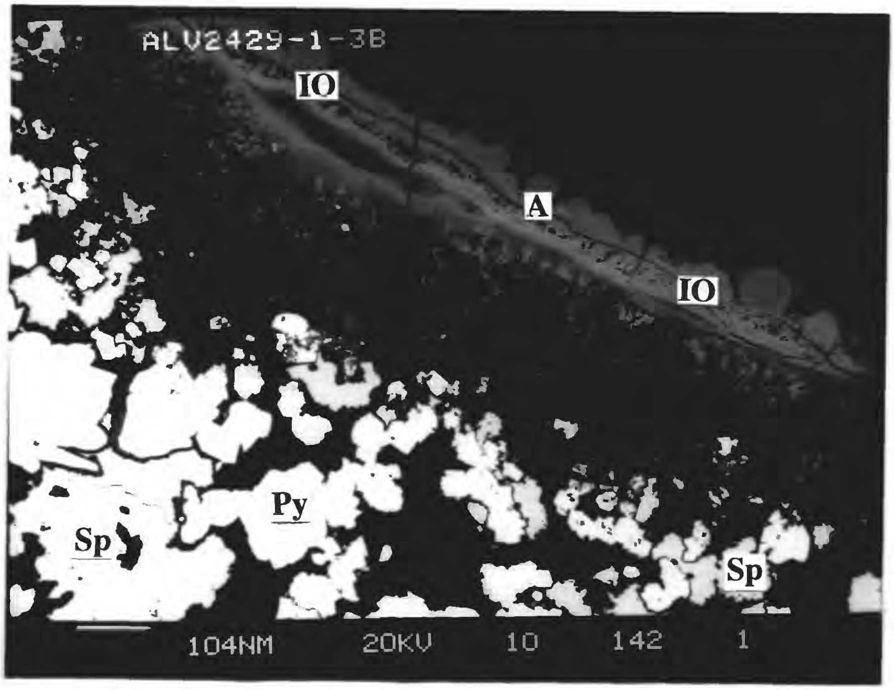

Figure 16a. ALV2429-1-3B: backscatter electron SEM photomicrograph of porous X-ray amorphous iron oxyhydroxide crust (IO=iron oxyhydroxide, Py=pyrite, Sp=sphalerite, A=point analyzed). Bar at lower left represents approximately 0.1mm.

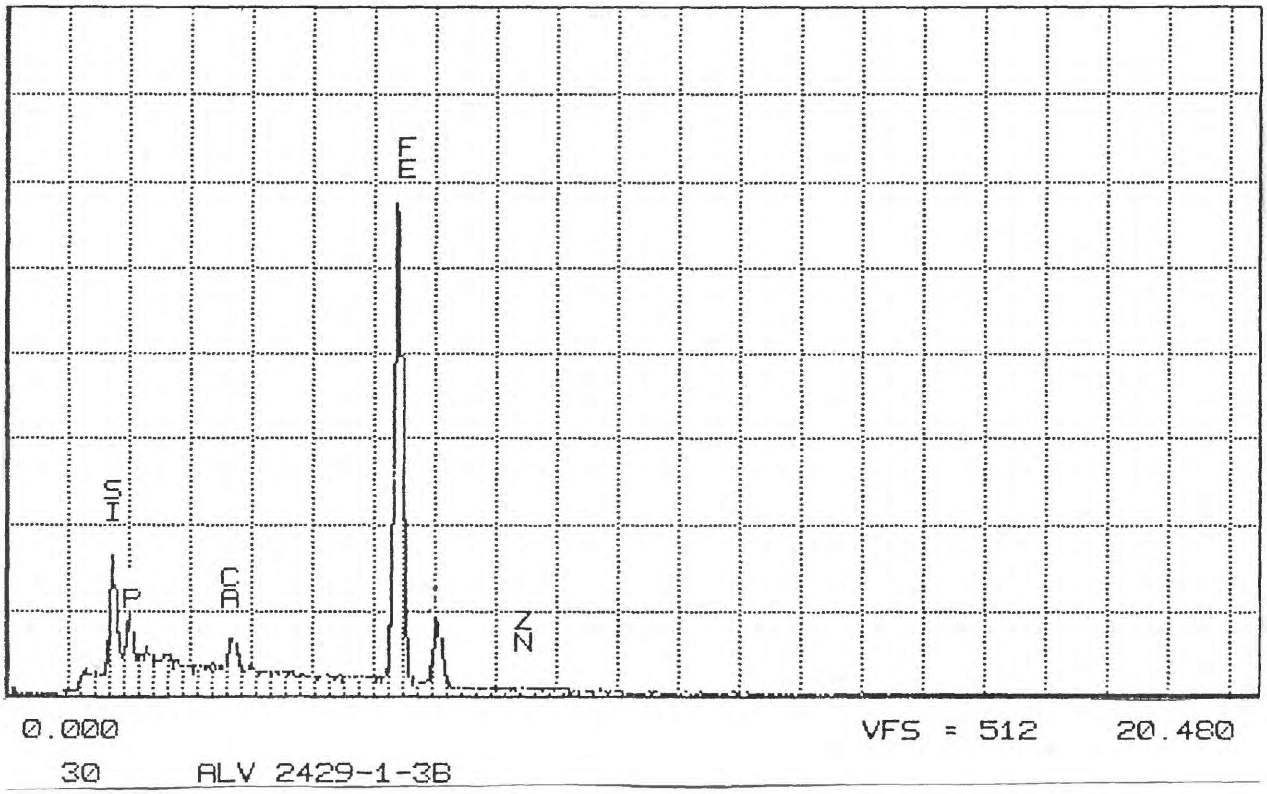

Figure 16b. EDAX spectrogram from point analysis of porous X-ray amorphous iron oxyhydroxide crust.

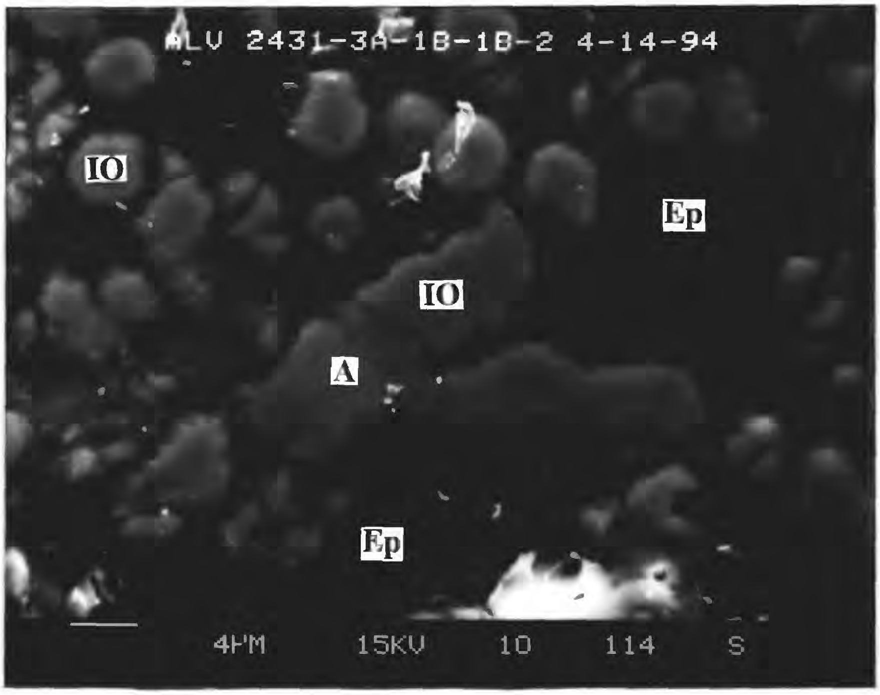

Figure 17a. ALV2431-3A-1B-1B-2: secondary electron SEM photomicrograph of iron oxyhydroxide-replaced bacteria (?) from chimney periphery (IO=iron oxyhydroxide, Ep=epoxy, A=point analyzed). Bar at lower left represents 4 microns.

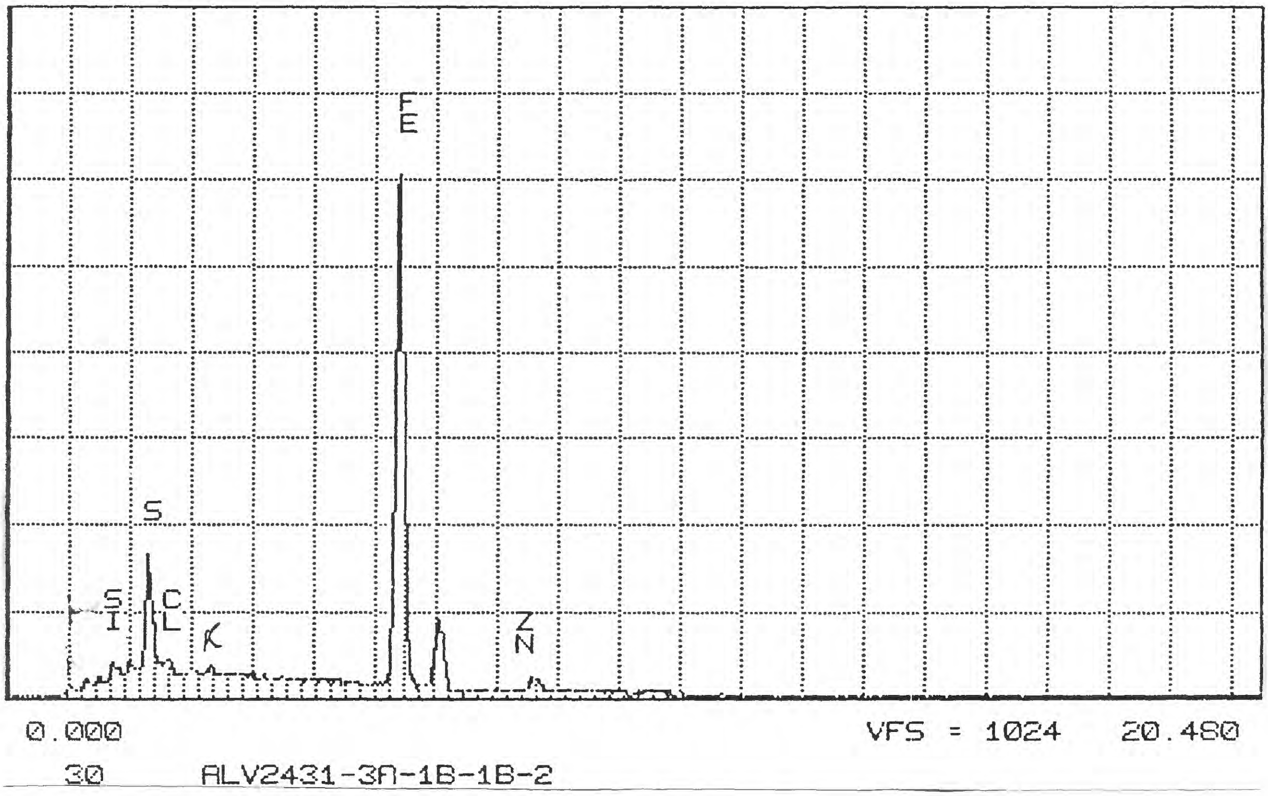

Figure 17b. EDAX spectrogram from point analysis of iron oxyhydroxide-replaced bacteria (?).

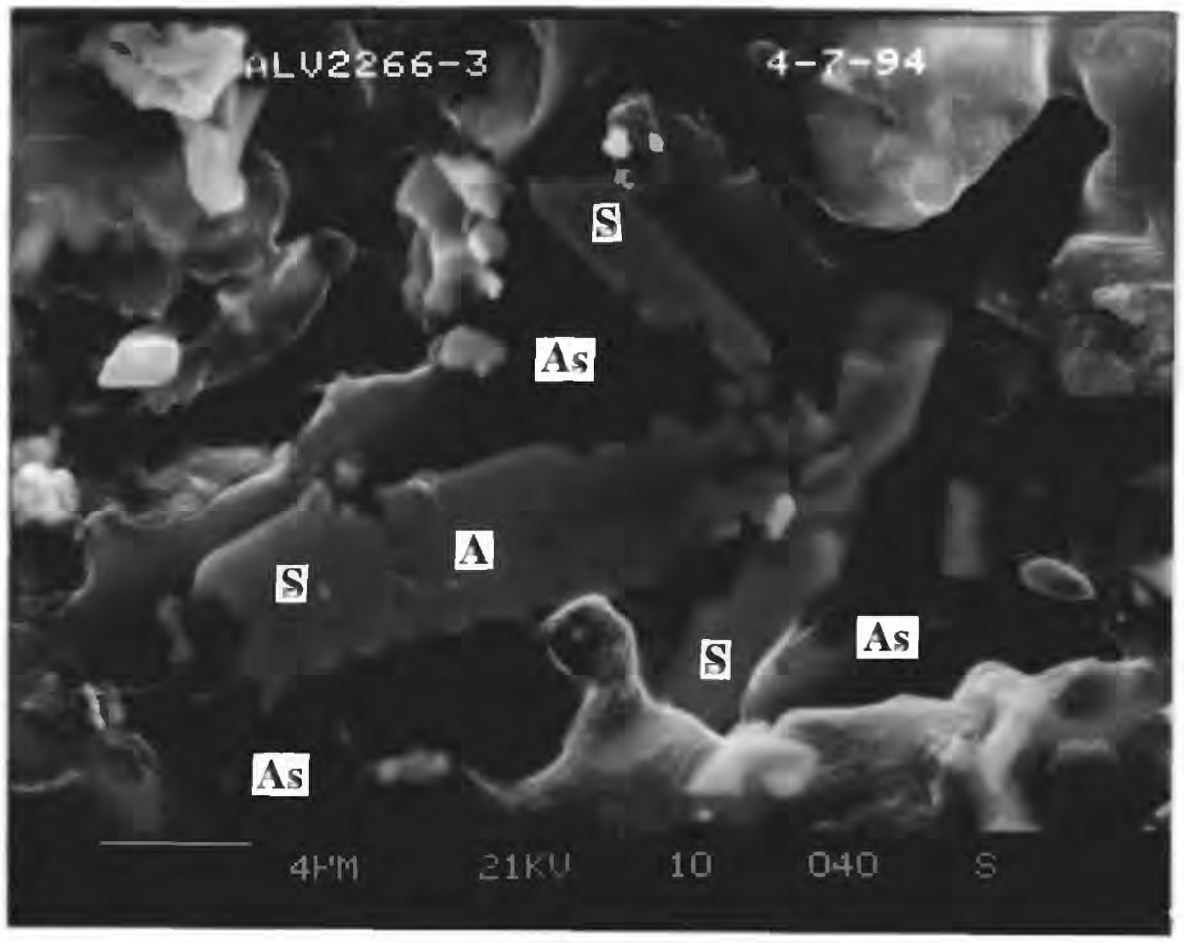

Figure 18a. ALV2266-3: secondary electron SEM photomicrograph of thin bladed sulfur crystals deposited on amorphous silica (As=amorphous silica, S=sulfur, A=analysis point). Bar at lower left represents 4 microns.

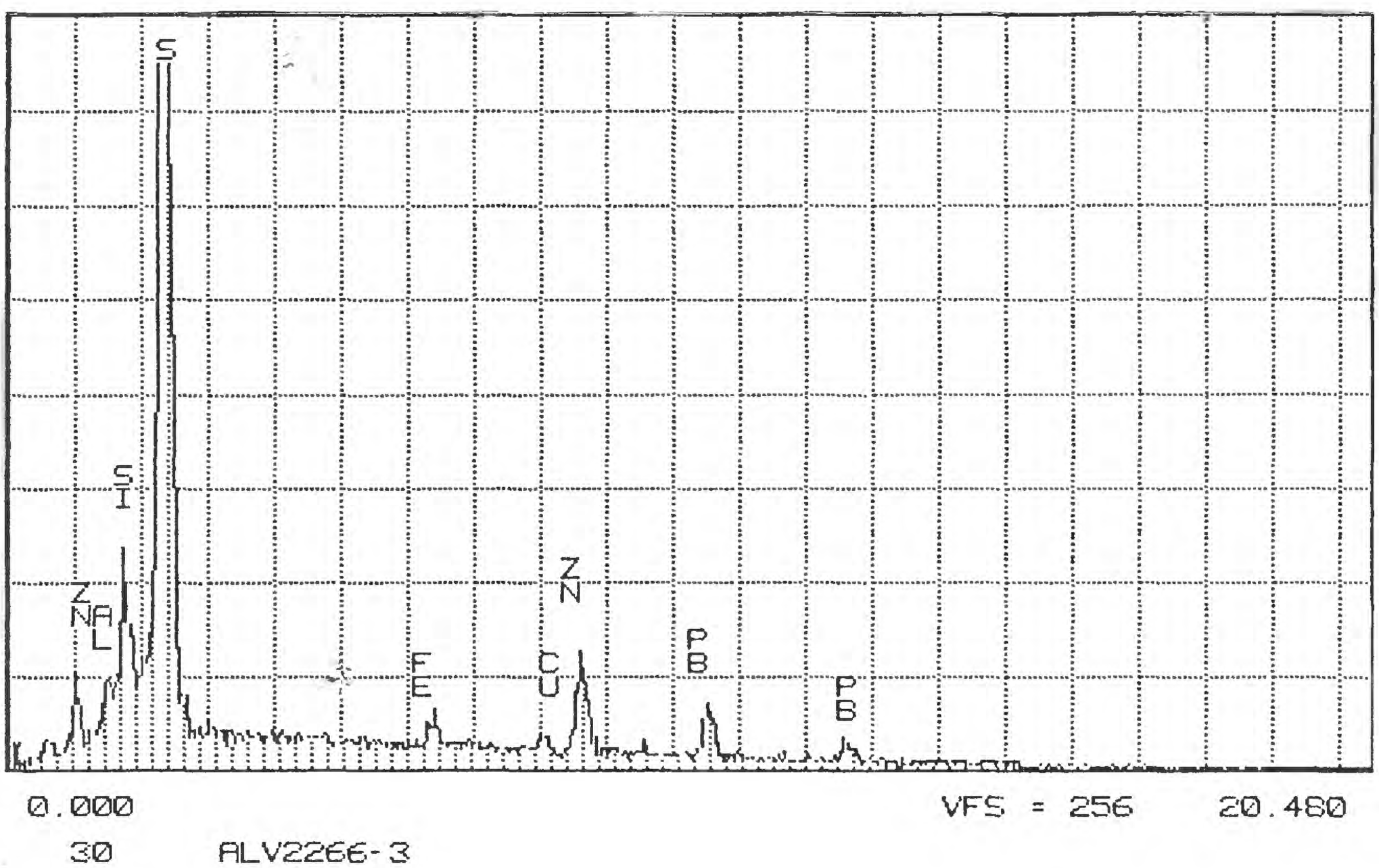

Figure 18b. EDAX spectrogram from point analysis of thin bladed sulfur crystal. (other elements in analysis may be from nearby metal sulfides).

Table 1. Mineralogy and petrography of hydrothermal chimney deposits of the northern Cleft segment of Juan de Fuca Ridge
(Mineral and porosity percentages derived by visual estimate; porosity values subtracted before normalizing to 100%).

Sample Number	Chimney type	Porosity	Major minerals		Minor minerals		Amorphous Phases		Sample descriptions/petrography
		%	Mineral	%	Mineral	%	Silica %	Iron oxide %	
ALV2078-2A	IV	15	Pyrite Marcasite	18 12	Sphalerite Wurtzite Pyrrhotite Phyllo-silicate Barite Galena Chalco-pyrite	9 4 4 4 2 1 <1	44	1	This sample is the top of a tapering gnarled inactive plugged chimney. The sample was divided in half longitudinally for thin sections. One longitudinal thin section was cut from the tip and one transverse thin section was cut from the base. The sample is composed primarily of a layered intergrowth of colloform, dendritic, and granular pyrite and marcasite. The iron sulfides are thickly overgrown locally with colloform sphalerite and wurtzite and wurtzite granules which include microgranular chalcopyrite. Granular marcasite is deposited as an overgrowth on the iron sulfides along channelways. The sulfides are locally overgrown first with microspherules of a brownish-yellow phyllosilicate, then with colloform opaline silica. Isotropic filamentous amorphous silica commonly fills sample channelways. Skeletal microcrystals of galena are included locally in wurtzite granules of the interior which are intergrown with pyrrhotite plates and chalcopyrite granules. The sample is rimmed with colloform, dendritic, and granular pyrite and marcasite, and the periphery of this rim is altered to iron oxyhydroxide. Barite rosettes are deposited locally on the inner surface of the iron sulfide rim.
-2B	-do-	20	Pyrite Marcasite	19 19	Barite Phyllo-silicate	3 3	55	<1	This sample is a fragment from the top of a 7m-high spire-like inactive chimney with numerous small circular openings at the top. The sample was divided in half by a tranverse cut. One thin section was cut to afford a complete cross section. The sample is composed primarily of colloform and granular pyrite thickly overgrown along channelways with dendritic marcasite and then thickly overgrown with colloform and filamentous opaline silica. Most of the channelways are plugged with such amorphous silica. Microspherules of a brownish-yellow phyllosilicate occupy the interstices between sulfides exposed along channelways. Barite rosettes thinly encrust some of the channelways. The sample periphery is superficially oxidized to iron oxyhydroxide.

ALV2081-1B	IV	18	Pyrite Sphalerite	27 12	Wurtzite Phyllo-silicate Marcasite Chalco-pyrite Iso-cubanite Anglesite	6 6 5 1 <1 <1	39	3	This sample is a tabular fragment from the exterior of the top of an 8m-high 1m-thick spire-like inactive chimney. Three thin sections were cut from transverse slabs to afford cross sections of the sample. The sample is composed of a sinuous marbled meshwork intergrowth of dendritic pyrite crystallites. Granular sphalerite and wurtzite locally occupy the interstices. The sulfide network is overgrown first with colloform pyrite/marcasite and then thickly overgrown with both colloform isotropic amorphous silica and opaline silica. Microspherules of a brownish-yellow phyllosilicate and rare anglesite euhedra are deposited locally in the interstices of the interior. Granular wurtzite lines channels and includes chalcopyrite and isocubanite microcrysts. The isocubanite displays chalcopyrite exsolution lamellae. The periphery of the sample is superficially altered to porous iron oxyhydroxide.
- 2B	-do-	22	Marcasite Pyrite	23 21	Wurtzite Sphalerite Phyllo-silicate Anglesite	9 8 1 <1	31	6	This sample is the tip of a large thin gnarled inactive chimney with numerous small leakage vents. The sample was divided in half by one longitudinal cut and two overlapping thin sections were made to afford a complete longitudinal cross section. The composition of the sample is primarily an intergrowth of colloform marcasite/pyite and dendritic and granular pyrite with local abundances of interstitial granular wurtzite. In open spaces the wurtzite is thickly overgrown first with colloform, dendritic, and granular pyrite and marcasite, then with isotropic filamentous amorphous silica, and less commonly with colloform opaline silica. Colloform sphalerite and granular wurtzite line channelways and are in turn overgrown with colloform opaline silica. Remaining channelway space is commonly choked with isotropic filamentous amorphous silica. Rare anglesite euhedra and microspherules of a brownish-yellow phyllosilicate are locally deposited in the interstices of the sample interior. The sample periphery is superficially altered to iron oxyhydroxide.

ALV2094-1A	IV	18	Pyrite Wurtzite Sphalerite Marcasite	20 17 15 10	Phyllo-silicate Chalco-pyrite Anhydrite Anglesite Barite Gypsum Pyrrhotite	7 4 <1 <1 <1 <1 <1	24	<1	This sample is the top broken off a large gnarled inactive pinnacle composed of coalesced chimneys displaying a large very irregular open central channel with numerous smaller branching channelways. A series of twenty overlapping thin sections traversing the breadth of the pinnacle was cut from a transverse slab from the bottom. The gross composition of the sample is a porous marbled intergrowth of dendritic/colloform/granular zinc and iron sulfides. The sulfides are thickly overgrown with colloform opaline silica which also fills many pore spaces. Filamentous opaline silica chokes many larger openings and channels. Opaline silica deposition reaches a maximum in the sample interior. Channelways and openings are lastly lined with colloform sphalerite and euhedral wurtzite. The wurtzite euhedra include chalcopyrite microcrysts. In some places, chalcopyrite first thinly coats the zinc sulfide channel deposits, particularly near the center of the sample. Aggregates of microspherules of a brownish-yellow phyllosilicate are deposited locally in interstices throughout the sample and abundantly so near the center. The central region is composed of alternating layers of dendritic sphalerite crystallites and colloform and granular pyrite/marcasite. Granular pyrrhotite is deposited locally in the intergrowths. The layers are disposed in concentric outgrowth from the central channelway. The dendritic sphalerite crystallites are thickly overgrown with colloform sphalerite and include abundant wurtzite euhedra in the interstices. Anglesite euhedra are deposited in interstices locally near the periphery of the sample and rare barite rosettes and relict anhydrite partly altered to gypsum are deposited in interstices of the sample interior. The periphery of the sample is altered superficially to iron oxyhydroxide.
-1B	-do-	27	Sphalerite Wurtzite Chalco-pyrite	21 21 14	Pyrite Marcasite	7 4	33	—	This sample is a fragment of the top of an inactive 2-3m-high spire-like chimney. The sample was divided by a cut parallel to the long axis and one thin section was made. The composition of the sample is primarily a porous meshwork intergrowth of dendritic and granular sphalerite with sparing granular marcasite. The sulfides are thinly overgrown with isotropic colloform amorphous silica and locally with isotropic filamentous amorphous silica. Included water has partly altered the surfaces of the sulfides locally to sulfates under the the amorphous silica overgrowth. The amorphous silica overgrowths are in turn thickly overgrown with granular wurtzite. The plugged central channelway and numerous small anastomoses are lined with granular chalcopyrite and granular wurtzite. The sample is rimmed with colloform pyrite/marcasite and the periphery is altered to iron oxyhydroxide.

ALV2094-4A1	III	28	Sphalerite Wurtzite Pyrite	46 13 10	Marcasite Barite Phyllo-silicate Gypsum Chalco-pyrite Bianchite	4 4 1 1 1 <1	15	4	This sample is an arcuate shell-like fragment of the outer wall of a collapsed old inactive chimney. The sample was divided by breaking it into three wedge-shaped pieces. Two thin sections were cut from the largest piece (A). One was cut transverse to the layering, traversing a peripheral flange hollow and the other transverse to the layering on the opposite periphery. The sample is composed primarily of a strongly-layered meshwork intergrowth of iron-poor gray dendritic sphalerite with interstitial granular wurtzite and colloform and granular pyrite/marcasite. These principal sulfides are overgrown with orange colloform sphalerite and more colloform pyrite/marcasite, especially near the sample periphery. The zinc sulfides are superficially altered to bianchite ($ZnSO_4 . 6H_2O$) locally in the sample interior. Rare isotropic colloform amorphous silica thinly overgrows the sulfides and locally includes microspherules of a yellowish phyllosilicate. The zinc sulfide layers alternate with thin deposits of wurtzite euhedra which include chalcopyrite microcrysts. Barite rosettes locally line flat elongate cavities and channels. Gypsum crystals are deposited locally in interstices of the chimney interior. The periphery of the sample is coated with siliceous/phosphatic iron oxyhydroxide then sooted with black manganese oxyhydroxide.
ALV2258-1	IV	25	Pyrite Marcasite	27 19	Phyllo-silicate Sphalerite Wurtzite Anglesite Sulfur Sulfates	4 3 <1 <1 <1 <1	41	4	This sample is the broken-off top of a gnarled 30cmX10cm inactive chimney. Longitudinal cuts were made through the sample to afford the removal of a slab. One thin section each was cut from either side of the slab. The composition of the sample is primarily porous colloform pyrite/marcasite overgrown with granular pyrite and marcasite. Rare granular wurtzite is deposited in locally in interstices. The sulfides are thickly overgrown first with colloform opaline silica, which also fills and cements old fractures, then with isotropic filamentous amorphous silica especially in channelways. Yellowish phyllosilicate microspherules, anglesite euhedra, sulfur microgranules, and iron sulfates are sparingly distributed through the colloform opaline silica deposits. Corroded sphalerite granules sparingly line the channelways. The periphery of the sample is altered to siliceous iron oxyhydroxide and subsequently sooted externally with manganese oxyhydroxide.

ALV 2259-1	I	13	Chalco-pyrite Sphalerite Wurtzite Anhydrite	23 22 17 11	Pyrite Marcasite Phyllo-silicate Barite	5 5 2 <1	1	<1	This sample is a bulbous tubular 45cmX10cm active "black smoker" chimney segment with a large open oval central conduit 6cmx4cm in diameter which pinches down near the chimney tip. The sample was divided into slabs for thin sections. Three thin sections were cut from the lowermost slab in a radial array of cross sections. The sample is composed of concentric bands of distinctly differing mineral deposits. The central conduit is thickly lined with chalcopyrite/pyrite. A porous band of intergrown dendritic and colloform sphalerite follows. The sphalerite crystallites are overgrown locally with colloform wurtzite and marcasite, and granular marcasite. Granular anhydrite and wurtzite locally fill the interstices. Chalcopyrite replaces zinc sulfides and anhydrite locally. At the outer margin of the zinc sulfide band, barite rosettes, isotropic colloform amorphous silica, and aggregates of microspherules of a brownish-yellow phyllosilicate locally fill the interstices. The sample is rimmed with a porous 1-2mm-thick band of colloform pyrite/marcasite which also has deposits of amorphous silica, barite rosettes, and smectite in the interstices. The periphery of the rim is oxidized superficially to iron oxyhydroxide and this is overlain by a thin ferruginous smectite deposit rich in worm tubes and worm debris.
-2	II	30	Sphalerite Wurtzite Pyrite	55 30 11	Marcasite Anhydrite Phyllo-silicate Chalco-pyrite	3 <1 <1 <1	—	—	This sample is composed of tabular arcuate fragments probably from the exterior of a large inactive collapsed chimney. A transverse thin section was cut from the largest of the four fragments. The composition of the sample is primarily a porous meshwork intergrowth of dendritic sphalerite bearing large granules of wurtzite and small globules of colloform pyrite in many of the interstices. The crystallites are locally overgrown with colloform wurtzite which includes microcysts of both pyrite and chalcopyrite. A band of colloform pyrite/marcasite parallel to the outer surfaces divides the interior. Interstices in the dendritic sphalerite near the inner surface of the iron sulfide band are filled with relict granular anhydrite and interstices near the outer (seaward) surface contain aggregates of brownish-yellow phyllosilicate microspherules in a thin discontinuous band.

ALV2261-2	III	25	Anhydrite Sphalerite Wurtzite	42 27 13	Marcasite Pyrite Chalco-pyrite Iso-cubanite Phyllo-silicate	8 8 1 <1 <1	—	—	This sample consists of outer wall fragments of a small active "gray smoker" chimney. One fragment was divided by a single cut transverse to the long axis of the chimney and one thin section was cut transverse to the chimney wall layering. Two additional overlapping thin sections were cut from another fragment in the same way. The fragments are composed primarily of a dense intergrowth of granular anhydrite with opaque dendritic sphalerite. Pyrite microgranules dot the interior of the anhydrite/sulfide intergrowth and microspherules of a brownish-yellow phyllosilicate fill interstices locally. Near the outer rim of the fragments, the sphalerite becomes overgrown locally with colloform wurtzite. The fragments are penetrated by numerous small meandering channelways which are lined with granular wurtzite. The wurtzite includes chalcopyrite microcrysts. In some places, the wurtzite grains are overgrown with smaller chalcopyrite grains and thin filagrees which display isocubanite exsolution lamellae. The fragments are rimmed first with colloform marcasite and then with colloform pyrite.
ALV2265-1	III	35	Sphalerite Wurtzite Pyrite	46 23 12	Marcasite Chalco-pyrite Iso-cubanite Phyllo-silicate	5 5 3 3	2	<1	This sample is a fragment from an inactive chimney (talus from base of the Monolith Vent?). Two parallel cuts were made through the short axis of the fragment and four overlapping thin sections were cut to afford a complete cross section of the layering. The composition of the fragment is primarily a layered porous meshwork of dendritic sphalerite overgrown with varicolored colloform sphalerite and wurtzite alternating with thin bands of colloform pyrite/marcasite. The zinc sulfide meshwork is penetrated by numerous tortuous, meandering channelways and cavities which are partially-to-completely filled with granular wurtzite and sphalerite. The zinc sulfides include chalcopyrite microcrysts which display isocubanite exsolution lamellae. Microspherules of isotropic amorphous silica and a colorless phyllosilicate are deposited in the interstices of interior zinc sulfides. The outer surface of the fragment is rimmed with porous colloform pyrite/marcasite which is superficially altered to iron oxyhydroxide.

ALV2266-3	IV	25	Pyrite Marcasite	27 16	Sphalerite Phyllo-silicate Anglesite Wurtzite Galena Chalco-pyrite	4 3 3 1 <1 <1	44	1	This sample is the *top* of a large gnarled coalesced plugged chimney pinnacle with several spires and flange structures. The sample was divided by several cuts transverse to the length of the chimney top to afford slabs for thin sections. Four thin sections were cut from the top two slices (-3A,-3B, -3C-1 and -3C-2) and one thin section was cut from a side flange (-3). The sample is composed primarily of colloform pyrite/marcasite overgrown with granular marcasite. The sulfides are overgrown locally with a colloform colorless phyllosilicate, then generally with filamentous isotropic amorphous silica and colloform opaline silica. The latter commonly includes anglesite microcrysts. Corroded sphalerite and wurtzite granules, overgrown sparingly with chalcopyrite and skeletal galena microcrysts, line channels locally. Iron sulfides of the sample periphery and along some channelways are superficially altered to iron oxyhydroxide. The sample exterior is sooted with manganese oxyhydroxide.
ALV2266-4	-do-	18	Marcasite Pyrite	21 10	Wurtzite Sphalerite Phyllo-silicate Anglesite Galena Chalco-pyrite Sulfur	9 9 5 2 <1 <1 <1	42	<1	This sample is a fragment from the outer wall of a chimney questionably related to (-3) above. The sample was divided by two parallel cuts through the middle transverse to the long axis. Three overlapping thin sections were cut to afford a complete cross section. The sample is composed primarily of colloform marcasite/pyrite locally overgrown with granular marcasite, wurtzite, and sphalerite. The zinc sulfides line and choke channelways and include chalcopyrite and galena microcrysts. Interstices are locally lined or filled with microspherules of a brownish-yellow phyllosilicate and overgrown thickly with colloform opaline silica which sparingly includes anglesite microcrysts. Rare sulfur microcrysts overgrow the zinc sulfides locally. The exterior of the sample is superficially altered to iron oxyhydroxide.
ALV2269-7	II(?)	50	Sphalerite Wurtzite	76 14	Anhydrite Pyrite Chalco-pyrite	6 2 2	—	—	This sample is a collection of slabby shell-like fragments of the exterior of a large inactive chimney. One thin section was cut from the top of the largest fragment to afford a cross section. The sample is composed primarily of an highly porous meshwork intergrowth of cyclically-deposited dendritic sphalerite crystallites overgrown with colloform sphalerite. The sulfides include pyrite microcrysts and are penetrated by numerous channelways lined with colloform wurtzite which includes chalcopyrite microcrysts. The wurtzite lining is studded with anhydrite euhedra.

ALV2429-1	I	20	Chalcopyrite	52	Sphalerite	8	—	<1	This sample is the horn-like tip of a high-temperature active chimney with a large continuous open central channel. The sample was sliced perpendicular to the length six times with parallel cuts. Four thin sections were cut from these slices to afford cross sections. The sample is strongly layered in concentric fashion from the central channel outward. The central channel is lined thickly with a coarse porous intergrowth of interlocking chalcopyrite crystals. Overlying the chalcopyrite is a porous band of interlocking anhydrite crystals with inclusions of chalcopyrite, colloform wurtzite, sphalerite, and pyrite. Overlying the anhydrite band is a thin layer of granular wurtzite. Overlying the wurtzite band is a porous meshwork intergrowth of dendritic sphalerite crystallites and isotropic amorphous silica filaments. Chalcopyrite granules are deposited locally in the interstices. Overlying the sphalerite band is a thin intergrowth of isotropic amorphous silica filaments, wurtzite granules and colloform sphalerite. The zinc sulfides are overgrown with finely fibrous layered colorless and brown transparent silicates. A thin band of colloform marcasite overlies the fibrous amorphous silica/ sulfides/silicates deposit and is overlain by more filamentous amorphous silica intergrown with dendritic sphalerite. The sample is rimmed with a porous colloform intergrowth of marcasite/sphalerite which is mostly altered to powdery iron oxyhydroxide.
			Anhydrite	26	Pyrite	1			
			Wurtzite	11	Marcasite	<1			
					Phyllosilicate	<1			
-2	II(?)	32	Sphalerite	31	Isocubanite	3	4	—	This sample is a collection of slabby fragments from an inactive "beehive" chimney. Slices were cut through the fragments perpendicular to the layering on piece numbers 2, 3, 5, 7, and 9, and one thin section was cut from each of these slices to afford cross sections. The sample is composed primarily of a meshwork intergrowth of dendritic sphalerite crystallites overgrown with colloform sphalerite and wurtzite. Granular pyrite, sphalerite, wurtzite, isocubanite, and chalcopyrite are deposited in the interstices and in concentrations on the undersides of the fragments. Microspherules of a colorless phyllosilicate and both isotropic amorphous silica and opaline silica are also deposited in some of the interstices. Some of the fragments are composed almost entirely of colloform pyrite/marcasite with accessory granular wurtzite and amorphous silica overgrowth.
			Pyrite	22	Phyllosilicate	3			
			Marcasite	18	Chalcopyrite	<1			
			Wurtzite	18					

ALV 2431-3A	III	36	Sphalerite Marcasite Wurtzite	44 25 17	Pyrite Phyllo- silicate Chalco- pyrite Anhydrite	8 2 <1 <1	2	<1	Two horn-like chimlets were taken from the top of a large spindle-shaped chimney with an irregular exterior. Both samples were cross-sectioned several times. Three thin sections were cut from sample number 1 and two overlapping thin sections were cut from sample number 2 to afford cross sections. The gross compostion of the samples is primarily a meshwork intergrowth of dendritic sphalerite crystallites. The crystallites are commonly overgrown with colloform sphalerite and wurtzite, and with granular wurtzite. The granular wurtzite includes chalcopyrite microcrysts and also lines the numerous small tortuous channelways which course through the zinc sulfide framework. Isotropic colloform amorphous silica locally overgrows the wurtzite channelway linings. The chimlets are thickly rimmed with colloform marcasite/pyrite which is peripherally altered to iron oxyhydroxide. The rim bears a thin discontinuous layer of a fine yellow substance (jarosite?) between the iron oxyhydroxide and the iron sulfide layers.
ALV 2433-2C	II	34	Anhydrite Pyrite	76 15	Sphalerite Wurtzite Chalco- pyrite Sulfur(?)	8 <1 <1 <1	—	—	This sample is a collection of arcuate fragments from a collapsed active "beehive" chimney growing from a large sulfide mound. The largest fragment was divided parallel to the long axis of the chimney and two thin sections were cut to afford cross sections. The gross composition of the samples is primarily a porous intergrowth of bladed granular anhydrite and minor colloform and granular pyrite and dendritic sphalerite. Rare chalcopyrite and wurtzite granules and sulfur (?) microspherules and dendrites are deposited locally in the interstices.
-3C	-do-	25	Anhydrite	85	Pyrite Sphalerite Chalco- pyrite Sulfur(?)	7 7 <1 <1	-do-	-do-	This sample is a collection of thick arcuate fragments from the base of a collapsed active "beehive" chimney. The largest fragment was thin sectioned to afford a cross section of the chimney wall. The gross composition of the sample is primarily a porous intergrowth of bladed granular anhydrite with minor colloform and granular pyrite and dendritic sphalerite. The sphalerite includes chalcopyrite microcrysts. Rare sulfur(?) microspherules and dendrites are deposited locally in interstices.

ALV2433-3D	I, II	26	Anhydrite Chalco- pyrite Pyrite Sphalerite	36 34 12 12	Wurtzite Phyllo- silicate Sulfur(?) Gypsum	3 <1 <1 <1	<1	1	This sample is a 44-cm long complex "beehive "chimney with numerous active openings. The chimney was formed in two stages: (1) deposition of ribbed layered sphalerite/anhydrite/pyrite (Type II) then (2) deposition of layered chalcopyrite/anhydrite along central channelways with chalcopyrite partially replacing earlier deposits of sphalerite/anhydrite/pyrite (Type I). A series of overlapping thin sections was cut from several transverse-cut slabs to afford multiple cross sections of the sample. The gross composition of the sample from interior to exterior is as follows: (1) Granular chalcopyrite which lines central channelways and is intergrown with sparing granular wurtzite and pyrite. (2) Overgrowth of chalcopyrite by coarse granular anhydrite which becomes finer-grained toward the exterior of the sample. The anhydrite is intergrown with colloform and granular sphalerite (some of which has a lavender tint in reflected light and is faintly pleochroic and anisotropic) and granular pyrite, wurtzite, and chalcopyrite. In the outer parts of the sample, the anhydrite is much dissolved leaving an highly porous relict structure of dendritic and colloform sphalerite. Patches of relict anhydrite remain locally, some of which is altered to gypsum. Microspherules of sulfur(?) and a brownish-yellow phyllosilicate appear in the interstices of the outer sample wall. The sample is rimmed with porous iron oxyhydroxide.
ALV2433-4A	II	32	Sphalerite Anhydrite Wurtzite	39 28 27	Pyrite Iso- cubanite Chalco- pyrite Phyllo- silicate	3 1 1 <1	—	—	This sample is a collection of three small active columnar and spire-like chimlets, each about 10cm long and of similar form and composition, recovered from the top of a "beehive" chimney. Chimlets 1 and 2 were slabbed transverse to the long axis and thin sections were cut to afford cross sections. Chimlet 3 was also slabbed transverse to the long axis, but the tip was also sliced lengthwise parallel to the long axis. Thin sections were cut to afford both transverse and longitudinal cross sections. The gross composition of the three chimlets is primarily a layered parly leached meshwork intergrowth of dendritic, colloform, and granular sphalerite and wurtzite. Local discontinuous bands of coarse granular relict anhydrite intergrown with dendritic and microgranular iron and zinc sulfides remain. The layers are arrayed concentrically around the central channelways. Granular wurtzite lines the central channelways and is locally intergrown with granular isocubanite which displays chalcopyrite exsolution lamellae and chalcopyrite overgrowths. Colorless microspherules of a phyllosilicate are deposited locally in interstices of the zinc sulfide framework.

ALV2434-1-20	III	22	Sphalerite Wurtzite Marcasite Pyrite	36 32 12 10	Phyllo- silicate Pyrrhotite Chalco- pyrite	 5 4 <1	<1	—	This sample is a collection composed of a small columnar 5cm-high active chimlets with associated chimney wall fragments collected from the Table Vent. The chimlet was divided by a several cuts transverse to the long axis and two overlapping thin sections were cut to afford a complete cross section. Two associated slabby fragments were each divided by cuts through the middle transverse to the layering and one thin section was cut from each to afford cross sections. The gross composition of the samples is primarily a layered meshwork intergrowth of dendritic and colloform sphalerite and pyrite penetrated by numerous small meandering channels lined with granular wurtzite. The wurtzite bears sparing inclusions of chalcopyrite microcrysts. The zinc sulfides are locally overgrown with isotropic colloform amorphous silica. Microspherules of a brownish-yellow-to-colorless phyllosilicate fill the interstices of the interior zinc sulfide framework in thin bands paralleling the sample periphery. The sample is rimmed thickly with colloform and dendritic marcasite/pyrite which locally bears granular pyrrhotite overgrowths on the underside.
ALV2435-3	IV	15	Pyrite	30	Anglesite Wurtzite Sphalerite Phyllo- silicate Pyrrhotite Marcasite Anhydrite Jarosite	9 7 5 4 <1 <1 <1 <1	37	1	This sample is a 24cm-high gnarled spire-like inactive chimney plugged with colloform opaline silica and filamentous isotropic amorphous silica The sample was divided into slabs by several cuts transverse to the long axis. One thin section was cut from the uppermost slab and another was cut from the middle slab to afford two complete cross sections. The sample is composed primarily of granular and colloform pyrite intergrown with sparing granular marcasite, pyrrhotite, and wurtzite. Colloform opaline silica overgrows the sulfides, filling most interstices. Filamentous isotropic amorphous silica chokes the channelways. The sample is rimmed with porous colloform pyrite. The pyrite rim bears a thin film of mixed jarosite and a brownish-yellow phyllosilicate which is then capped with iron oxyhydroxide.
ALV2435-8	-do-	15	Marcasite Pyrite Wurtzite	29 14 10	Sphalerite Barite	2 <1	24	18	This sample is composed of three small fragments of the horn-like tip of a 2m-high inactive iron sulfide/amorphous silica chimney. One fragment was sliced through the middle with a cut transverse to the long axis and one thin section was cut to afford a cross section. The sample is composed primarily of colloform marcasite/pyrite intergrown with granular wurtzite, first overgrown with colloform sphalerite, then thickly overgrown with both colloform opaline silica and isotropic filamentous amorphous silica. Colloform pyrite/marcasite lines the central channel, includes barite rosettes, and is highly altered to siliceous iron oxyhydroxide.

ALV2435-9A	IV	10	Pyrite Marcasite	23 11	Pyrrhotite Sphalerite Anglesite Wurtzite Barite Anhydrite Phyllo-silicate	9 <1 <1 <1 <1 <1 <1	53	<1	*This sample is a gnarled pinnacle-like inactive chimney broken* from the base of a larger structure. The lower half of the chimney was slabbed several times transverse to the long axis. Four thin sections were cut along the length of the chimney to afford complete cross sections. The gross composition of the sample is primarily a concentrically-layered intergrowth of colloform and granular pyrite and marcasite overgrown locally with granular pyrrhotite and marcasite, the layering developed around the central channelway. The granular iron sulfides are partly altered to iron oxyhydroxide in places and thickly overgrown with colloform opaline silica. Isotropic filamentous amorphous silica fills the central channel and the anastomosing channelways which penetrate the sample structure. Barite rosettes are deposited sparingly in the filamentous amorphous silica deposits. Depositional boundaries are defined in the amorphous silica deposits by thin films of a yellowish phyllosilicate. Colloform sphalerite, granular wurtzite, anglesite, and relict anhydrite are deposited locally in interstices of the iron sulfide framework.
ALV2436-1E	III	32	Sphalerite Wurtzite Pyrite	48 28 16	Iso-cubanite Chalco-pyrite Marcasite Barite Phyllo-silicate	4 2 <1 <1 <1	—	<1	This sample is a 17cmX4cm inactive spire-like chimney. The sample was divided in half by a longitudinal cut and one longitudinal thin section was cut from the chimney tip and one thin section transverse to the long axis was cut from the base to afford a cross section. The gross composition of the sample is primarily a meshwork intergrowth of dendritic sphalerite and pyrite crystallites with granular wurtzite and sphalerite in the interstices. The crystallites are overgrown with colloform sphalerite and wurtzite. This sulfide framework is penetrated with numerous small tortuous channelways lined with granular wurtzite and sphalerite. The central channelway is studded with these phases and also with granular isocubanite overgrown with chalcopyrite. Microspherules of a brownish-yellow phyllosilicate are deposited locally in the interstices of the zinc sulfide framework. The sample is rimmed with colloform pyrite/marcasite which includes rare barite rosettes and anhydrite grains and is peripherally altered to iron oxyhydroxide.

ALV2436-1F	II	20	Sphalerite Wurtzite Anhydrite Marcasite	28 27 16 13	Phyllo- silicate Pyrite Chalco- pyrite	 6 4 3	—	—	This sample is a collection of three slabby exterior wall fragments from an inactive "beehive" chimney. The largest fragment was divided by a cut transverse to the layering and a thin section was cut to afford a cross section. The chimney wall is strongly layered, displaying a band of colloform marcasite/pyrite midsection paralleling the fragment periphery. Below the iron sulfide band is a thick layer of porous dendritic sphalerite crystallites overgrown with colloform sphalerite and locally with colloform wurtzite. Interstices are commonly filled with granular wurtzite. The wurtzite granules include chalcopyrite microcrysts. Relicts of the granular anhydrite which once formed a dense intergrowth with the sulfides remain in places in the structure. The narrow layer above the iron sulfide band displays reduced porosity and smaller grain size. The upper layer displays a much greater abundance of granular anhydrite. Microspherules of a brownish-yellow phyllosilicate are deposited locally in the interstices of both zinc sulfide-rich layers.
-2F-1	III	15	Sphalerite Wurtzite Marcasite	48 19 15	Pyrite Chalco- pyrite Anglesite Phyllo- silicate	4 <1 <1 <1	12	—	This sample is a collection of three slabby fragments from a large active "beehive" chimney. One fragment was divided transverse to the layering and one thin section was cut to afford a cross section. The sample is composed primarily of a meshwork of dendritic sphalerite crystallites penetrated by numerous small tortuous channelways lined with colloform and granular wurtzite and, rarely, anglesite euhedra. The wurtzite includes chalcopyrite and pyrite microcrysts. Isotropic colloform amorphous silica locally overgrows the sulfides. Isotropic filamentous amorphous silica locally chokes channelways. Rare microspherules of a yellowish phyllosilicate are deposited in the interstices of the sphalerite framework. The sample is rimmed thickly with colloform marcasite/pyrite.
-2F-2	-do-	30	Marcasite	56	Pyrite Sphalerite Wurtzite Barite Anglesite	6 1 <1 <1 <1	5	<1	This sample is composed of two shell-like iron sulfide outer wall fragments from a small fragile hornlike active chimney which collapsed in the attempt to collect it. Each fragment was divided by a cut longitudinal to the long axis and both fragments were placed on the same thin section to afford juxtaposed cross sections. The composition of the sample is primarily spherulitic colloform marcasite/pyrite with rare colloform wurtzite thinly overgrown with colloform opaline silica. Microspherules of marcasite/pyrite intergrown with rare barite rosettes line the interiors of the shells and the exteriors include rare granules of anglesite. The shell exteriors are superficially altered to iron oxyhydroxide.

ALV2436-2F-3	III	44	Sphalerite Wurtzite Pyrite	45 25 18	Marcasite Anhydrite Barite Phyllo- silicate	7 1 1 1	1	1	*This sample is a fragment of the outer wall of a fragile elbow-like* active chimney which collapsed in the attempt to collect it. The fragment was divided by cuts through the middle parallel to the long axis. One thin section was cut to afford a cross section. The sample is composed primarily of a meshwork intergrowth of dendritic sphalerite crystallites and minor granular pyrite. The sulfide dendrites and granules are overgrown with colloform sphalerite. The sulfide framework is penetrated by numerous small tortuous channelways which are lined with colloform sphalerite and then overgrown with colloform wurtzite. Locally, the interstices are filled with isotropic colloform amorphous silica and microspherules of a yellowish phyllosilicate. The sample is rimmed thickly with porous colloform pyrite which includes rare barite rosettes and anhydrite granules. The rim is underlain by colloform marcasite and the periphery of the rim is altered to iron oxyhydroxide.
ALV2437-3A	-do-	40	Sphalerite Wurtzite	53 12	Pyrrhotite Pyrite Iso- cubanite Chalco- pyrite Marcasite Barite Anhydrite Gypsum Phyllo- silicate	5 3 3 1 1 1 1 1 1	17	1	*This sample is a 41cm-high inactive double columnar chimney* from the Pipe Organ active vent area. The sample was divided by parallel slices transverse to the long axis. Five overlapping thin sections were cut from the lowest slab traversing the long diameter to afford a complete cross section of both chimneys. The gross composition of both chimneys is primarily a layered meshwork intergrowth of dendritic sphalerite crystallites overgrown with colloform sphalerite and wurtzite. The colloform overgrowths are especially well-developed in the outer walls. The sulfide framework is deposited in concentric layers around the central channelways of both chimneys. Light-colored wurtzite overgrows dark-colored sphalerite in the younger chimney. The sulfides are overgrown thinly with opaline silica in both chimneys. Pyrrhotite plates and pyrite granules are intergrown with the zinc sulfides with increasing abundance toward the interior of both chimneys. Porosity also increases toward the interior in both chimneys. The sulfide framework of both chimneys is penetrated by numerous tortuous channelways lined with pyrrhotite plates which are partially altered to iron oxyhydroxide. The pyrrhotite plates become intergrown with chalcopyrite and isocubanite granules around the central channelways. The isocubanite granules display plumose chalcopyrite exsolution. The zinc sulfides become granular toward the chimney interiors. Microspherules of a yellowish phyllosilicate are deposited locally in interstices and as thin overgrowths on the zinc sulfides, particularly in the younger of the two chimneys. Relicts of granular anhydrite (partly altered to gypsum) intergrown with dendritic sphalerite remain in the interior of the older of the two chimneys. Both chimneys are rimmed thinly with colloform pyrite/marcasite which includes barite rosettes and is altered peripherally to iron oxyhydroxide.

ALV2442-7	II	36	Sphalerite Wurtzite Phyllo- silicate	53 19 11	Marcasite Chalco- pyrite Pyrite Anhydrite Barite Gypsum	6 5 2 1 1 1	—	1	This sample is a large ovoid domical inactive "beehive" chimney. The entire deposit was recovered and divided into several slabs by parallel cuts transverse to the chimney accretion axis. Thin sections were produced as follows: slab 1 (lowermost) - eight overlapping thin sections were cut to afford a cross section from the chimney exterior to the central channel region. Slab 3 (middle) - three overlapping thin sections were cut to afford a cross section from the chimney exterior to a point halfway to the central channel. Piece 7B (a shell-like outer wall fragment whose position could not be determined exactly) - one thin section was cut to afford a cross section. The gross composition of the sample is primarily a fragile highly porous leached meshwork intergrowth of gray dendritic sphalerite crystallites overgrown with colloform sphalerite and wurtzite. Granular sphalerite and wurtzite which include chalcopyrite and pyrite microcrysts are deposited in the interstices locally. The sulfide framework is deposited in concentric shells around the central channelway. Only isolated relicts of the original granular anhydrite/sulfides intergrowth remain. Gypsum euhedra derived from the hydration and recrystallization of the original anhydrite are deposited locally in interstices. Barite rosettes are also deposited in some of the interstices. The shells are crowned locally with colloform pyrite/marcasite and underlain with concentrations of chalcopyrite granules. Thick dense deposits of a cream-white phyllosilicate which include granular sphalerite and chalcopyrite fill interstices and voids in the sulfide framework around the central channelway. Where these deposits are exposed along channelways, they are coated first with chalcopyrite then with dark-colored granular sphalerite. Piece 7B is the only portion that displays any iron oxyhydroxide deposits.

ALV2444-3A-1	III	50	Sphalerite	40	Iso-cubanite	6	—	16	*This sample is the completely sealed tip of a 5m-high inactive* chimney. The sample was divided into slabs transverse to the long axis and three thin sections were cut from the lower slab to afford cross sections. One thin section was cut from a fragment of the thick iron sulfide rim of the chimney which spalled off in slabbing to afford a cross section. The gross composition of the sample is as follows: the outer wall is primarily a porous cyclically-layered meshwork intergrowth of dendritic sphalerite crystallites overgrown thickly with colloform sphalerite, then colloform wurtzite, then granular sphalerite. The granular sphalerite includes pyrite microcrysts. Some layers are dotted with pyrite granules. The outer wall encases a broad highly porous interior which is composed of an open intergrowth of pyrrhotite plates and isocubanite granules. The isocubanite granules locally display exsolution lamellae of chalcopyrite. Some of the isocubanite granules are overgrown thinly with chalcopyrite and then overgrown with brown granular sphalerite. The pyrrhotite plates are extensively altered to iron oxyhydroxide. Sulfur granules and microspherules of a colorless phyllosilicate are deposited locally on the sulfides. The sample is rimmed thickly with colloform marcasite which displays minor colloform pyrite cores. Rare barite rosettes are deposited along the underside of the rim. The exterior of the rim is altered to iron oxyhydroxide.
			Marcasite	20	Wurtzite	4			
			Pyrite	10	Chalco-pyrite	1			
					Sulfur	1			
					Barite	1			
					Phyllo-silicate	1			

Table 2. Petrography, chemical data, and mineralogy of selected late-stage hydrothermal and alteration phases detected in hydrothermal chimney deposits of the northern Cleft segment of Juan de Fuca Ridge.

Petrography (Light Microscopy)	Chemistry (EDAX)	Mineralogy (XRD)
Sample Number: ALV2094-1A-7: This sample was cut from a transverse slab taken from the interior of a large pinnacle-like chimney. A series of overlapping thin sections was cut to effect a complete cross-section. This thin section was cut from the chimney interior and reveals an intergrowth of colloform pyrite globules and wurtzite granules thinly overgrown with colloform sphalerite and granular marcasite. The sulfides are thickly overgrown with opaline silica and isotropic filamentous amorphous silica. Chalcopyrite microcrysts are included in the zinc sulfides. Traces of yellowish phyllosilicate microspherules[1], colorless, faintly birefringent iron sulfates, and relict anhydrite partly altered to gypsum locally encrust the sulfides beneath the amorphous silica.	[1]Major: Si Trace: Al, K, Ca	[1]-not analyzed-
Sample Number: ALV2094-1A-8 to 9A: This sample is similar to 2094-1A-7 and was taken just outward from it in the zone peripheral to a large channelway. Varying from the previous sample, wurtzite is more abundant than pyrite and marcasite is decreased. Chalcopyrite and anhydrite are increased in abundance. Phyllosilicates,[1] occurring as very fine encrusting microfolia, are much more abundant, filling many interstices. Amorphous silica[2] occurs as isotropic filaments and microspherules, and as opaline silica overgrowths on sulfides.	[1]Major: Si Minor: Al Trace: K, S [2]Major: Si	Moderate: sphalerite, wurtzite Minor: pyrite, phyllosilicate[1] (21.02Å, glyc.), sulfur Trace: marcasite [2]Major: amorphous (amorphous silica?)

Sample Number: ALV 2094-4A1-3A: This sample is a fragment of a collapsed inactive chimney. Thin sections were cut from opposite ends of the strongly layered fragment to effect a cross-section. This thin section revealed a composition primarily of intergrown pyrite and dendritic sphalerite crystallites overgrown with colloform pyrite and sphalerite. Oxidized colloform pyrite and marcasite with amorphous silica overgrowths sheath the chimney exterior. Sprays of barite[1] microcrysts thinly line the underside of the iron sulfide/amorphous silica outer wall. A sooting of manganese oxyhydroxide coats the chimney exterior and a thin sheath of banded siliceous/argillaceous/phosphatic iron oxyhydroxide[2] coats the inner wall.	[1]Major: Ba Moderate: S [2]Major: Fe Moderate: Si Minor: S Trace: Cl (from epoxy?), Mn (exterior only), P, Al	[1]Minor: barite, sphalerite [2]Major: amorphous (iron oxyhydroxide+amorphous silica?)
Sample Number: ALV 2094-4A1-3B: This sample was cut from the interior of the same chimney fragment as 4A1-3A, transverse to the length. The sample is composed of highly-layered dendritic sphalerite crystallites overgrown with colloform sphalerite. Some of the sphalerite is altered to bianchite ($ZnSO_4.6H_20$)(?)[1]. Abundances of granular wurtzite, pyrite, and marcasite occur with smaller amounts of barite needles in spray-like groupings in some interstices. Chalcopyrite microcrysts are included in the zinc sulfides. Amorphous silica thinly overgrows most of the sulfide phases and locally includes fine folia of a yellowish phyllosilicate[2]. The phyllosilicate deposits are most abundant in the sample interior. The inner and outer walls of the sample are altered to siliceous and phosphatic iron oxyhydroxide[3].	[1]Major: Zn Moderate: S Minor: Cl (from epoxy?) [2]Major: Si Trace: Al [3]Major: Si, Fe Trace: S, P Zn (exterior only) Cl (?) (from epoxy?)	Major: amorphous (aluminum oxyhydroxide+amorphous silica?), sphalerite Minor: wurtzite Trace: bianchite(?)[1] [2]Major: amorphous (aluminum hydroxysilicate+amorphous silica?) [3]Major: amorphous (iron oxyhydroxide+amorphous silica?)

Sample Number: ALV2258-1A: This sample is the tip of a gnarled partially plugged inactive chimney. The sample was divided lengthwise and a thin section was cut to effect a longitudinal cross-section. The thin section revealed a composition mainly of intergrown colloform marcasite and pyrite overgrown locally with granular marcasite and pyrite. The sulfides are overgrown thickly with white opaque opaline silica and isotropic filamentous amorphous silica [1] which locally include anglesite euhedra, phyllosilicates, sulfur, and iron sulfates. Commonly, the iron sulfides have superficially oxidized under the amorphous silica to iron sulfates and sulfur. White and brownish-yellow phyllosilicates locally overgrow the iron sulfides and fill interstices. Corroded anhedra of sphalerite and wurtzite line channelways locally. Siliceous iron oxyhydroxide [2] rims the sample.	[1]Major: Si [2]Major: Fe Minor: Si Trace: S	[1]-not analyzed- [2]-not analyzed-
Sample Number: ALV2258-1B: This sample is similar to ALV 2258-1A and was cut from the other side of the same slab. Mineral distribution varies considerably from -1A: Analysis Area # 1[1]- a fracture in opaline silica laden with colloform marcasite/pyrite and filled with brownish-yellow iron sulfates. Analysis Area #2[2]- the dense, mottled siliceous iron oxyhydroxide rim on the exterior of the chimney. Analysis Area #3[3]- heavy opaline silica overgrowth on colloform marcasite/pyrite from the region of the central channelway.	[1]Major: Fe Moderate: S [2]Major: Fe Moderate: S Minor: K, Si Trace: Cl (from epoxy?), Al [3]Major: Si	[1]-not analyzed- [2]Major: amorphous (iron oxyhydroxide+amorphous silica?) Trace: dahllite (?) [3]-not analyzed-

Sample Number: ALV2265-1B: This sample is a chimney fragment which was slabbed transverse to the long axis and this thin section was taken from the center. The sample is composed mainly of dark dendritic sphalerite crystallites overgrown with colloform sphalerite and wurtzite. The intergrowth is penetrated by numerous small meandering channelways many of which are sheathed with abundant granular wurtzite and sphalerite. The sulfide granules include chalcopyrite microcrysts and are commonly overgrown with chalcopyrite filagrees. Granules of chalcopyrite with isocubanite cores are locally intergrown with the ZnS granules. Colorless microspherules of a phyllosilicate[1] locally fill interstices in the granular wurtzite/sphalerite sheathing the conduits in the center of the sample. The exterior is superficially altered to iron oxyhydroxide. Sinuous bands of colloform pyrite/marcasite compartment the sample concentrically.	[1]Major: Si Moderate: Al Trace: Fe, K, S, Zn	[1]-not analyzed-
Sample Number: ALV2266-3: This sample was taken from near the top of a pinnacle of coalesced chimneys. Sample #3 was slabbed transverse to its length and this thin section was cut from the slab interior. The sample is composed mainly of colloform and granular pyrite and marcasite laced with many tortuous channelways. The channelways are very sparingly lined with granular wurtzite and then thickly with opaline silica. Isotropic filamentous amorphous silica[1] which locally bears anglesite euhedra and sulfur and anglesite microcrysts lines the channelways in places. Spherulitic overgrowths of a cream-white phyllosilicate[2] thickly coat the iron sulfides and fill interstices and channelways locally. Associated with iron sulfides are brightly birefringent microspherules[3] intergrown with the phyllosilicate and amorphous silica. The sample exterior is superficially altered to iron oxyhydroxide and then sooted with manganese oxyhydroxide.	[1]Major: Si Trace: Cl (from epoxy?) [2]Major: Si, Al Trace: K, Ca, Cl (from epoxy ?), S, Zn [3]Major: S Minor: Si, Zn Trace: Al, Pb, Fe, Cu	[1]-not analyzed- [2]Major: amorphous (phyllosilicate+opal ?) [3]Major: amorphous (opal+phyllosilicate ?), sphalerite Minor: anglesite

Sample Number: ALV2266-4A/B: This sample is a fragment assumed to be from the same pinnacle as ALV 2266-3. This thin section was cut from the middle of the fragment. The sample is composed primarily of an intergrowth of colloform marcasite with subordinate pyrite, with granular wurtzite and sphalerite deposited in some interstices. The iron sulfides are overgrown locally with a brownish-yellow phyllosilicate[1] then generally with opaline silica. The phyllosilicate locally fills interstices in the granular wurtzite/sphalerite deposits forming aureoles around the numerous tortuous channelways which penetrate the sulfide intergrowth toward the interior of the sample. Anglesite and sulfur[2] euhedra occur sparingly in interstices of the wurtzite/sphalerite channelway lining. The sample exterior is superficially altered to iron oxyhydroxide.	[1]Major: S, Si Moderate: Al Trace: V, K, Ca(?), Fe, Zn [2]Major: S	[1]Major: amorphous (opal+phyllosilicate ?) Moderate: wurtzite Minor: sphalerite Trace: pyrite, marcasite, phyllosilicate (?) [2]-not analyzed-

Sample Number: ALV2429-1-3B: This sample is from a small horn-like active chimney with a single large smooth-walled central channel. This thin section was cut from the center of the chimney transverse to the long axis. The sample is constructed of concentrically-deposited narrow bands of distinctly different mineral deposits. Lining the central channelway is a thick band of intergrown chalcopyrite crystals. Overlying the chalcopyrite is a much thinner band of radially-arranged coarse-grained bladed anhydrite with included colloform sphalerite, wurtzite, chalcopyrite, and pyrite granules. Overlying the anhydrite is a thin deposit of granular wurtzite. Overlying the wurtzite is a mixed deposit of dendritic sphalerite intergrown with isotropic amorphous silica filaments. Chalcopyrite granules are deposited in interstices locally. The mixed deposit is crowned by a thin intergrowth of amorphous silica filaments[1], wurtzite granules, and colloform sphalerite overgrown with layers of finely fibrous silicates[2] which vary in composition and color. A thin layer of colloform marcasite overlies the silicate deposits. The marcasite layer is overlain by another deposit of dendritic sphalerite intergrown with filamentous amorphous silica The chimney is rimmed with iron oxyhydroxide, amorphous silica and relict sphalerite.	[1]Major: Si [2]Major: Si, Fe (tan outer layer), Minor: Mg (white inner layer) Trace: Mg (tan outer layer), S (white layer only), Cl (from epoxy?), Mn (tan outer layer only), Zn (only in white layer) [3]Major: Fe Moderate: Si (decreases toward exterior) Trace: Ca (increases toward exterior), P (increases toward exterior), Cl (from epoxy?)	[1]-not analyzed- [2]Major: amorphous (amorphous silica+phyllosilicate?) Minor: sphalerite 3Major: amorphous (iron oxyhydroxide+amorphous silica?) Minor: sphalerite
Sample Number: ALV2429-2-3A-1: Only fragments of the outer wall of this chimney were recovered. This thin section was cut as a cross-section of one of the fragments. The sample is composed primarily of an cyclical intergrowth of dendritic sphalerite crystallites overgrown with colloform and dark brown granular sphalerite/ wurtzite. Narrow hollows separate the layers. The undersides of the sulfide layers bear colorless microspherules of a phyllosilicate[1] in the interstices between wurtzite and sphalerite granules.	[1]Major: Si Moderate: Al Trace: Cl (from epoxy?), Zn, S, K	[1]Major: amorphous (amorphous silica+phyllosilicate?) sphalerite Trace: wurtzite

Sample Number: ALV2431-3A-1A-1: This sample was broken from the top of a pinnacle chimney and a thin section was cut from the tip. The thin section reveals a dense intergrowth of dendritic sphalerite crystallites overgrown with colloform sphalerite and wurtzite. Wurtzite granules occupy many of the interstices and become more numerous toward the sample interior. The intergrowth is penetrated with meandering channelways which widen toward the sample interior. The channelways are lined with granular wurtzite which includes chalcopyrite microcrysts. The sample exterior is rimmed thickly with colloform marcasite/pyrite which is altered peripherally to iron oxyhydroxide with included sulfur and relict iron sulfide grains[1]. Other external alteration products include local botryoidal overgrowths composed of iron oxyhydroxide, sulfur, and jarosite[2].	[1]Major: S Moderate: Fe [2]Major: S, Fe Minor: K Trace: P, Cl (from epoxy?), Si (?), Na (?), Zn	[1]Major: amorphous (iron oxyhydroxide+FeS_2+S ?) [2]Major: amorphous (iron oxyhydroxide+sulfur ?) Minor: hydroxylapatite (?)
Sample Number: ALV 2431-3A-1B-1B-2: This sample was taken from the same chimney as ALV 2431-3A-1A-1 but from about 10cm below it. A thin section was cut to effect an exterior cross-section. The thin section reveals composition and structure similar to that those of 3A-1A-1, except that isotropic amorphous silica thinly overgrows sulfides locally and barite rosettes appear sparingly in some interstices. Relict anhydrite grains and phyllosilicate microspherules occupy some interstices locally. The sample exterior is thinly and discontinuously rimmed with colloform marcasite. The marcasite rim is superficially altered to siliceous iron oxyhydroxide[1]. Some of the iron oxyhydroxide is cavernous and contains bead-like growths of fibrous microspherules[2] which may be of biological origin.	[1]Major: Fe Minor: S Trace: Si, Cl (from epoxy?), Zn [2]Major: Fe Minor: S Trace: Cl (from epoxy ?), Zn, Si, P(?), K(?), Al(?), Na(?)	[1]Major: amorphous (iron oxyhydroxide+amorphous silica?) [2]-not analyzed-

Sample Number: ALV2434-1 20B-1A: This sample is from a small columnar chimney. This thin section was cut near the chimney top to afford a cross-section. The thin section reveals a layered intergrowth of dendritic sphalerite crystallites and granular sphalerite and wurtzite which include chalcopyrite microcrysts. Microspherules of a brownish-yellow phyllosilicate[1] are aggregated in interstices of the granular zinc sulfides on the undersides of the layers. The sample is rimmed with layered cavernous deposits of colloform and dendritic marcasite/pyrite.	[1]Major: Si Moderate: Al Trace: Fe(?)	Major: sphalerite, amorphous (phyllosilicate+amorphous silica?) [1]Minor: phyllosilicate (16.98 Å, glyc.), wurtzite
Sample Number: ALV2435-3-2 TOP: This sample is from a well-sealed gnarled chimney spire. A thin section was cut from the upper end to effect a cross-section. The thin section reveals a composition mainly of colloform and granular pyrite. Subordinate colloform and granular wurtzite and sphalerite are deposited in interstices. The sufides are thickly overgrown with opaline silca and isotropic filamentous amorphous silica Most of the numerous sinuous concentric channelways are filled with amorphous silica. The sample is rimmed with porous colloform pyrite which is altered externally to siliceous and phosphatic iron oxyhydroxide[1]. Overlying the oxidized crust locally are thin deposits of jarosite[2] and a brownish-yellow phyllosilicate[3].	[1]Major: Fe Minor: Si, P, S, Cl (from epoxy?) Trace: Mn, Na (?) [2]Major: S, Fe Moderate: K [3]Major: Si Minor: Al, Ca, Fe Trace: S, Cl (from epoxy?), K, Mn (?), Na (?)	[1]Major: amorphous (iron oxyhydroxide+amorphous silica?) [2]Major: amorphous (opal+phyllosilicate ?) Moderate: jarosite Trace: dahllite (?), phyllosilicate (?) [3]-not analyzed-

<u>Sample Number</u>: <u>ALV 2435-8A-1</u>: This sample was taken from the tip of an inactive chimney which broke into three long axis-parallel fragments. A thin section was cut transverse to the long axis of one of the fragments to afford a complete cross section. The thin section reveals a composition primarily of intergrown colloform pyrite and marcasite thickly overgrown with colloform opaline silica and isotropic filamentous amorphous silica along channelways. Granular wurtzite lines the tubular open central channelway and is overgrown by colloform sphalerite. Deposits of ferruginous amorphous silica[1] filaments which include barite[2] rosettes in turn coat the zinc sulfides.	[1]Major: Fe Trace: Si, P, Cl (from epoxy?), S [2]Major: Ba, S	[1]Major: amorphous (iron oxyhydroxide+amorphous silica?) [2]Major: barite
<u>Sample Number:</u> <u>ALV2442-7A-1B-5:</u> This sample was taken from a large inactive mound-like chimney and was slabbed several times transverse to the doming. A series of overlapping thin sections was cut from one of the interior slabs. This thin section was taken from the phyllosilicate-rich zone surrounding the central channelway. The thin section reveals the edge of the large irregular central channelway lined with dense deposits of a white-to-cream-white phyllosilicate[1] with included microgranules of sphalerite and chalcopyrite. Phyllosilicate projections into the central channelway are coated first with a thin layer of chalcopyrite then with a thicker layer of dark colloform sphalerite.	[1]Major: Si Moderate: Al Trace: S, Fe, K(?), Zn, Na(?)	[1]Major: amorphous (phyllosilicate+amorphous silica?) sphalerite Minor: chalcopyrite, phyllosilicate (14.48 Å, glyc.)

Sample Number: ALV2444-3A-1C-2: This sample was taken from a sealed inactive spire-like chimney. The tip of the sample was cut transverse to the long axis and a thin section was cut to effect a cross-section. The thin section reveals a very porous chimney interior composed of a boxwork intergrowth of oxidized pyrrhotite[1] plates with minor sphalerite, isocubanite, chalcopyrite, and sulfur granules. Above the boxwork is an outer layer composed of dendritic sphalerite crystallites overgrown thickly with colloform wurtzite which includes chalcopyrite microcrysts. In the interior of the outer layer, granules of drusy sphalerite overgrow the wurtzite. Channelways are lined with colloform wurtzite which includes pyrite microcrysts. Barite rosettes are abundant in the periphery of the the outer layer. Colloform pyrite/marcasite with local inclusions of anglesite rims the chimney. This rim is partly altered to iron oxyhydroxide.	[1]Major: Fe, S Trace: Al, Mg, Si, Cl (from epoxy ?), Zn (?)	[1]-not analyzed-