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ACTIVE VENTS AND MASSIVE SULFIDES AT 26°N (TAG) AND 23°N (SNAKEPIT) ON THE MID-ATLANTIC RIDGE

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Abstract

Two active hydrothermal vent sites on the Mid-Atlantic Ridge at 26°N (TAG) and 23°N (Snakepit) have recently been discovered at depths of 3700 and 3500 m, respectively. Although black smokers are present at both sites, their geological settings differ. The TAG area is located on older sedimented crust a few km from the spreading axis, at the junction of the rift-valley floor and the east wall; the Snakepit site is atop a large volcanic ridge (40 km long, up to 600 m high) in the axial zone of the rift valley. The TAG site is the larger of the two and is probably older. Hydrothermal discharge from vents at both sites ranges from shimmering water, through white smokers (226°C) to black smokers (335°C and 350°C). Hydrothermal solutions are similar in major-element composition to those from the East Pacific Rise. Mineralization is similar to that occurring on faster-spreading ridges, *e.g.*, the dominant polymetallic sulfides are pyrite, pyrrhotite, chalcopyrite and sphalerite; anhydrite is the main sulfate phase. The deposits differ from some of those on the East Pacific and Juan de Fuca ridges in having little or no barite, very little amorphous silica, and in having abundant aragonite as a late-stage precipitate. Diagenesis and weathering, particularly at the TAG site, have produced abundant amorphous iron oxides and hydroxyoxides, goethite, hematite, atacamite, jarosite and sulfur. At the Snakepit site the black smokers consist mainly of pyrrhotite, but this sulfide phase is absent from the active chimneys at TAG. Zinc sulfide occurs as the predominant phase in the lower-temperature white smokers at both sites.

Keywords: polymetallic sulfides, hydrothermal, Mid-Atlantic Ridge, TAG, Snakepit.

Sommaire

Deux sites d'évents hydrothermaux actifs, situés à 26°N (TAG) et 23°N (Snakepit) le long de la dorsale médio-Atlantique, viennent d'être découverts, respectivement, à une profondeur de 3700 et 3500 m. Malgré la présence de «fumeurs noirs» dans les deux cas, les contextes géologiques diffèrent. Dans la région de TAG, les évents se trouvent sur une croûte ancienne et d'origine sédimentaire, à quelques kilomètres de l'axe de la ride, à l'intersection de la vallée du rift et de la paroi orientale. Par contre, le site de Snakepit est situé sur un édifice volcanique, de 40 km de longueur et jusqu'à 600 m de hauteur, dans la zone axiale de la vallée du rift. Des deux, c'est le site de TAG qui est le plus étendu et probablement le plus âgé. La décharge hydrothermale des évents aux deux sites varie, de l'eau chatoyante à des «fumeurs noirs» (335 et 350°C), en passant par des «fumeurs blancs» (226°C). En termes de teneur en éléments majeurs, les solutions hydrothermales ressemblent à celles de la dorsale Est Pacifique. La minéralisation est typique de celle qui caractérise les dorsales à séparation rapide des plaques: les sulfures polymétalliques dominants sont pyrite, pyrrhotine, chalcopyrite et sphalérite, avec anhydrite comme sulfate principal. Les dépôts diffèrent de ceux qui caractérisent les dorsales Est Pacifique et Juan de Fuca, par la rareté ou l'absence de baryte, ainsi que la quantité infime de silice amorphe, et l'abondance de l'aragonite comme précipité tardif. La diagenèse et le lessivage, surtout au site de TAG, ont produit une abondance d'oxydes (hydroxylés ou non) amorphes de fer, ainsi que goethite, hématite, atacamite, jarosite et soufre. À Snakepit, les «fumeurs noirs» ont surtout donné de la pyrrhotine, mais ce sulfure est absent des cheminées actives à TAG. Un sulfure de zinc constitue la phase dominante dans les «fumeurs blancs», à température inférieure, aux deux sites.

(Traduit par la Rédaction)

Mots-clés: sulfures polymétalliques, hydrothermal, dorsale médio-Atlantique, TAG, Snakepit.

Introduction

Early indications of the importance of hydrothermal circulation at mid-ocean ridges to heat and mass transfer came from heat-flow measurements and observations on hydrothermally altered basaltic rocks from the Mid-Atlantic Ridge (Shand 1949, Melson *et al.* 1968, Deffeyes 1970, Talwani *et al.* 1971). Mn and Fe oxides precipitated from hydrothermal solutions were subsequently observed at the TAG hydrothermal field at 26°N (Rona 1973, Scott *et al.* 1974), the flank of the Ridge at 23°N (Thompson *et al.* 1975, Lalou *et al.* 1988), and the FAMOUS area at 36°N (Hoffert *et al.* 1978). The first direct observations of active hydrothermal systems were made on the Galapagos Ridge in 1977 (Corliss *et al.* 1979); large amounts of polymetallic sulfides were discovered on the East Pacific Rise shortly afterwards (CYAMEX 1978, RISE 1980).

The TAG hydrothermal area has been the focus of a number of studies over the past thirteen years (Rona 1980, Rona *et al.* 1984). Submersible observations at a low-temperature hydrothermal field at the TAG site, and the morphology, mineralogy and chemistry of hydrothermal precipitates at that field have been described by Thompson *et al.* (1985).

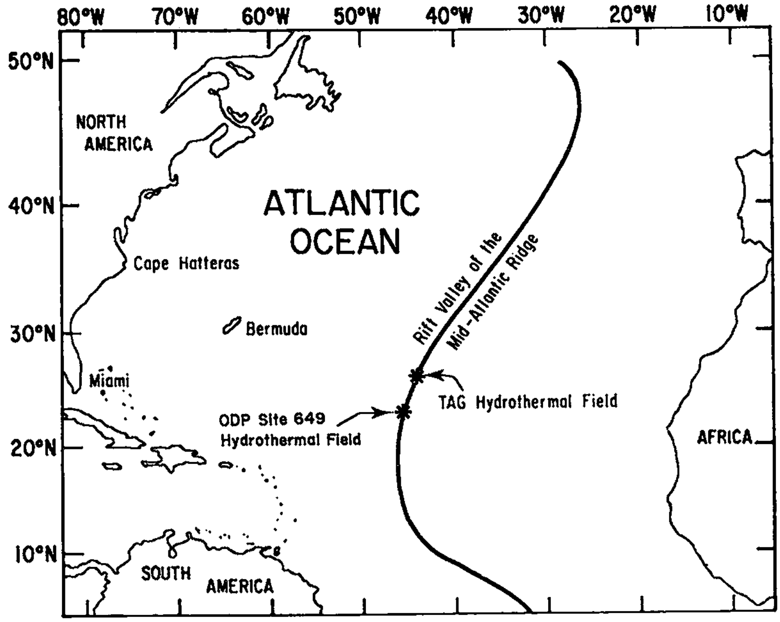

FIG. 1. Location of the two Mid-Atlantic Ridge hydrothermal sites: TAG and ODP Site 649 (Snakepit).

In July 1985 the NOAA ship *Researcher*, using a combination of water-column Mn anomalies (Klinkhammer *et al.* 1985), light-scattering measurements (Nelsen *et al.* 1985), and deep-towed instrumentation (Rona 1985), discovered an active high-temperature hydrothermal system at the TAG location (Rona *et al.* 1986a). During the cruise, active black smokers were photographed, and massive sulfides were recovered in a single dredge haul through the deposit. As a result of the discovery, three dives were made in May 1986 on the active high-temperature field at TAG using the deep research submersible ALVIN. We recovered massive sulfides, hydrothermal waters and biota, and did bottom photography and heat-flow measurements (Rona *et al.* 1986b, Thompson *et al.* 1986, Edmond *et al.* 1986, Schroeder *et al.* 1986, Grassle *et al.* 1986).

In May 1985, during a site survey for the Ocean Drilling Program (ODP), mottled sediment was noted in bottom photographs from one location on the ridge axis about 23°N (Kong *et al.* 1985). In December 1985, Leg 106 of the ODP occupied the site and discovered an active high-temperature vent field (Scientific Party 1986a,b). Drilling recovered massive and unconsolidated sulfides. In May 1986, after the three dives at the TAG location, ALVIN made one dive at the Leg 106 site, also known as the Snakepit hydrothermal area. Massive sulfides, hydrothermal sediment and waters, and various biota were recovered.

These two localities (Fig. 1), TAG and Snakepit, are the only known sites of active high-temperature hydrothermal activity on the slow-spreading Mid-Atlantic Ridge. Relative to hydrothermal sites at other spreading axes, the TAG and Snakepit biological communities have organisms that are more mobile, and have fewer sessile biota. The two localities differ from each other in their geological setting and in their mineralogy. Their water depths are about 1 km deeper than black-smoker vents at the more rapidly spreading ridges in the Pacific Ocean. Thus the Atlantic hydrothermal systems operate under higher pressure conditions than do the Pacific sites. In this paper we report data on the geological settings of the TAG and Snakepit sites, and on the mineralogy and chemistry of the recovered hydrothermal precipitates, particularly those recovered by dredging at TAG. The Mid-Atlantic Ridge is part of a system of slowly spreading oceanic ridges that extend through the Atlantic Ocean and the Western Indian Ocean; such ridges constitute more than half of the 55,000 km length of the global mid-ocean ridge system. Thus, observations on the temperature and composition of hydrothermal solutions, and the mineralogy and composition of hydrothermal precipitates at the TAG and Snakepit sites will be important in assessing the role of slow-spreading ridges in hydrothermal exchange processes that affect ocean chemistry, heat transfer, seafloor mineralization and biological adaptation.

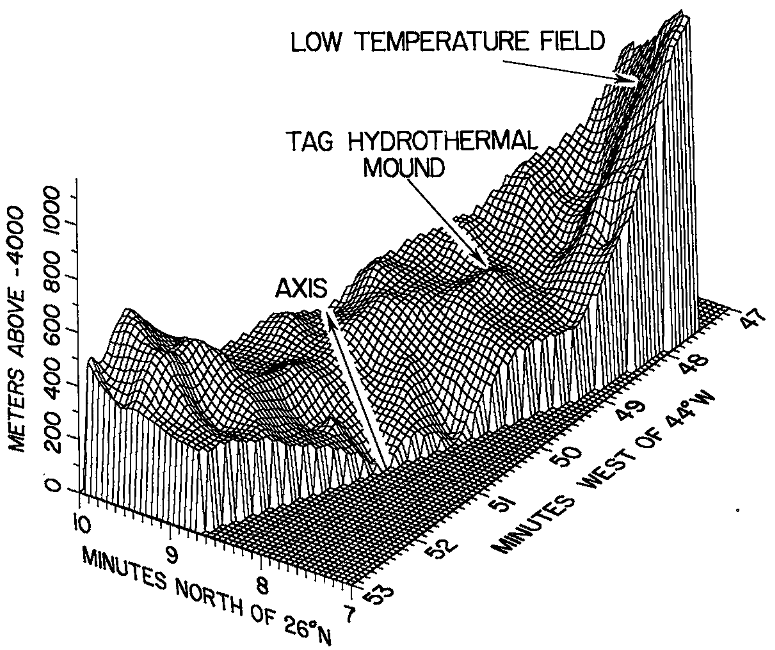

FIG. 2. Orthorhombic projection, made from Seabeam swath across the TAG region (Rona *et al.* 1986a). The active TAG hydrothermal site and major features such as the rift axis, east-wall salient, and low-temperature hydrothermal field are shown. Position of the site is 26°08′N, 44°49′W.

THE TAG HYDROTHERMAL FIELD

Geological setting

The TAG field is on a 10-km long segment of the east wall of the rift valley between two short transform faults (Rona *et al.* 1976). At this location the east wall projects westward as a broad salient towards the spreading axis (Fig. 2). The seafloor is spreading asymmetrically at a half-rate (averaged over 10 × 10^6 yr) of 1.1 cm yr^{-1} to the west, and 1.3 cm yr^{-1} to the east (McGregor & Rona 1975). The east wall rises from the valley floor, near 4000 m depth, to a height of 2000 m through a series of steps formed by fault blocks (Temple *et al.* 1979). Previous work delineated a zone of low-temperature hydrothermal activity between 2400 and 3100 m depth on the east wall (Rona *et al.* 1984).

The metalliferous deposits of this low-temperature zone include widespread surficial metal-rich staining of carbonate ooze, as well as discrete, massive layered deposits of manganese oxide (birnessite), iron oxide (amorphous), and iron silicate (nontronite). The stratiform deposits range from less than 1 m across to about 15 m × 20 m. They vary in composition from thick, laminated, crystalline birnessite precipitates, through Fe-rich tubular vents, to deposits of loose, earthy, interlayered birnessite, nontronite, and amorphous Fe oxides (Thompson *et al.* 1985). Anomalous temperatures (Rona *et al.* 1984) and excessive ^{3}He (Jenkins *et al.* 1980) were recorded in near-bottom waters above the low-temperature field. Metal enrichments in the sediments have been recorded both at the surface and at 30-cm depth (Cu and Zn >1000 ppm, Fe >8%); these enrichments were attributed to past and recent episodes of high-temperature venting in the area (Shearme *et al.* 1983). The hydrothermal deposits in this low-temperature field exhibit a linear distribution along fault zones, trending sub-parallel to the valley floor, that are inferred to focus hydrothermal discharge (Scott *et al.* 1974, Rona *et al.* 1984, Thompson *et al.* 1985).

The presently active black-smoker system occurs at the juncture between the rift-valley floor and the east wall at a depth of 3620–3700 m and at approximately 26°08′N, 44°49′W (Fig. 2). The low-temperature field described above lies 3.7 km upslope to the east; the bathymetric axis of the rift valley is 1.5 km to the west. The active high-temperature field lies on oceanic crust at least 100,000 years old, as calculated from the present seafloor spreading rate. The black smokers lie in an elliptical, compound mound consisting of concentric inner and outer portions (Rona *et al.* 1986a). The inner mound is about

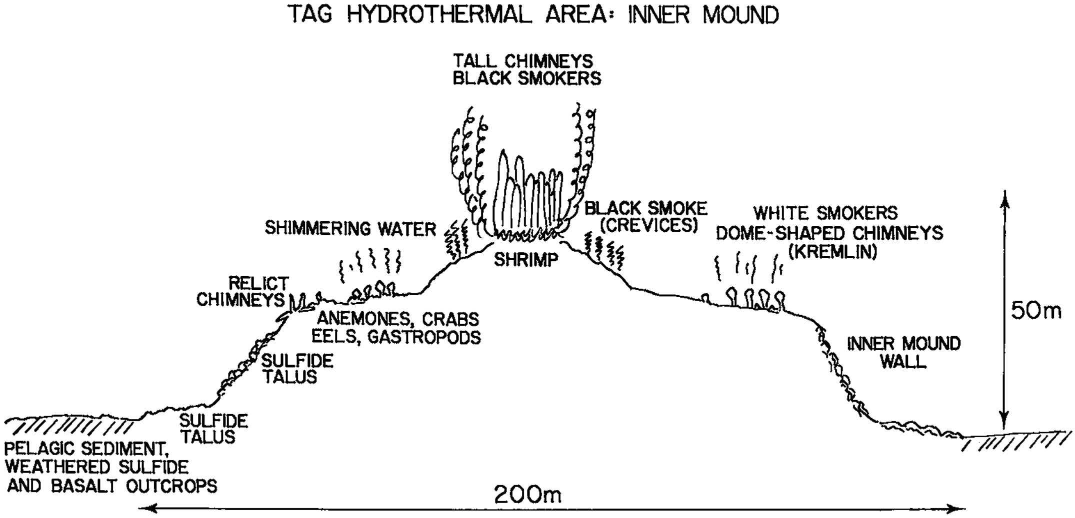

FIG. 3. Generalized cross-section of the inner, active hydrothermal mound of the TAG area, showing principal geological and biological features.

250 m wide and lies between 3620–3675 m depth; the outer mound is approximately 580 m wide and lies between 3675–3700 m depth. The submersible observations made in 1986 were mostly restricted to the inner, active mound with only one transect across the outer mound to about 1 km outside.

Structure of the hydrothermal mound

The outer mound is covered predominantly with carbonate ooze ranging in thickness from a few cm to tens of cm. Basalt talus and occasionally massive sulfide blocks with deeply oxidized outer rims outcrop through the ooze, commonly at or near the tops of small ridge-like structures. No signs of active hydrothermal activity were noted. The first signs of fluid flow and vent biota are at the junction of the inner and outer mounds, near the base of the inner mound wall; some relict chimneys also occur there.

The inner-mound wall is very steep and rises about 30 m above the outer mound (Fig. 3). The wall is composed of massive sulfide talus which weathers red, yellow and green. There are no basaltic outcrops or basalt talus in the inner mound. Gulleys are common, but even in the gulley walls only sulfide blocks outcrop. At the top of the inner-mound wall shimmering waters were observed; these may be associated with white particulate matter, some of which is floc-like in appearance. Anemones and crabs are common (Fig. 4A), and eels, gastropods and small worm tubes on sulfide talus are present. Although upright and fallen chimneys were observed, most of the shimmering water appeared to come from cracks and fissures in the surrounding talus. At one location just within the outer wall, white to blue-grey smoke was emanating from a 20-m-diameter zone of small, bulbous chimneys 1–2 m high. Because of their distinctive bulbous shapes, we designated this region of chimneys the 'Kremlin' (Fig. 4B). Samples of the chimneys were recovered but we did not obtain a water sample or reliable temperature measurement. By analogy with white smokers at Pacific sites and at the Snakepit site, and from the zinc sulfide-rich nature of the recovered chimney, we infer a temperature of $<300°C$ for the exiting solutions.

The central part of the mound is marked mostly by chimney fragments and sulfide and anhydrite blocks. Anemones and gastropods decrease in abundance relative to the outer portion where shimmering water was observed, although crabs remain abundant. Numerous small cracks and fissures have black smoke emanating from them (Fig. 4C); surrounding each are generally swarms of a new genus of shrimp (Williams & Rona 1986, Van Dover *et al.* 1988). Presumably, the basis for the ecosystem is similar to other hydrothermal discharge sites wherein bacteria utilize H_2S and other chemical species. Van Dover *et al.* (1988) hypothesized that the shrimp feed on a rapidly replenished bacterial food source on the surface of active chimneys.

The center of the mound consists of an edifice about 30–40 m in diameter topped by large chimney-like structures at least 10 m high. The slopes near the base of these chimneys are heavily and deeply fissured with anhydrite blocks interspersed with massive sulfides (Fig. 4D). The anhydrite has an ornate and corroded texture and is clearly undergoing dissolution. Black smoke emanates from the deep fis-

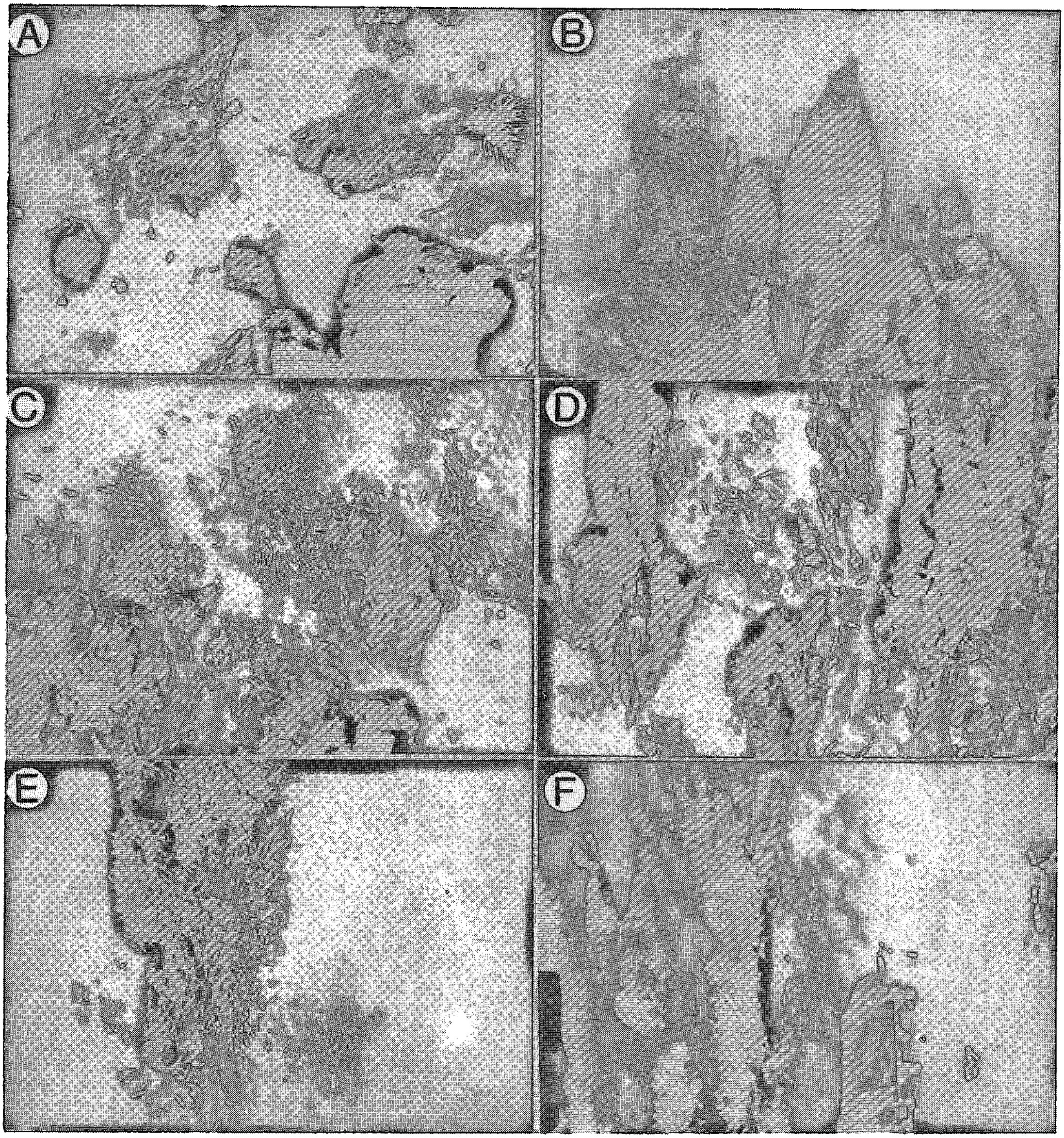

FIG. 4. (A): outer part of inner mound of TAG hydrothermal area showing massive-sulfide talus in area of shimmering water seepage. Anemones, gastropods and worm tubes are present. (B): Kremlin region of TAG hydrothermal mound showing white smokers with onion-like morphologies and crenulate exteriors. (C): central part of TAG hydrothermal mound showing black smoke emanating from fissures in basal mound; fissures are surrounded or filled by shrimp. (D): lower part of central black-smoker complex of TAG hydrothermal mound showing large crystalline anhydrite blocks interspersed with massive sulfides. (E): shrimp-encrusted black smoker from central chimney complex of TAG hydrothermal mound. (F): outpouring of black smoke from fissures at base of central chimney complex; smoke forms a dense cloud hiding the chimneys.

sures and cracks. The most intense discharge occurs at the base of the chimney structures, and as a result the entire system is enshrouded in a thick, dense cloud of smoke. All surfaces where hot water emanates are covered with thousands of shrimp (Figs. 4E, F). Although we were able to sample some of the active chimneys, we were unable to obtain good hydrothermal water samples or temperature measurements because of the smoke cloud and shrimp. The maximum temperature measured was

TABLE 1. COMPOSITION OF REPRESENTATIVE FE SULFIDES, TAG HYDROTHERMAL AREA

% wt	1-10	1-43(5)	1-14(2)	1-12A	1-16
Fe	34.2	36.2	30.5	33.5	16.9
Cu	0.09	2.35	1.78	1.76	2.74
Zn	2.78	1.09	2.40	4.25	4.45
S	52.1	41.9	44.0	39.9	29.2
Si	0.45	1.96	1.00	3.66	2.02
Ca	0.02	0.10	3.20	0.10	19.4
Pb	0.10	0.10	0.08	0.11	0.05
Ag(ppm)	50	115	75	150	165
Sr "	<5	17	630	12	4550
Description:	Inner layer of chimney fragment	Inner, yellow layer of chimney	Grey layer, weathered chimney fragment	Brown interior, weathered chimney fragment	Grey, veined sulfide layer
Major Mineralogy:	Pyrite Marcasite Sphalerite	Pyrite Marcasite	Pyrite Aragonite	Pyrite Marcasite	Pyrite Aragonite
<0.01% wt.:	Ba, Ti, Co, Ni, Cr, Mn, Al, V. All analyses by X-ray fluorescence spectroscopy (Schroeder et al. 1980).				

305°C; end-member venting solutions were probably hotter. The hydrothermal water sample was 90% diluted with seawater during the collecting, but the end-member composition was estimated to be similar in major-element composition to solutions at the Snakepit site, and at some Pacific vents. Minor elements and boron isotope measurements, however, were distinctly different in the TAG solutions compared to other vents (Edmond *et al.* 1986). The maximum plume velocity at the base of the chimneys was visually estimated at 1–2 m per second; rates of discharge from the small cracks surrounding the central chimney mound were about an order of magnitude lower.

Mineralization and chemistry

Active chimneys. The chimneys that make up the central black-smoker complex are not as dense as most of the relict chimneys or chimney fragments that make up the basal talus. The outer 0.5 to 1 cm of a chimney wall is mainly fibrous-textured pyrite with minor marcasite; the wall is slightly oxidized to reddish black on the surface. The inner part of the chimney has a granular, crumbly texture, and is black to bronze in color with numerous intergrown white crystals of anhydrite. X-ray diffraction studies indicate that the inner part of the chimney consists mainly of chalcopyrite and anhydrite with minor pyrite and marcasite.

The active smoker chimneys in the Kremlin area are distinctly different in shape, size, texture and mineralogy (Fig. 4B). White to blue-grey smoke emanates from the top, or in a much more diffuse pattern from the sides of the ovoid top. Outer portions, particularly the tops, display ridge and crenulate structures, are whitish grey, and consist of mixtures of anhydrite and sphalerite (Fig. 5A). Inner parts (Fig. 5B) are composed of a bluish black sphalerite with traces of chalcopyrite, pyrite and anhydrite. The inner portions of these chimneys display a complex discharge network with many radiating branches that are lined with brassy chalcopyrite and traces of pyrite and sphalerite.

Talus and relict chimneys. The active chimneys sit atop a basal mound made up of inactive chimneys (some still intact, but the majority fallen and in pieces), large blocks of massive sulfide mostly showing variable degrees of alteration and oxidation, and, locally, other precipitates. The major mineral groups observed are based primarily on the 1985 *Researcher* dredge (Rona *et al.* 1986a) but were confirmed by the ALVIN recoveries.

The predominant phase in the TAG mound samples is pyrite. Some representative Fe-sulfide analyses are given in Table 1. These samples, and those in subsequent Tables, represent bulk samples and only the major mineralogy as determined by XRD is indicated. Other phases are often present, particularly in the older, weathered samples; thus the analyses may not be truly representative of the normative mineralogy or stoichiometry of the phases listed. A variety of reference ore samples were used to standardize the bulk X-ray fluorescence analyses; however, precision and accuracy are estimated at only ±10%. The samples vary from relatively crystalline, chimney fragments or specific layers in complex chimneys (*e.g.*, 1-43) to older weathered or veined fragments (Fig. 5C). All samples except one contain at least 1% each of Cu and Zn; Pb contents are less than 0.1 wt. %; Ag ranges from 50 to 165 ppm. Increased concentrations of Si and Ca characterize the more oxidized samples. The veined samples (*e.g.*, 1-8 and 1-16) contain abundant aragonite as a late-stage precipitate (Fig. 5D).

Chalcopyrite is the next most abundant phase in the TAG samples. It occurs mainly as inner-vent linings in the lower temperature Zn-rich samples, and as thick spongy layers in older relict chimney fragments. Analyzed samples (Table 2) vary from dense well-crystallized layers in chimney fragments (*e.g.*, 1-44, Fig. 5E; 1-46) to complex interlayers in relict chimneys (1-43, Fig. 5F) and weathered portions of talus (1-7 and 1-26). Pb concentrations are less than 0.05%; Ag values vary from 5 to 285 ppm. The weathered samples are commonly altered to atacamite ($Cu_2Cl[OH]_3$); one sample has a relatively high

TABLE 2. COMPOSITION OF REPRESENTATIVE CU-FE SULFIDES, TAG HYDROTHERMAL AREA

% wt	1-43(4)	1-46(1)	1-7B(2)	1-26A(1)	1-44
Fe	19.4	23.0	24.7	19.0	28.5
Cu	42.6	39.0	39.8	32.5	25.0
Zn	6.25	0.64	0.04	1.50	0.53
S	27.7	22.6	16.5	26.4	35.8
Si	0.32	0.35	0.27	9.00	1.22
Ca	0.04	0.09	0.04	0.02	0.01
Pb	0.04	0.02	<0.01	0.02	<0.01
Ag(ppm)	265	155	285	50	<5
Description:	Chimney interior, blue-black sulfide layer	Chimney interior, yellow layer	Oxidized outer chimney layer	Chimney interior, scoriaceous sulfide layer	Layered, chimney fragment
Major Mineralogy:	Chalcopyrite Digenite Sphalerite	Chalcopyrite	Atacamite Goethite Chalcopyrite	Chalcopyrite	Pyrite Chalcopyrite
<0.01% wt.:	Ba, Ti, Co, Ni, Cr, Mn, Al, V.				

TABLE 3. COMPOSITION OF REPRESENTATIVE ZN-FE SULFIDES, TAG HYDROTHERMAL AREA

% wt	1-8A(1)	1-13A(1)	1-45(2)	1-11(3)
Fe	24.4	16.3	30.5	18.8
Cu	0.17	0.13	0.16	0.02
Zn	21.6	17.25	10.9	6.28
S	40.4	19.9	47.8	29.10
Si	3.25	10.16	0.10	9.68
Ca	0.35	9.0	0.02	10.35
Pb	0.13	0.04	0.06	0.04
Ag(ppm)	185	225	85	10
Sr "	81	2520	<5	3100
Description:	Chimney interior, yellow-grey layer	Weathered chimney fragment, grey interior with white veins	Chimney interior, yellow-grey layer	Veined, talus block, greyish-white layer
Major Mineralogy:	Sphalerite Pyrite	Sphalerite Pyrite Aragonite	Pyrite Sphalerite	Pyrite Sphalerite Aragonite
<0.01% wt:	Ba, Ti, Co, Ni, Cr, Mn, Al, V.			

silica content of 9.0% (1-26A). Fe contents range from 19 to 29%. Pyrite, bornite and digenite are common.

X-ray diffraction data indicate that sphalerite (commonly intergrown with pyrite) is an important phase in the TAG samples (Table 3). Replacement of sphalerite by pyrite or chalcopyrite (or both) is common of the complex chimneys (*e.g.*, 1-45). Preliminary thin-section studies also indicate the presence of wurtzite in a few of the samples (*e.g.*, 1-8). Sphalerite and wurtzite are difficult to distinguish by XRD, especially in bulk samples where grinding can convert the wurtzite to sphalerite. In this paper we have not distinguished between these polymorphs. Similarly, the XRD data do not allow us to differentiate between chalcopyrite or isocubanite. Aragonite and amorphous silica are common in the older more weathered samples (*e.g.*, 1-11, 1-13). Within the Zn-rich layers of chimney fragments, Cu and Pb concentrations are less than 0.2%; Ag varies from 10 to 225 ppm.

Soft, earthy fragments of Fe oxide display hues variable from yellowish orange to dark red. Thin, dark crystalline layers are common in the friable, amorphous, Fe-rich groundmass. Many of these samples are reminiscent of the low-temperature precipitates found higher up the slope of the TAG field (Thompson *et al.* 1985). It is unknown whether these samples represent weathered fragments of the massive sulfides in the central mound or low-temperature primary phases. Table 4 gives analyses of representative samples ranging from layered earthy deposits (1-3), some with dark crystalline layers (1-18), to outer oxidized layers of massive-sulfide fragments (1-43; 1-25A, Fig. 5C). Unlike the low-temperature precipitates of the upslope TAG field, which contain almost no Cu, Zn or S, all the dredged samples have at least 0.1% of these elements but contain less than 100 ppm Mn (abundant in the low-temperature precipitates). Further, the close similarity between the outer oxidized zone of a massive sulfide fragment and the other discrete oxide samples (Table 4) suggests that the latter were derived by oxidation of sulfide material. The various hues of the Fe oxides reflect variable silica concentrations. The dark crystalline layers are goethite that probably formed through recrystallization of the Fe oxides.

Other minerals include sulfates and carbonates (Table 5). These phases, like the sulfides, generally contain less than 0.01% Ba, Mn, Ni, Co, V, Al, Cr and Ti. Anhydrite is found on the outer part of active chimneys, near their tops (the bases of these chimneys are anhydrite-free); anhydrite also occurs as interspersed crystals in the interiors of the black smokers, and as large crystalline slabs (*e.g.*, 1-4) on the steep slopes leading to the base of the central black-smoker complex (Fig. 4D). A trace of gypsum was detected in the X-ray study of the anhydrite sam-

TABLE 4. COMPOSITION OF REPRESENTATIVE FE OXIDES, TAG HYDROTHERMAL AREA

% wt	Layered Oxide Fragments 1-3(1)	1-3(2)	1-3(3)	Veined Oxide Fragment 1-18	Outer oxidized layer of sulfide 1-43(2)
Fe	31.0	45.2	51.6	59.2	36.3
Cu	0.16	0.21	0.57	0.10	0.12
Zn	0.62	0.49	0.96	0.32	1.87
S	0.31	0.29	0.22	0.18	0.28
Si	13.56	7.38	4.28	1.59	10.92
Ca	0.19	0.18	0.19	0.29	0.23
Pb	0.02	0.09	0.09	0.05	0.04
Al	0.04	0.06	0.06	0.03	0.06
Na	5.77	2.86	1.38	0.08	3.26
K	0.28	0.19	0.14	0.07	0.37
Mg	1.00	0.50	0.37	0.28	0.94
P	0.03	0.16	0.27	0.36	0.10
V(ppm)	80	290	375	300	60
Ag "	15	<5	<5	<5	<5
Sr "	58	45	38	65	73
Description:	Pale yellow layer	Orange-red layer	Dark red layer	Dark red with dark crystalline veins	Orange-red, grading into sphalerite rich sulfide phase
Major Mineralogy:	Amorphous	Amorphous	Amorphous plus Goethite	Goethite	Amorphous
<0.01% wt:	Ti, Co, Ni, Mn, Cr				

TABLE 5. COMPOSITION OF OTHER PHASES, TAG HYDROTHERMAL AREA

% wt	Sulfate 1-4A	Chlorides 1-7C(2)	1-7B(1)	Carbonates 1-8(2)	1-43(1)	Silica 1-36	1-39(2)
Fe	0.7	1.8	24.4	4.9	3.8	1.0	3.6
Cu	0.77	68.3	43.8	0.1	0.29	0.08	0.10
Zn	0.01	0.06	0.10	6.65	0.47	1.55	0.06
S	22.2	0.04	1.17	2.40	0.20	1.90	0.58
Si	0.09	0.06	0.43	7.58	0.97	41.0	38.4
Ca	27.3	0.01	0.06	23.7	47.20	0.02	0.07
Pb	<0.01	<0.01	<0.01	0.01	0.02	<0.01	0.03
Sr	0.18	<0.001	0.001	0.43	0.08	0.002	0.005
Ba	0.001	<0.001	<0.001	0.07	0.001	<0.001	0.002
Ag(ppm)	30	<5	<5	95	40	160	150
Description:	Blue-grey crystalline fragment	Dark green crystals	Green crystals on Fe-oxide	White botryoidal lining in chimney cavity, coating sphalerite-rich sulfide	Carbonate ooze on outer-part of sulfide chimney	Hard, grey pebble	Scoriaceous, reddish white fragment
Major Mineralogy:	Anhydrite	Atacamite Paratacamite	Atacamite Paratacamite Goethite	Aragonite	Calcite	Amorphous	Quartz Hematite
<0.01% wt:	Ti, Al, Co, Ni, Cr, V, Mn (except 1-43(1) with 0.15% Mn)						

ples, but it is not certain whether this mineral is a primary phase.

Aragonite is a common carbonate phase, particularly in the relict chimneys. It occurs as discrete crystalline veins which line old vents, or is interspersed in the inner matrix, particularly of sphalerite-rich areas. Aragonite also occurs as botryoidal linings of orifices of old chimneys, where it appears to have been the last phase to precipitate (*e.g.*, 1-8). Aragonite was not observed in active chimneys. The pelagic calcareous ooze that covers the surrounding regions of the TAG area is generally absent from the inner mound. However, a few of the relict chimneys and older talus near the mound margin do have local pockets of calcite-rich carbonate ooze on their weathered surface (*e.g.*, 1-43).

Other phases also include atacamite, which commonly forms as discrete crystals in the outer weathered parts of chalcopyrite-rich samples, and associated amorphous Fe oxide or geothite (*e.g.*, 1-7). Silica-rich samples are sparse, and only two small samples were recovered during the dredging (1-36, 1-39).

SNAKEPIT HYDROTHERMAL FIELD

Geological setting

The Snakepit hydrothermal area is located in the rift valley of the Mid-Atlantic Ridge (MAR) at 23°22.08′N, 44°57.00′W. Unlike the TAG high-temperature field, which is on older crust on the eastern side of the rift valley at the junction of the floor and east wall, the Snakepit area is on the top of a large volcanic ridge in the axial portion of the rift valley (Fig. 6). The ridge is 400–600 m high and about 40 km in length; it trends 040°, slightly oblique to the regional strike of the MAR axis. Photographic surveys and direct observations from ALVIN confirm that the ridge is a large constructional volcanic feature made up of a series of discrete pillow flows, each of 20–40 m aggregate thickness. A slight covering of pelagic ooze indicates that volcanic activity ceased some time ago. Tectonic fissuring of the pile, begun only recently, is not widespread and has had little effect on the overall morphology. The regional tectonic setting and geology have been discussed by Karson *et al.* (1987).

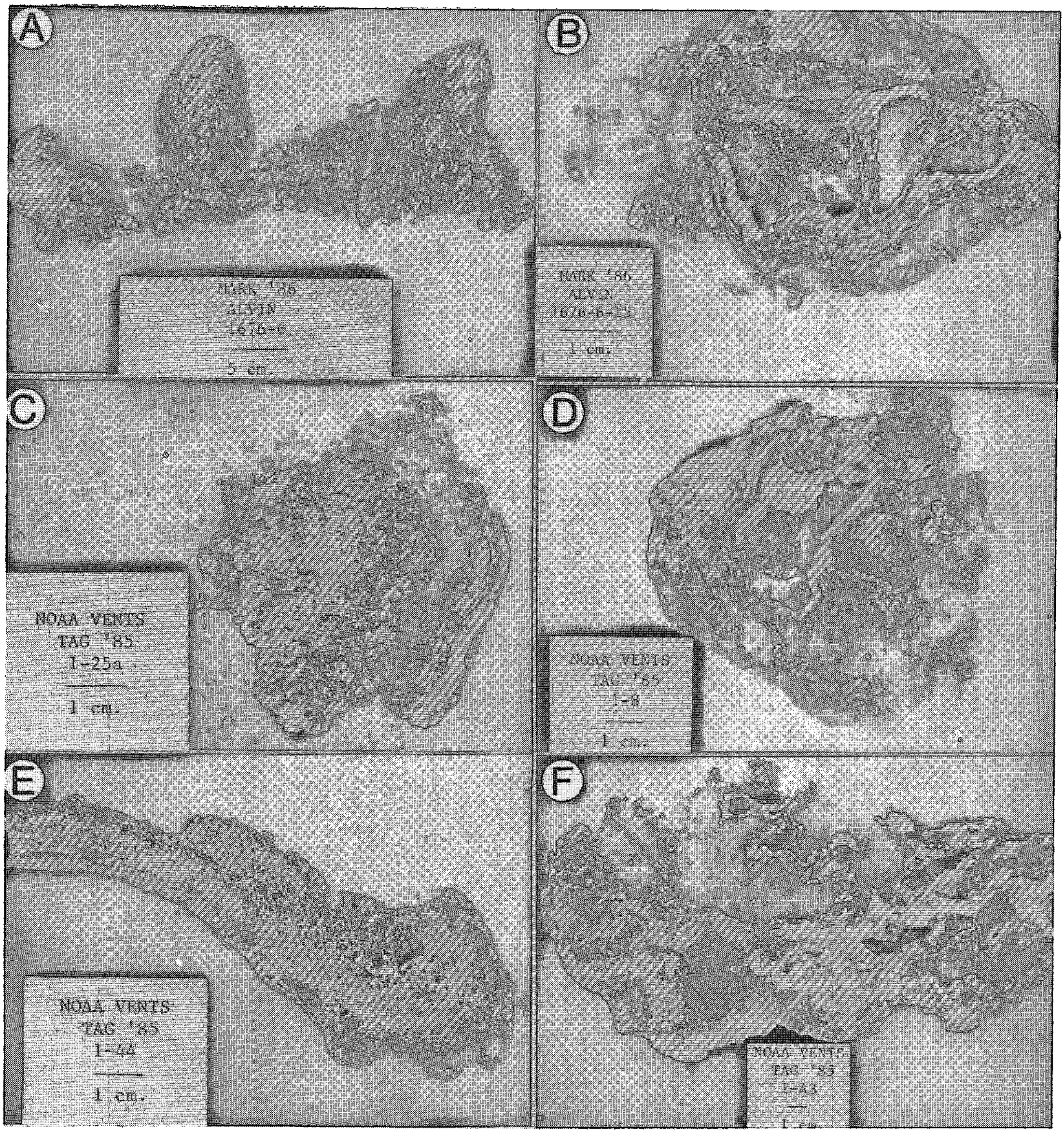

FIG. 5. (A): active white-smoker chimney from the Kremlin region of TAG hydrothermal mound. Sample ALVIN 1676-6. Sample was originally oriented 90° to right. (B): cross-section through chimney of Figure 5A. Interior sphalerite-rich vents are lined with chalcopyrite. Crenulations of outer wall are mixture of pyrite and anhydrite. (C): sulfide fragment showing gradation from pyrite-rich interior to oxidized (amorphous Fe oxide) outer layers. Sample 1-25. (D): cross-section of massive-sulfide chimney fragment showing internal vents lined by botryoidal aragonite. Sample 1-8. (E): layered chimney fragment rich in crystallized chalcopyrite. Sample 1-44. (F): complex chimney showing separate pyrite-rich, chalcopyrite-rich, and sphalerite-rich internal regions. Sample 1-43.

The hydrothermal field is located near the top of the ridge (Fig. 6), on a small terrace at depths of 3440–3480 m (based on ALVIN recorded depths; ODP depths for the field were given as 3500–3540 m). The field is at least 200 m by 100–200 m, but the maximum boundaries have not been determined.

Structure of the hydrothermal field

Only one ALVIN dive was made at the Snakepit

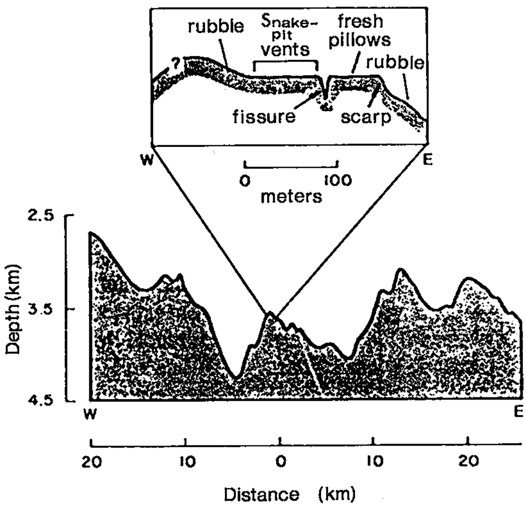

FIG. 6. Bathymetric profile across Mid-Atlantic Ridge rift valley through the Snakepit area (after Scientific Party 1986b).

field. As far as we can ascertain, the hydrothermal field consists of 3 elongate parallel ridges about 20–30 m high and at least 100 m long. They follow the trend of the volcanic ridge and are parallel to a fissure, 2–3 m wide, that bounds the eastern side of the field. The flat areas between the ridges are covered by mottled hydrothermal sediment which, based on the Leg 106 drilling, is up to several meters thick but decreases in thickness with distance from the ridges (Scientific Party 1986b). The western side of the field is defined by a sharp contact between hydrothermal sediment and a ridge of pillow-basalt talus. A cross-section of the three ridges in the field is shown in Figure 7.

Each ridge is composed of sulfide talus and chimney debris. The tops of the ridges have active or relict chimney structures aligned along the ridge strike. The easternmost ridge has 10 to 12 large, complex, branched chimneys, about 10 m high, that are mostly active black smokers. Samples of discharging solution recovered from two separate localities on this ridge had temperatures of 350°C and 335°C. The two hydrothermal solutions had, respectively, pH 4.02 and 3.66, and alkalinity −64 and −243 μ Equ. Calculated end-member concentrations per liter were 18.80 and 18.30 mM $Si(OH)_4$, 5.8 and 6.0 mM H_2S, 0.558 and 0.559 mM Cl, 483 and 506 μM Mn, and 2136 and 1848 μM Fe (Edmond *et al.* 1986). Flow rates of black smoke discharging from a broken-off chimney were visually estimated at 1.5–2 m per second. The central ridge is apparently inactive: only relict chimney structures on sulfide talus were found. The westernmost ridge has only small, 1–2 m chimneys which emanate white smoke; considerable water seepage takes place through fissures and cracks in the talus pile. Solution discharging from one white smoker on this ridge had a temperature of only 226°C. Thus, like the TAG hydrothermal field, there is a marked temperature difference across the whole field.

With a few exceptions, biological activity and vent biota are similar to those observed at TAG (Grassle *et al.* 1986). Eels are much more abundant in the Snakepit region (hence the name). Sedimented regions between the ridges are densely populated by small polychaete worms (Fig. 8A). Anemones, crabs (galatheid and brachyuran), gastropods, and eels are common near the bases of active chimneys (Fig. 8B). The active black smokers are covered in shrimp of the same new genus described at TAG (Williams & Rona 1986; Fig. 8C). On the lower temperature western ridge, anemones are predominant and white (bacterial?) mat coatings are common on the ridge flank; a few mussels were also recovered. Shrimp were rarely seen on the white smokers.

Mineralization

The active black smokers on the easternmost ridge are large, complex, multibranched structures (Fig. 8D). The upper parts are commonly mushroom- or ovoid-shaped with grey, crenulated outer coats made up principally of pyrite and anhydrite. The lower parts are brownish red with no anhydrite. Chimney fragments have an outer, fibrous-textured wall of pyrite and marcasite, with a thin (<1 mm) red oxidized surface. The inner matrix consists of crumbly, dark yellow, granular pyrrhotite with chalcopyrite and pyrite. The vent walls are made up of bornite, pyrrhotite, pyrite, and chalcopyrite. Thus the black smokers of the Snakepit region contain more pyrrhotite than those of the TAG field. The easternmost-ridge talus samples are predominantly pyrite and chalcopyrite, with some minor pyrrhotite, marcasite and bornite. The samples are similar to the massive sulfides recovered by the ODP at Hole 649G (Honnorez *et al.* 1986).

All samples from the central inactive ridge are slightly oxidized and weathered, but to a lesser degree than in the TAG region. The outer rims (1–2 mm thick) are composed of amorphous Fe oxides that overlie pyrite and minor marcasite. Sample interiors are predominantly pyrite; relict vent linings consist of chalcopyrite with some pyrite and traces of sphalerite (Fig. 8E). Pyrrhotite and bornite, common in the active chimneys, are absent from the relict chimney samples.

Massive-sulfide talus on the western side of the hydrothermal field consists of pyrite–marcasite interiors, with native sulfur, jarosite, amorphous Fe oxides, goethite and hematite on the outer surface (Fig. 8F). Chimney fragments from the westernmost

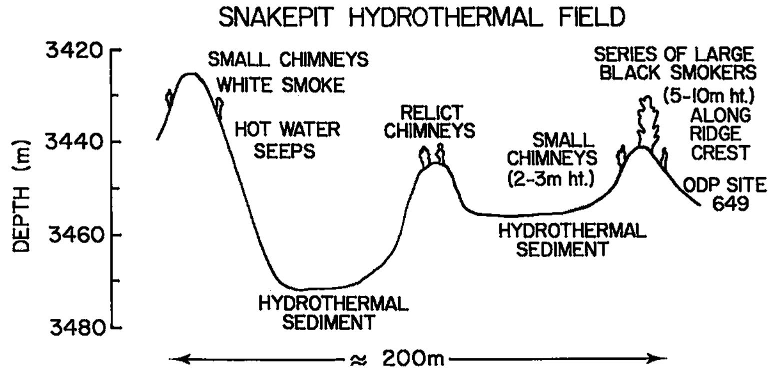

FIG. 7. Cross-section of Snakepit hydrothermal area showing the three main ridges and chimney structures. ODP leg 106 drilled on the side of the easternmost high-temperature ridge.

ridge consist of an outer pyrite and anhydrite layer, with the inner parts consisting of crumbly, granular sphalerite, pyrite, and traces of marcasite. This mineral suite represents a lower temperature assemblage than that of the black smokers; apart from the absence of chalcopyrite, the suite is similar to the assemblage of the Kremlin region at TAG.

The hydrothermal sediment between the ridges is composed of dark, granular sulfides, principally pyrrhotite, chalcopyrite, marcasite and pyrite, and minor sphalerite. Similar mineralogy was found in hydrothermal sediment recovered by the ODP from Hole 649B, about 17 m from an active vent (Honnorez *et al.* 1986).

DISCUSSION

Hydrothermal mineralization at the two Mid-Atlantic Ridge fields is similar to that of active vent fields on the East Pacific Rise (Haymon & Kastner 1981, Oudin 1981, Styrt *et al.* 1981, Zierenberg *et al.* 1984), and on the Juan de Fuca Ridge (Koski *et al.* 1984, Tivey & Delaney 1986). Paragenetic sequences are similar: pyrite, chalcopyrite, pyrrhotite, marcasite and bornite are the common phases in high-temperature (300–350°C) active chimneys. In apparently lower temperature samples from the Snakepit field (226°C site) and the Kremlin region at TAG, sphalerite dominates. Many chimneys show complex mineralization: Fe, Cu and Zn-rich minerals and replacement textures attest to variations in the fO_2, fS_2, pH, and temperature of hydrothermal solutions during chimney growth.

Anhydrite, common within and on the walls of active chimneys, also forms large crystalline deposits near the fissured base of the central complex of black smokers in the TAG area. The lower parts of active chimneys, relict chimneys, and basal talus lack anhydrite, presumably due to dissolution.

The late-stage aragonite found lining vent orifices in the TAG area is absent, or a minor phase, in the East Pacific Rise and Juan de Fuca vent fields. At Pacific vents, amorphous silica is the dominant late-stage precipitate; it apparently forms from sluggishly circulating hydrothermal solutions or seawater–hydrothermal mixtures (Tivey & Delaney 1986). It is not certain why aragonite precipitates at the TAG Atlantic site. The recharge areas for this hydrothermal field are covered with carbonate ooze (at least 1 m thick). In addition, Mid-Atlantic Ridge basalts commonly have abundant CO_2 in their vesicles. Aragonite also is common as a late-stage precipitate in serpentinized peridotites in transform faults and in the walls of the median valley of the Mid-Atlantic Ridge (Thompson 1972). Barite was not observed at the Atlantic sites, although it is common in many of the East Pacific Rise and Juan de Fuca deposits.

Diagenetic products are more abundant in the TAG hydrothermal field than in the Snakepit region, suggesting that some of the sulfide deposits in the former area are older or supergene processes are more active. Diagenetic products include sulfur, jarosite, amorphous Fe oxides or oxyhydroxides, goethite, hematite, gypsum and atacamite. High concentrations of gold (up to 16 ppm Au) are found in secondary Cu-rich sulfides with native Cu, and result from supergene alteration of primary Cu–Fe sulfides in the TAG area (Hannington *et al.* 1988).

The Atlantic sites are amongst the largest hydrothermal deposits at spreading axes. The TAG inner mound is estimated to contain at least 5×10^6 tonnes of sulfides. If the outer mound contains appreciable sulfide deposits, the estimated tonnage would be much greater. The Snakepit deposit contains over a million tonnes; this value may increase considerably when the maximum dimensions of the deposit are determined. Other hydrothermal deposits of similar size include those on the Endeavor and

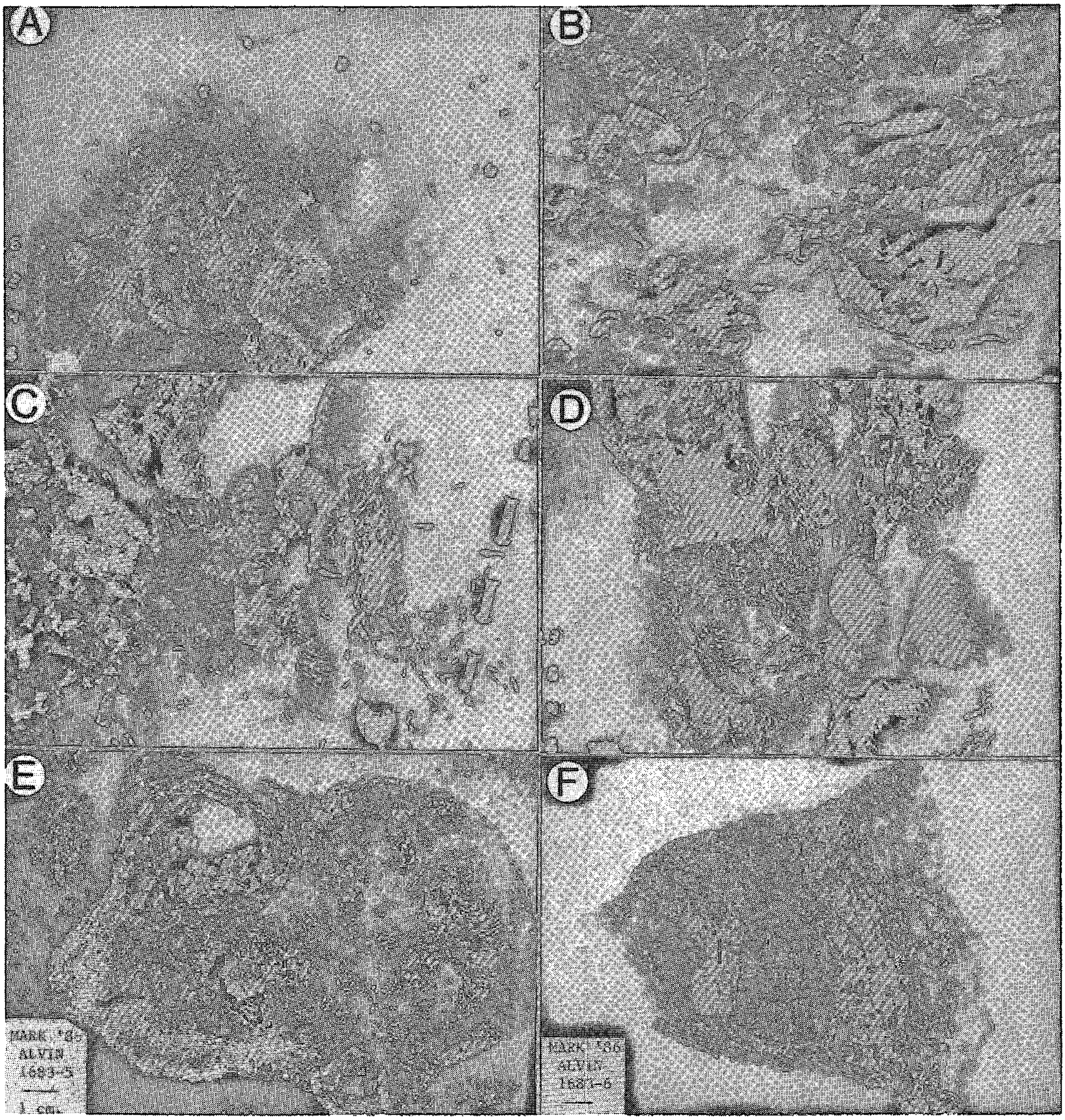

FIG. 8. (A): hydrothermal sediment in region between massive-sulfide ridges in Snakepit hydrothermal area. Upper parts of tubules of small polychaete worms protrude through the sediment giving it a mottled appearance. (B): chimney debris, crabs and eels near base of active black smoker at Snakepit hydrothermal area. (C): active black smoker in Snakepit hydrothermal area. The chimney was broken off by ALVIN; black-smoke discharge rates of 1.5–2 m per sec were visually estimated. Meter stick is divided into 10-cm intervals. (D): upper part of black-smoker chimney in Snakepit region showing complex morphology and branching. Shrimp cover regions of the chimney where hot water emanates. (E): cross-section through massive-sulfide chimney fragment rich in pyrite. Chalcopyrite lines the relict vent structures in upper left of the sample. Sample ALVIN 1683-5 is from the central inactive ridge of the Snakepit field. (F): cross-section through a slightly weathered massive-sulfide block. The dense crystalline interior is pyrite-rich. Sample ALVIN 1683-6 is from the southern boundary of the Snakepit field between the central and western mounds.

Middle Valley segments of the Juan de Fuca Ridge (respectively, Tunnicliffe *et al.* 1986, Davis *et al.* 1987) and the Galapagos Rift (Malahoff 1982).

For the Snakepit deposit, hydrothermal convection presumably is driven by heat from the inferred magma chamber responsible for the present-day neovolcanic ridge in the median valley axis on which the hydrothermal field sits. Based on the silica contents of discharging solutions, the sub-crustal depth of the magma chamber has been suggested to be about 2 km (Edmond *et al.* 1986).

At the TAG site, which is located off-axis on older crust, the volcanic heat source may underlie the neovolcanic zone of the present ridge axis to the west (Fig. 2). The large salient of the eastern wall, which is made up of a series of lystric fault steps, may affect the underlying plumbing system channelling hydrothermal solutions along faults to their present venting site (Thompson *et al.* 1985). Some of the sulfides at the TAG site appear to be much older than those at Snakepit, and thus the hydrothermal activity at TAG may have spanned a considerable period of time. It will be interesting to drill the central mound at TAG to investigate internal structures and chemical zoning in such an older deposit.

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