OCEAN DRILLING PROGRAM

LEG 158 SCIENTIFIC PROSPECTUS

TAG: DRILLING AN ACTIVE HYDROTHERMAL SYSTEM ON A SEDIMENT-FREE SLOW-SPREADING RIDGE

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This Scientific Prospectus is based on pre-cruise JOIDES panel discussions. The operational plans within reflect JOIDES Planning Committee and thematic panel priorities. During the course of the cruise, actual site operations may indicate to the Co-Chief Scientists and the Operations Superintendent that it would be scientifically or operationally advantageous to amend the plan detailed in this prospectus. It should be understood that any proposed changes to the plan presented here are contingent upon approval of the Director of the Ocean Drilling Program in consultation with the Planning Committee and the Pollution Prevention and Safety Panel.

ABSTRACT

The overall scientific objectives of Leg 158 are to investigate the fluid flow, geochemical fluxes and associated alteration and mineralization, microbiological processes, and the subsurface nature of an active hydrothermal system on a slow-spreading sediment-free ridge. The active mound within the Trans-Atlantic Geotraverse (TAG) hydrothermal field at 26°N latitude on the Mid-Atlantic Ridge (MAR) is a large, mature deposit of varying mineralogy with emanating fluids displaying a wide range of temperatures and two distinct, but related, chemistries. The large size and age argue for a reasonably large and altered crustal root zone suitable for good drill penetration and recovery with conventional drill bits. Studies of this feature will give insight into fluid flow, structure, and "zone-refining" in active hydrothermal systems, and clarify how large, massive sulfide deposits, similar in size to those mined on land today, are formed on the modern seafloor.

A transect of three holes (plus one alternate, but lower priority hole) is proposed to investigate the nature of fluids, deposits, and altered crust in the near-surface part of the hydrothermal system. At least one hole will penetrate into the stockwork zone underlying the surface deposit. Although it is anticipated that these objectives can be achieved with the currently available technology in this hostile environment, the nearby inactive *Alvin* and *Mir* zones are proposed as back-up drilling sites.

Drilling at TAG will directly address the processes occurring during hydrothermal circulation. Understanding these processes, and the implications for energy transfer, geochemical fluxes, and the formation of ore deposits, are of fundamental importance to our knowledge of crustal accretion.

INTRODUCTION

Ridge-crest hydrothermal systems play a fundamental role in transferring a large fraction of the heat from the Earth's interior to its surface. Through thermally induced flow of seawater in fractures and fissures in the permeable portion of the crust and upper mantle, much of the mantle-derived thermal energy is dissipated into the lithosphere, hydrosphere, and biosphere along the global mid-ocean ridges. This circulation gives rise to a complex series of physical, chemical, and biological interactions that affect the composition of both seawater and the oceanic crust, and lead to the creation of many types of seafloor ore deposits, and to the existence of unusual biological communities.

Although a considerable amount of surficial sampling has been completed on a number of ridge hydrothermal systems, only drilling an active system on a mid-ocean ridge can clarify 1) the permeability, pressure, and temperature structure within the upflow zone beneath an active hydrothermal system, 2) the nature of the chemical reactions between water and rock in both the upflow zone and the underlying reaction zone, 3) the mechanisms of sulfide precipitation and subsequent modification below the seafloor, 4) the structural control on the plumbing system within both the upflow and reaction zones, and 5) the evolution of major black smoker systems.

To date, attempts to answer such questions have relied upon the chemistry of waters from active vents, samples collected from surface outcrops, experimental and theoretical analyses of basalt/seawater systems, and observations of fossil systems in ophiolites. However, interpretation of these data requires that assumptions be made about the conditions which are present in the sub-seafloor part of an active system, sometimes about which rocks are in equilibrium with which fluids, and sometimes about the nature of the physical structure of an active system. Drilling a major, sediment-free black smoker system will provide the necessary evidence to discriminate between the models that have been put forward.

Hydrothermal systems on unsedimented ridge axes dominate global hydrothermal activity, and hence are an important contributor to global mass and energy fluxes. Drilling a mature, large volcanic-hosted deposit such as the TAG mound will clarify the processes of recrystallization and "zone-refining," the distribution of minerals, the hydrothermal circulation and plumbing, the nature of the root zone, and the processes occurring during ore formation and deposition.

The TAG area has many features that make it the prime target for drilling an active volcanic-hosted hydrothermal deposit. Firstly, it is located in a slow-spreading environment, a major characteristic of the global rift system. The hydrothermal field is situated in the central part of a ridge segment bounded by small non-transform offsets or axial discontinuities, typical of many such segments on slow-spreading ridges. The active mound represents a good drill target, as the combination of size and maturity argues for a large surface areal target, with a well-developed root zone. The presently active mound is approximately 200 m in diameter and 50 m in height. It is composed of massive sulfides probably well in excess of 5 x 10^6 tons, being equivalent in size to some of the deposits in the Cyprus, Oman, and other ophiolites (e.g., Fouquet et al., 1988; Constantinou and Govett, 1973). No basalt has been observed outcropping either on the surface of the mound or on the 20-m-high talus slopes that bound the mound to the west, north, and east. Furthermore, the deposit is mature. Geochronological studies indicate the mound to be of the order of 40-50,000 years old, and to have undergone intermittent activity, possibly every 5-6,000 years over the last 20,000 years. Duration of an active cycle still has to be resolved, but the present-day activity is of, at least, 50 years' duration based on radiometric dating (Lalou et al., 1990, 1993). The TAG mound exhibits a wide range of polymetallic sulfides with predominantly Fe-Cu-Zn varieties (e.g., Thompson et al., 1988; Tivey et al., 1994). Two series of *Alvin* dives in 1990 and 1993 indicate that the active mound is zoned, both in terms of type of activity and mineralogy, thereby providing the opportunity to study relationships of mineral alteration. There is also evidence of supergene reactions resulting in enrichment in metals such as gold (Hannington et al., 1988; Herzig et al., 1991). Exiting hydrothermal solutions range from high (363°C) through medium to low temperatures at the boundaries of the active mound. These fluids are somewhat different from EPR fluids and have been hypothesized as showing interaction with weathered crust (Campbell et al., 1988). This may be a feature of slow-spreading ridges which can be tested by drilling. In addition, a unique biological community is associated with the active mound and is based on the activity of chemosynthetic bacteria.

Two former sites of high-temperature venting within the TAG hydrothermal field are proposed as backup drilling targets. The *Alvin* hydrothermal zone includes four mound structures that appear to be of dimensions similar to those of the active mound. The *Mir* hydrothermal zone includes a variety of weathered sulfide debris, metalliferous sediments, and large standing and toppled chimneys showing a range in sample type and mineralogy similar to those seen at TAG. Both zones show evidence of extensive recrystallization, which makes them excellent targets for drilling.

STUDY AREA

Regional Geologic and Tectonic Setting

The ridge segment along which the TAG hydrothermal field is located (Fig. 1) is about 40 km long, trends north-northeasterly, and is bounded by non-transform discontinuities to the south and north at 25°55'N and 26°17'N, respectively (Sempéré et al., 1990; Purdy et al., 1990; Smith and Cann, 1992). Seafloor spreading has been asymmetric over the last 10 m.y.; half spreading rates are 13 mm/yr to the east and 11 mm/yr to the west (McGregor et al., 1977).

The seafloor morphology of the TAG ridge segment is well defined by SeaBeam bathymetric surveys of the Mid-Atlantic Ridge (MAR) in this area (Rona et al., 1986a; Sempéré et al., 1990; Purdy et al., 1990). The segment has a morphology typical of the 15-18 ridge segments lying between the Kane and Atlantis fracture zones (Sempéré et al., 1990; Smith and Cann, 1992). In plan view, the floor of the median valley has an hourglass shape, narrowing and shallowing toward the center of the segment at about 26°10'N. In cross section, the median valley has an asymmetrical shape, the eastern wall being higher, steeper, and less rough than the western wall (Karson and Rona, 1990; Zonenshain et al., 1989). Using SeaBeam and high-resolution deep-towed side-scan sonar data, Smith and Cann (1990, 1993) documented the style of crustal accretion from 24° to 30°N. Along this section of the MAR, the floor of the median valley is built of superposed, small-scale seamounts, with the axial volcanic ridges being formed by overlapping individual volcanic edifices. However, the data are insufficient to resolve the critical geological features needed to establish the distribution of hydrothermal activity and hence its relation to volcanism and tectonism. A more detailed survey using a 120-kHz sidescan system with co-registered bathymetry will be conducted in a 200 km^2 area in the central part of the segment in June-July 1994 by M. Kleinrock and S. Humphris.

Additional data on the geological structure of this segment, primarily concentrated in the vicinity of the hydrothermal field, has been collected from deep-towed camera profiles, piston-coring, water temperature profiling, dredging, and submersible dives (Eberhart et al., 1988; Karson and Rona, 1990; Rona, 1980; Rona et al., 1984, 1986b; Thompson et al., 1988). The western wall of the median valley consists of fault-controlled basaltic scarps and sediment-covered terraces (Eberhart et al., 1988; Zonenshain et al., 1989). Much of the eastern wall is covered with debris-slide deposits partly buried by calcareous ooze; fault scarps range in height from 10 to 20 m but are locally up to 150 m (Karson and Rona, 1990). Outcrops of pillow lavas were also observed on the eastern wall (Zonenshain et al., 1989). Karson and Rona (1990) suggested that an east-west-trending scarp on the eastern wall represents a structural accommodation zone resulting from differential extension and rotation of crustal blocks to the north and south.

Important constraints on the along-axis changes in stress state and seismic velocity structure are provided by a microearthquake survey and seismic refraction experiment carried out on this ridge segment (Kong, 1990; Kong et al., 1992). These studies suggest that most of the microearthquake activity occurs at the axial high at the center of the segment; earthquakes are also distributed along-axis and in the eastern rift valley walls. No seismic events were detected in the immediate vicinity of the TAG hydrothermal field. The maximum depth of seismicity shoals toward the center of the segment, where a low-velocity zone is observed there. The distribution of seismicity, the low-velocity zone, and the recent hydrothermal activity suggest recent crustal injection near the axial high.

Magnetic field data from regional surface ship studies indicate that a broad NNE-SSW-trending area of low residual magnetic intensity about 12 km long and 8 km wide is associated with the TAG hydrothermal field (McGregor and Rona, 1975; Tivey et al., 1989). This has been interpreted to result from hydrothermal alteration of the basaltic crust (Wooldridge et al., 1992).

Sea-surface gravity data indicate that the TAG segment contains a "bull's eye" anomaly (Lin et al., 1990), suggesting that either the crust is anomalously thick or that there is anomalously warm mantle upwelling buoyantly beneath this ridge segment. There may be a relation between the presence of the bull's eye and the presence of the TAG hydrothermal system on this segment.

Geologic and Tectonic Setting of the TAG Hydrothermal Field

Tectonic Setting

Hydrothermal activity in the TAG field is located along a section of the eastern wall of the median valley (Fig. 2). At this location, the east wall forms a broad salient toward the spreading axis and 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).

The TAG hydrothermal field consists of presently active low- and high-temperature zones, as well as a number of relict deposits. The zone of low-temperature activity occurs 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 x 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. 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 that is at least 100,000 years old, on the basis of the present seafloor-spreading rate. Sediment thickness around the active mound is variable depending on the local morphology. *Alvin* studies show that local basins may have >1 m of ooze, steep slopes are bare, and less steep areas have 30-60 cm of sediment.

It is clear that both volcanism and tectonism play an important role in the spatial and temporal distribution of hydrothermal activity in this area, and three hypotheses have been presented that address their interactions. On the basis primarily of observations in the low-temperature field, Scott et al. (1974), Temple et al. (1979), and Thompson et al. (1985) hypothesized that hydrothermal activity was associated with ridge axis-parallel faults. They suggested that these listric faults were the pathways for fluids and that the heat source was probably at the zero-age neovolcanic axis. More recently, on the basis of observations of east-west faults high on the eastern wall in the vicinity of the low-temperature field, Karson and Rona (1990) suggested that these transfer faults may intersect the ridge-parallel faults, concentrating hydrothermal activity at the intersections. However, due to lack of data, no direct evidence exists for, or against, the extension of east-west faults in the low-temperature field to the presently active TAG mound.

SeaBeam bathymetry suggests that the active TAG mound is located on the edge of a dome-shaped high. The domes are suggested to be discrete volcanic centers that may act as heat sources for localized hydrothermal activity. Several observations support this hypothesis. Zonenshain et al. (1989) noted very recent volcanics, as well as older basalt outcrops, located on the volcanic dome to the southeast of the presently active hydrothermal mound, suggesting intermittent volcanic activity with a very recent eruption. Rocks have been observed and collected from at least two older eruptions at this site, although not of the very recent age observed by the Russians.

The two large relict hydrothermal zones are also believed to be associated with volcanic domes. The *Alvin* and *Mir* hydrothermal zones both lie to the northeast of the active mound and have been described by Rona et al. (1993a). The *Alvin* hydrothermal zone is about 2 km long and is located on the lower east wall at a depth of 3400-3600 m. It is composed of discontinuous sulfide deposits between four mound-like features up to 200 m in diameter. Three of these were identified from sidescan imagery, while the fourth, located at the southern end of the *Alvin* zone, was mapped and sampled during the 1993 *Alvin* dive series (Rona et al. 1993b). This mound appears to have overall dimensions similar to the active mound, and is composed of hard aggregates of recrystallized massive pyrite with minor chalcopyrite and sphalerite, the surfaces of which are coated with iron oxyhydroxides (Rona et al., 1993a).

The *Mir* hydrothermal zone is located to the south of the *Alvin* zone and occurs on the lower east wall about 2 km east-northeast of the active mound between 3430 and 3575 m. The *Mir* zone contains inactive hydrothermal deposits in various stages of weathering situated on normal fault blocks. Apart from weathered sulfide debris and metalliferous sediments, some areas contain numerous standing and toppled sulfide chimneys, some up to 25 m in length and up to 3 m in diameter (Rona et al., 1993b). A range of sample types has been collected from this area, including chimney debris similar in mineralogy to both the black smokers and white smokers on the active mound, massive sulfide blocks, iron oxide gossan, and manganese oxide crusts. Almost all samples show signs of extensive hydrothermal reworking and replacement (Rona et al., 1993b). Radiometric ages for samples from this area range from 140 to 9.4×10^3 yr, and suggest multiple stages of venting (Lalou et al., 1993).

Geologic Setting

The black smokers are located on top of an elliptical mound surrounded by an apron dominated by carbonate ooze and metalliferous sediment that is about 500 m in diameter. The mound is about 200 m in diameter and rises about 50 m from a depth of 3670 m (Fig. 3). It is composed of massive sulfides, with distinct sample types being distributed from the interior to the exterior of the mound (Rona et al., 1993b; Tivey et al., 1994). A cluster of chalcopyrite-anhydrite-rich black smoker chimneys emitting fluids up to 363°C is located northwest of the center of the mound. This chimney cluster sits on the top of a 10-20-m-high, 40-50-m diameter cone, the surface of which is covered by a 3-6-cm-thick plate-like layer of massive chalcopyrite and marcasite, with interspersed blocks of corroded massive anhydrite with variable amounts of chalcopyrite and pyrite. The remainder of the top of the mound (at a depth of 3660-3665 m) is relatively flat with an irregular surface. Samples of amorphous Fe-oxyhydroxide and silica have been recovered from the west, south, and east rims of the mound, and bulbous mixed Zn, Fe, and Cu-Fe sulfides with cavities filled by amorphous silica were recovered from the northern rim and central portions of the mound (Tivey et al., 1994). A complex of white smokers venting fluids from 260° to 300°C is located in the southeast quadrant of the mound approximately 70 m away from the black smoker complex; these "Kremlin"-like spires are small (1-2 m) and are composed dominantly of low-Fe sphalerite with minor amounts of chalcopyrite, pyrite, and amorphous silica. Fluids from the white smokers have a very low pH, contain no magnesium, and contain lesser amounts of iron than the black smoker fluids (Edmond et al., 1990). They are thought to be derived from the black smoker fluids by conductive cooling plus small amounts of mixing with seawater and precipitation of sulfides within the mound.

Mass-wasting of the edges of the inner mound results in steep outer slopes to the west, north, and east. Two sample types are exposed: pyrite-rich blocks with trace amounts of late-stage amorphous silica, quartz, and goethite and with outer oxidized layers that include atacamite, and deep-red to orange-brown blocks of amorphous Fe-oxide, goethite, hematite, and silica (as both amorphous silica and quartz). Analogues for these sample types are not found in other known seafloor vent sites, but are present in massive sulfide deposits of Cyprus (Herzig et al., 1991; Tivey et al., 1992).

The distribution of sample types, their mineralogy, and the distinct compositions exhibited at the black smoker and Kremlin locations, suggest a flow pattern within the mound similar to that shown in Figure 3 (Tivey et al., 1994). Fluid exiting the black smoker complex is extremely focused. Fluid emanating from the Kremlin area has undergone conductive cooling and mixing with seawater as evidenced both by the presence of amorphous silica and the chemistry of the fluids (Edmond et al., 1990). As the fluid cools and circulates within the mound, pyrite is precipitated, and blocks of this material are exposed during mass-wasting.

Preliminary geochronological studies of samples recovered by dredging suggest that the mound is on the order of 40-50,000 years old (Lalou et al., 1990). More detailed studies of *Alvin* samples suggest that activity has been intermittent over the past 20,000 years, with a periodicity of 5000-6000 years (Lalou et al., 1993). The presence of late-stage quartz in pyritic and iron oxide blocks exposed on the steep slopes of the inner mound are consistent with such episodicity. Present activity commenced about 50 years ago after a hiatus of about 5000 years (Lalou et al., 1993).

A detailed, near-bottom magnetic survey conducted from *Alvin* in 1990 over the TAG mound showed a magnetization low located directly beneath the mound with a possible dip to the south. This has been interpreted as the alteration pipe of the upflow zone beneath the mound (Tivey et al., 1993).

The thermal output from the TAG active mound has been estimated to be about 120×10^6 W using a transistor array and a grid survey at a height of about 20 m above the mound (Rona and Speer, 1989). During the 1993 *Alvin* dive series, about 50 measurements of conductive heat flow were made using 0.6 or 1.0 m probes, which with a few exceptions could be pushed into most locations on and off the mound (Fig. 4; Becker et al., 1993). These stations document coherent variations in surface heat flow, which are probably related to subsurface convective patterns and suggest one alternative on-mound drill site described below.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

The overall scientific objectives of drilling at TAG are to investigate fluid flow, geochemical fluxes and associated alteration and mineralization, microbiological processes, and the subsurface nature of an active hydrothermal system on a slow-spreading, sediment-free mid-ocean ridge.

Understanding the processes operating within a hydrothermal system, and their interrelations, requires answering a number of questions that can be addressed only by drilling. Although studies of fossil hydrothermal deposits preserved in ophiolites have provided valuable insights into their subsurface geometry and composition, the hypothesis that these systems provide a useful analogue for mid-ocean-ridge hydrothermal processes still needs to be tested. In addition, a number of critical parameters cannot be determined from extinct systems; for example, variations in permeability and porosity of the host rocks, the composition of the circulating fluid, and the dynamics of the water/rock interface. In order to meet the scientific objectives of this leg, whole-round samples may be required for microbiological, petrologic, physical property, and structural geological studies.

Within the near-surface part of the hydrothermal system, Leg 158 will investigate:

1) the temporal and spatial variation in the mineralogy, chemistry, and physical properties of the hydrothermal precipitates;
2) the spatial and temporal variation in the composition of the circulating fluids and the effects of conductive cooling and mixing on the composition of these fluids and their relationships to mineralogical variations within the deposits;
3) the method of fluid circulation within the deposit and the spatial characteristics (focused or diffuse) of the flow;
4) the effects of fluid circulation within the mound, e.g., possible remobilization and concentration of metals in distinct zones; and
5) the physical and chemical effects of epigene and supergene alteration reactions on the deposits, and on the fluxes of elements between the deposits and seawater.

In the stockwork zone below the surface deposits, studies aim to clarify:

1) the variation in mineralogical and chemical composition of deposits in this zone;
2) the degree to which fluids have reacted with the adjacent host rocks, the nature of the rock-seawater interactions, and subsequent effects upon the magnetics;
3) the physical and hydrogeological properties of the upper crust in this zone;
4) the chemical composition of the hydrothermal fluid in this zone;
5) the mechanism focusing the fluid flow within this part of the hydrothermal cell; and
6) the amount of heat exchanged in the system and the associated energy fluxes.

DRILLING STRATEGY

Complete characterization of the subsurface nature of an active hydrothermal system requires a drilling program of more than one leg, since determining the location and nature of the reaction zone would require drilling a deep hole to the base of the sheeted dikes (i.e., to a depth of about 1.5-2 km). However, an initial transect of holes 200-500 m deep will enable us to characterize the upper part of the hydrothermal system.

Proposed Holes

Leg 158 will complete a transect of three (possibly four) holes across the TAG mound (Fig. 5, hole information tables). The first proposed hole will be TAG-2, which will be a reentry hole that will be drilled to at least 500 m on this leg. TAG-2 is located off-center in the "Kremlin" area, where warm (250°C) waters are discharging from small (1-2 m) high chimneys composed dominantly of Zn-Fe sulfides. Heat flow is quite high, on the order of 3-9 W/m^2. The surface of the mound at this location is relatively flat, less than 5 m of relief over an area of roughly 50 x 50 m, and is suitable for setting a guide base. It is also located over the magnetic low and thus has a high probability of intersecting the stockwork zone. Fluids emanating from this region are believed to have undergone conductive cooling and mixing with seawater within the mound; consequently, this hole will provide information on the mineralogical and chemical variability within the mound related to these different fluids and physical controls. If drilling conditions are favorable, then the highest priority will be to continue drilling this hole.

Proposed secondary holes TAG-1 and TAG-3 will be shallow (at least 200 m), non-reentry holes and will be designed to penetrate through the hydrothermal deposits and into the top of the altered basaltic crust. The decision as to whether these holes will be drilled will depend on the results of drilling TAG-2. Proposed hole TAG-1 is located near the center of the mound on the shoulder of the central cone in an area that has a slope of less than 10° and is roughly 20-30 m wide. This is the area closest to the black smokers that, from submersible observations, is the most suitable for drilling near the region of high-temperature activity. Heat-flow values are extremely variable within 20 m of the black smokers. This hole is designed to penetrate through the entire section of hydrothermal deposits and into the uppermost portion of the highly altered crust. In this region, large black smoker chimneys occur, from which hot (363°C) fluids are emanating. The chemistry of the fluids suggests that they have not mixed with seawater in the subsurface region of the mound, and it is likely that the ascending flow is well-focused beneath the chimneys (Fig. 3). This hole provides the best opportunity to recover a stratigraphic section of the hydrothermal mound and to determine the nature of the fluid flow beneath the most active part of the mound.

Proposed hole TAG-3 is located at the south-southeastern edge of the mound, out of which cool (<100°C) waters are diffusing. In this area, heat flow is very high (5-10 W/m^2) on the sedimented terraces that form the slope down from the Kremlin area to the volcanic center south-southeast of the mound. Drilling this hole will have two objectives: first, investigation of the degree of sulfide oxidation, and the mobilization and reconcentration of trace elements; second, determination of differences in the plumbing system within the mound related to diffuse, rather than focused, flow.

There is a coherent belt of very low heat flow (<20 mW/m^2), 20-30 m west of the black smokers, on the sulfide rubble plateau that surrounds the central smoker peak. To investigate possible recharge within the mound, this area is suggested for proposed hole TAG-4. Time may not permit drilling this hole, as it is the fourth priority.

Alternate Sites

There is the possibility that drilling into this active system may prove difficult, e.g., it may not be well-consolidated, and/or the high temperatures may cause problems (although similar high-temperature fluids posed no problems on Leg 139). Consequently, alternate sites have been identified that will allow most of the objectives to be accomplished, except for those addressing fluid composition and flow. The southern mound in the *Alvin* hydrothermal zone will be the highest priority alternate site, and will be drilled as deep as possible. The second alternate site is within the *Mir* hydrothermal zone. The location of this site will be determined during a site survey cruise in June 1994.

OPERATIONS

Drilling

A reentry cone and up to three casing strings will be used to drill proposed hole TAG-2 to as great a depth as possible. After setting the hard-rock guide base, the hole will be rotary cored to about

20 m (3 cores) and 20 m of 16-in. casing will be deployed. The hole will then be rotary cored to 200 m, logged as described below, and cased to 200 m using 13-3/8-in. casing. If three casing strings are required, rotary coring will continue to about 400 m, the new section of hole will be logged, and the hole will be cased to 400 m using 10-3/4-in. casing. Subsequently, the hole will be rotary cored to 500 m or deeper. If only two casing strings are required, the hole will be rotary cored to 20 m, then cased using 16-in. casing. The hole will then be rotary cored to 200 m, logged, and cased using 13-3/8-in. casing. Finally, the hole will be rotary cored from 200 m to 500 m (or deeper), then logged. If sufficient time remains after either casing scenario, drilling operations will begin at either proposed hole TAG-1 or TAG-3. This will allow hole TAG-2 to equilibrate prior to end-of-leg temperature measurements and the installation of a borehole seal. The ship will return to TAG-2 at least two days prior to leaving the TAG area to measure borehole temperature, take fluid samples, and install an instrumented borehole seal (CORK, described below).

Whether or not proposed hole TAG-1 or TAG-3 will be drilled depends upon the results of drilling TAG-2 and the time available. If TAG-1 is drilled, it will be rotary cored to 200 m and logged. If TAG-3 is drilled, one hole will be piston-cored (APC/XCB) to refusal (20 m?) and then rotary cored to 200 m and logged.

Logging and Downhole Measurements

Logging and special downhole measurements will be very important to the objectives of Leg 158, especially as the core recovery may not be high. A full logging program will be run at each hole, and an extensive program of special downhole experiments will be run at the deep reentry hole at TAG-2. Tools planned for possible use in all holes include the full set of Schlumberger logs, several downhole temperature tools, the BRG high-temperature magnetometer, the CSMA high-temperature resistivity tool, the DMT high-temperature borehole televiewer, and, if an appropriate tool can be borrowed, a high-temperature borehole fluid sampler. In addition, several special hydrogeological experiments are planned for the reentry hole at TAG-2, including permeability measurements using a packer and/or flowmeter, and installation of a long-term instrumented borehole seal ("CORK") with pressure sensors, thermistor cable, and fluid-sampling capability.

The logging strategies and suites of tools run at each hole will be contingent on the downhole thermal conditions and such factors as whether or not the side-entry sub (SES) is required to cool the hole during logging. The thermal conditions will be evaluated at the end of each phase of coring to determine the best strategy for the subsequent logging phase. If the hole can be kept cool enough, either by active cooling using the SES or by the downhole flow of ocean bottom water that may be induced by drilling, then the logging suite will include four Schlumberger runs and the magnetometer. The four Schlumberger runs would include sonic/resistivity, density/porosity, geochemical log, and FMS. If the hole cannot be kept cool enough for the Schlumberger tools, then the logging suite will consist of the high-temperature suite: CSMA resistivity, BRG magnetometer, DMT televiewer, and (if a tool can be obtained) downhole fluid sampling. At TAG-2, the drilling/casing strategy will require that the logging and packer experiments be run in stages after each phase of coring, before that section of hole is cased. At the conclusion of operations in TAG-2, a temperature log and fluid sampling will be conducted when the borehole conditions have re-equilibrated from the drilling disturbance as much as possible, and then the CORK will be emplaced.

Safety

The sulfide deposit is volcanogenic-hosted, so hydrocarbons are not expected to pose a problem. The hot circulating solutions and their hydrogen sulfide concentrations have already been demonstrated not to pose a problem with drilling in these systems. TAG is significantly deeper than the drilling at Middle Valley on Leg 139, where no problems were encountered. However, precautions for early detection of high levels of hydrogen sulfide will be necessary.

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TABLE 1

TIME ESTIMATES

Hole	Time on Site (days)	Drilling (days)	Logging (days)	Transit (days)
Transit				
(Las Palmas to TAG)				5.7
TAG-2	38.5* (30.6)**	24.2* (21.8)**	14.3* (8.8)**	
CORK	1.8		1.8	
Transit				
(TAG to Dakar)				6.8
Total:	52.8* (44.9)**			
Additional Holes				
TAG-1	7.9	3.0	4.9	
TAG-3 (APC)	1.2	1.2		
TAG-3 (RCB)	7.7	5.6	2.1	
TAG-4	7.9	3.0	4.9	

* Time estimated on basis of three casing strings at TAG-2.
** Time estimated on basis of two casing strings at TAG-2.

Time estimates are based on penetration rates of 1-2 m/hr in sulfides (taken from rates achieved at Holes 856G and 856H) and a similar rate in highly altered basalts.

TAG-2 is the highest priority hole and will be extended to at least 500 mbsf. It will be drilled to as great a depth as possible prior to drilling either TAG-1 or TAG-3.

FIGURE CAPTIONS

Figure 1. SeaBeam bathymetry of the TAG segment. Contour interval is 50 m; + marks the location of the active hydrothermal mound (data from Purdy et al., 1990).

Figure 2. SeaBeam bathymetry of the eastern side of the median valley (50-m contours) showing the locations of the active mound (TAG) and relict hydrothermal zones (*Alvin* and *Mir*). The dashed line marks the region of low-temperature activity (SeaBeam data from Purdy et al., 1990; locations of each hydrothermal area from Rona et al., 1993b).

Figure 3. Schematic cross section of the active TAG hydrothermal mound derived from submersible observations showing the relative positions of the holes to be drilled during Leg 158. The fluid flow pattern within the mound is determined from the mineralogy of the deposits and the fluid chemistry. (Adapted from Tivey et al., 1994.)

Figure 4. Conductive heat flow measurements on the active TAG hydrothermal mound (data from Becker et al., 1993).

Figure 5. Plan view of the active TAG hydrothermal mound showing the Leg 158 drill holes in relation to the principal boundaries and tectonic features as derived from submersible observations and photography. The circles around each hole location denote the bounds of the areas that might be affected during drilling operations.

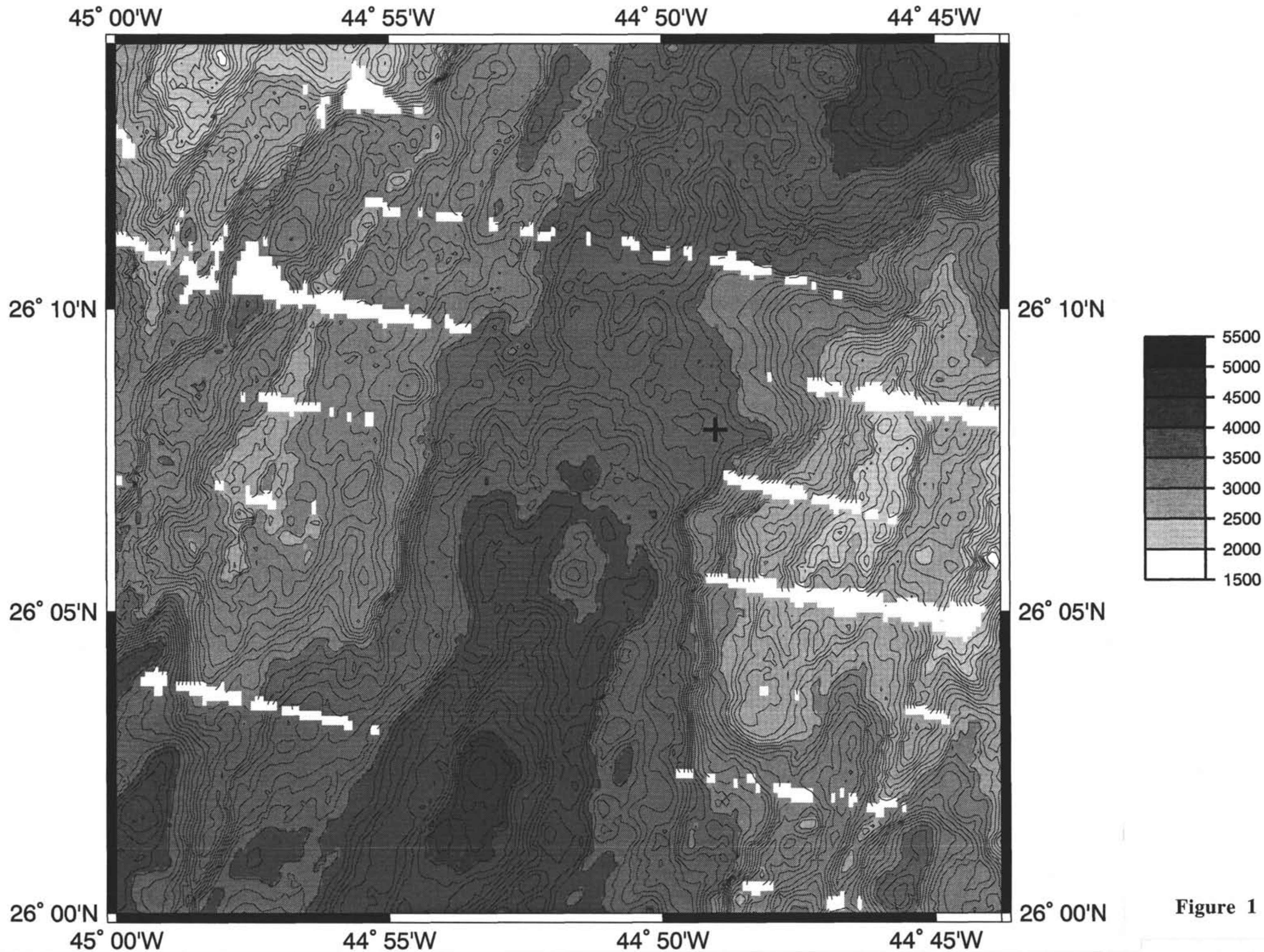

45° 00'W
44° 55'W
44° 50'W
44° 45'W
26° 10'N
26° 05'N
26° 00'N
5500
5000
4500
4000
3500
3000
2500
2000
1500
meters

Figure 1

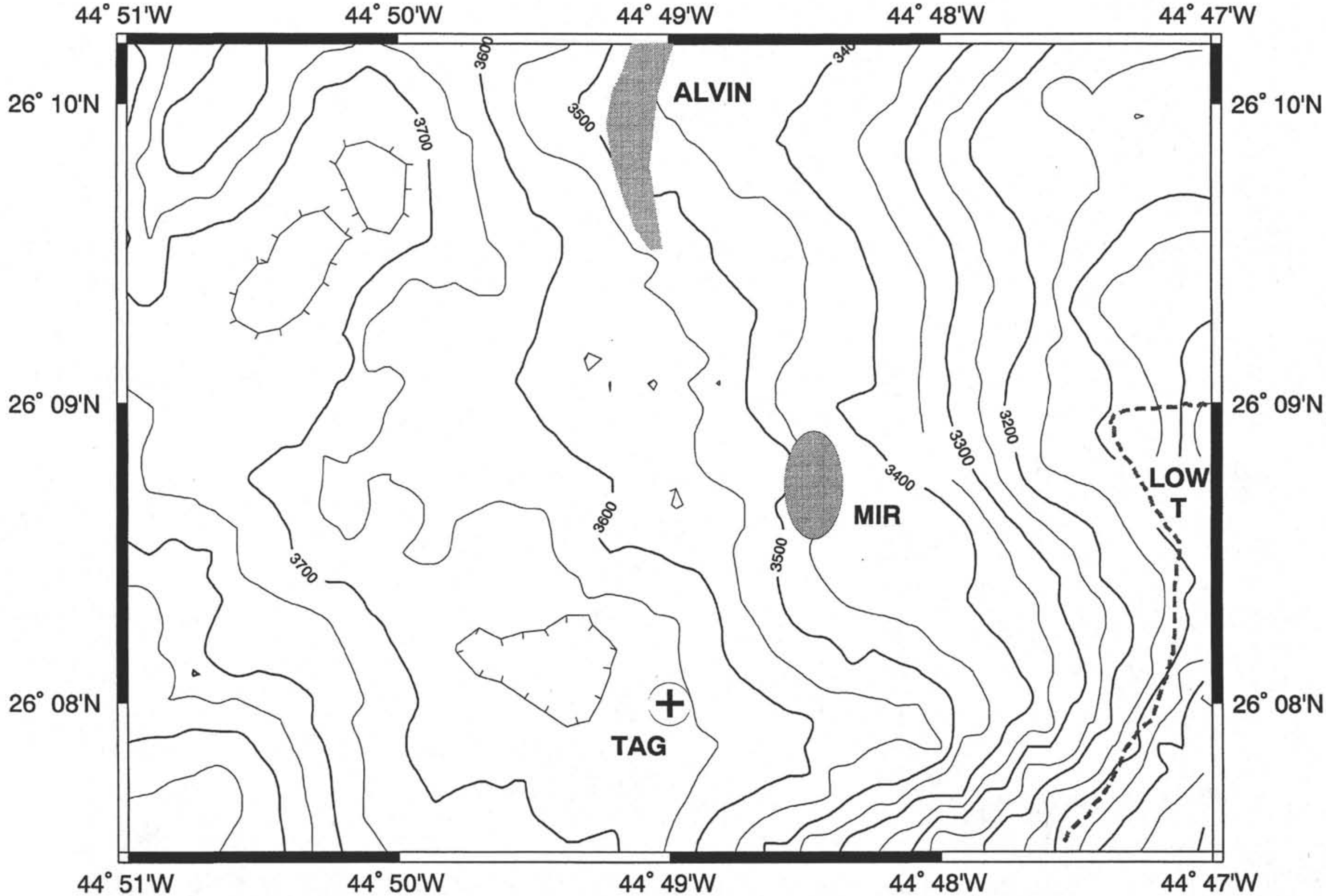
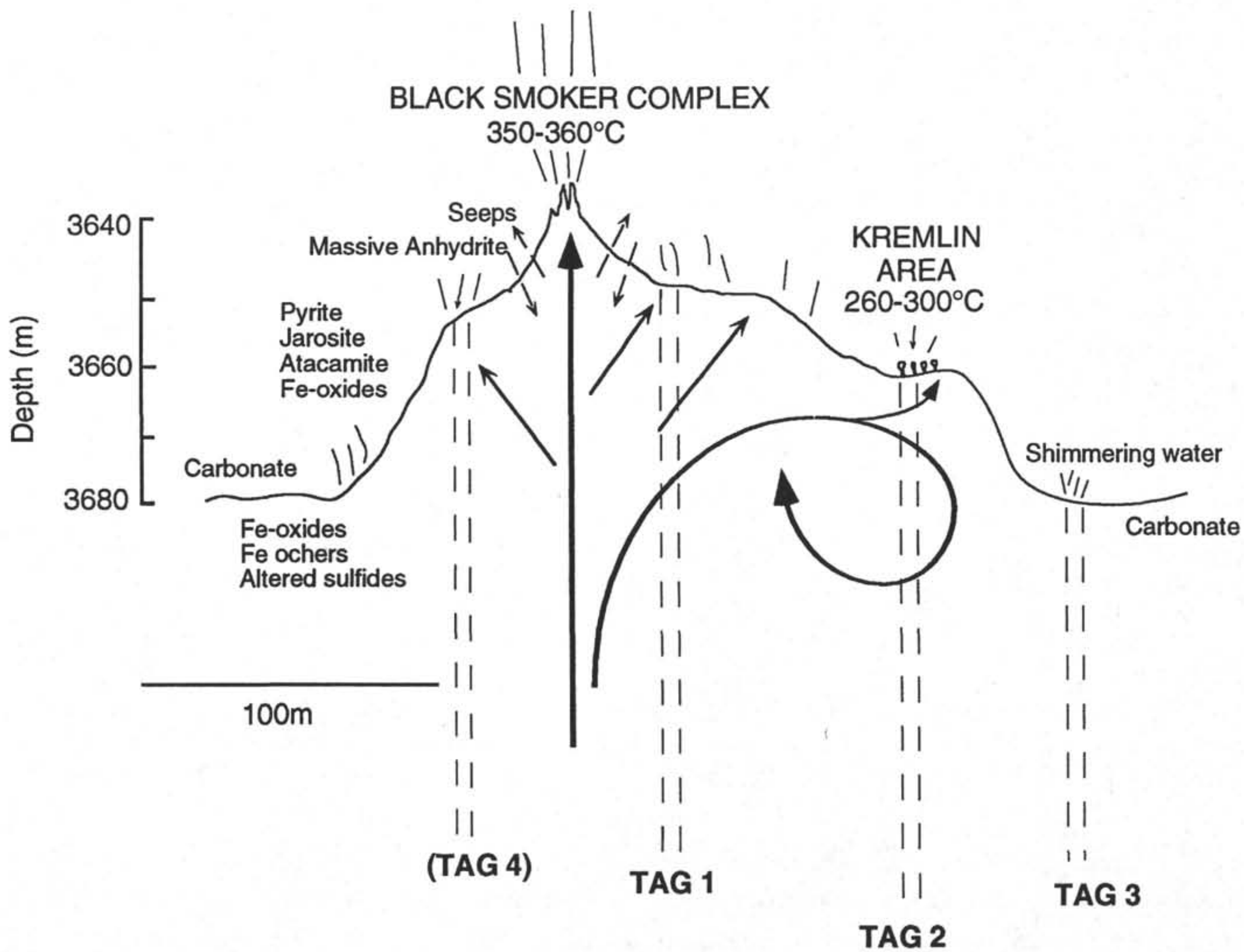

44° 51'W
44° 50'W
44° 49'W
44° 48'W
44° 47'W
26° 10'N
26° 09'N
26° 08'N
ALVIN
MIR
TAG
LOW T
3700
3600
3500
3400
3300
3200

Figure 2



BLACK SMOKER COMPLEX
350-360°C
Seeps
Massive Anhydrite
Pyrite
Jarosite
Atacamite
Fe-oxides
Carbonate
Fe-oxides
Fe ochers
Altered sulfides
KREMLIN
AREA
260-300°C
Shimmering water
Carbonate
3640
3660
3680
Depth (m)
100m
(TAG 4)
TAG 1
TAG 2
TAG 3

Figure 3

Alvin Heat Flow Values at TAG Mound

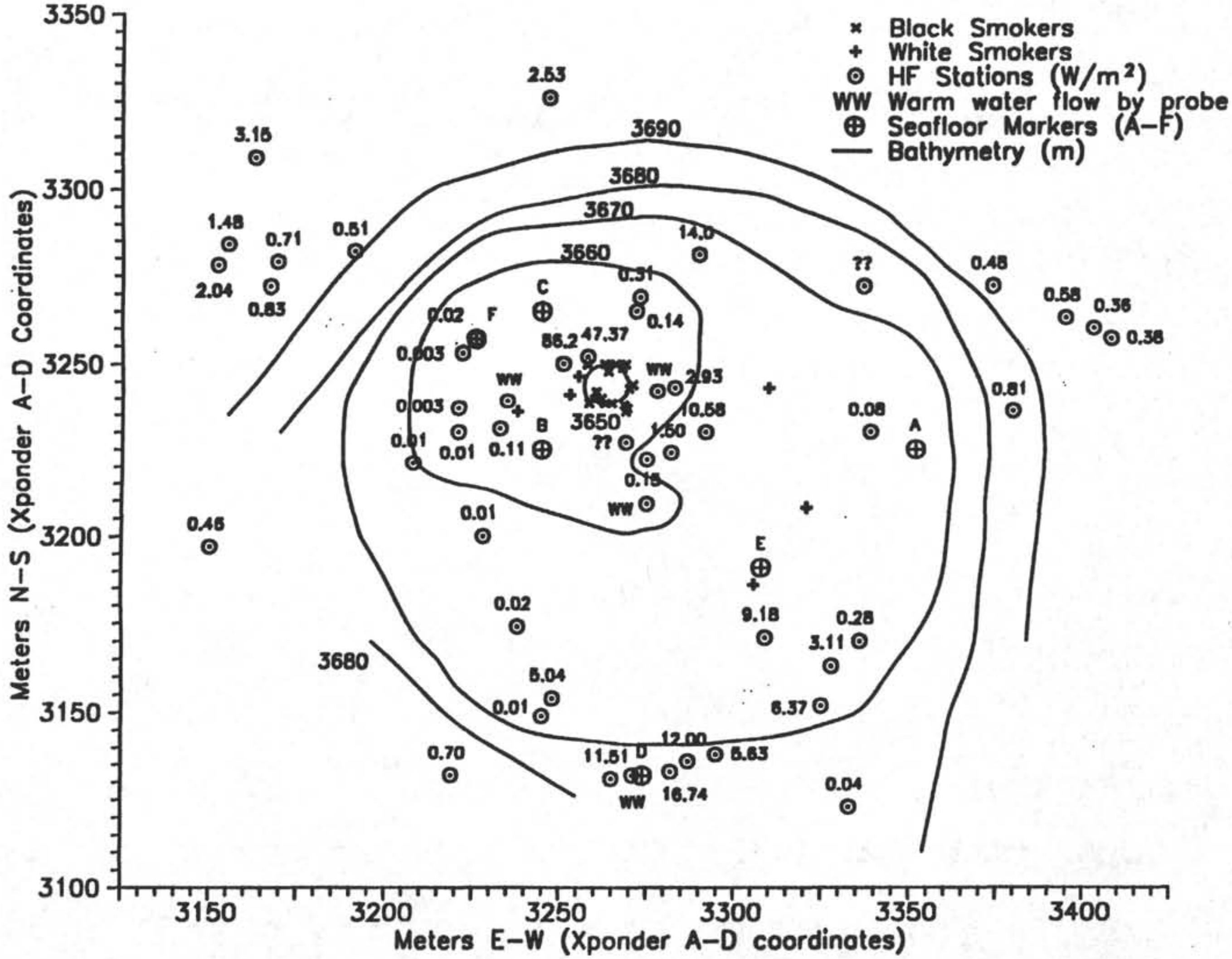


Figure 4

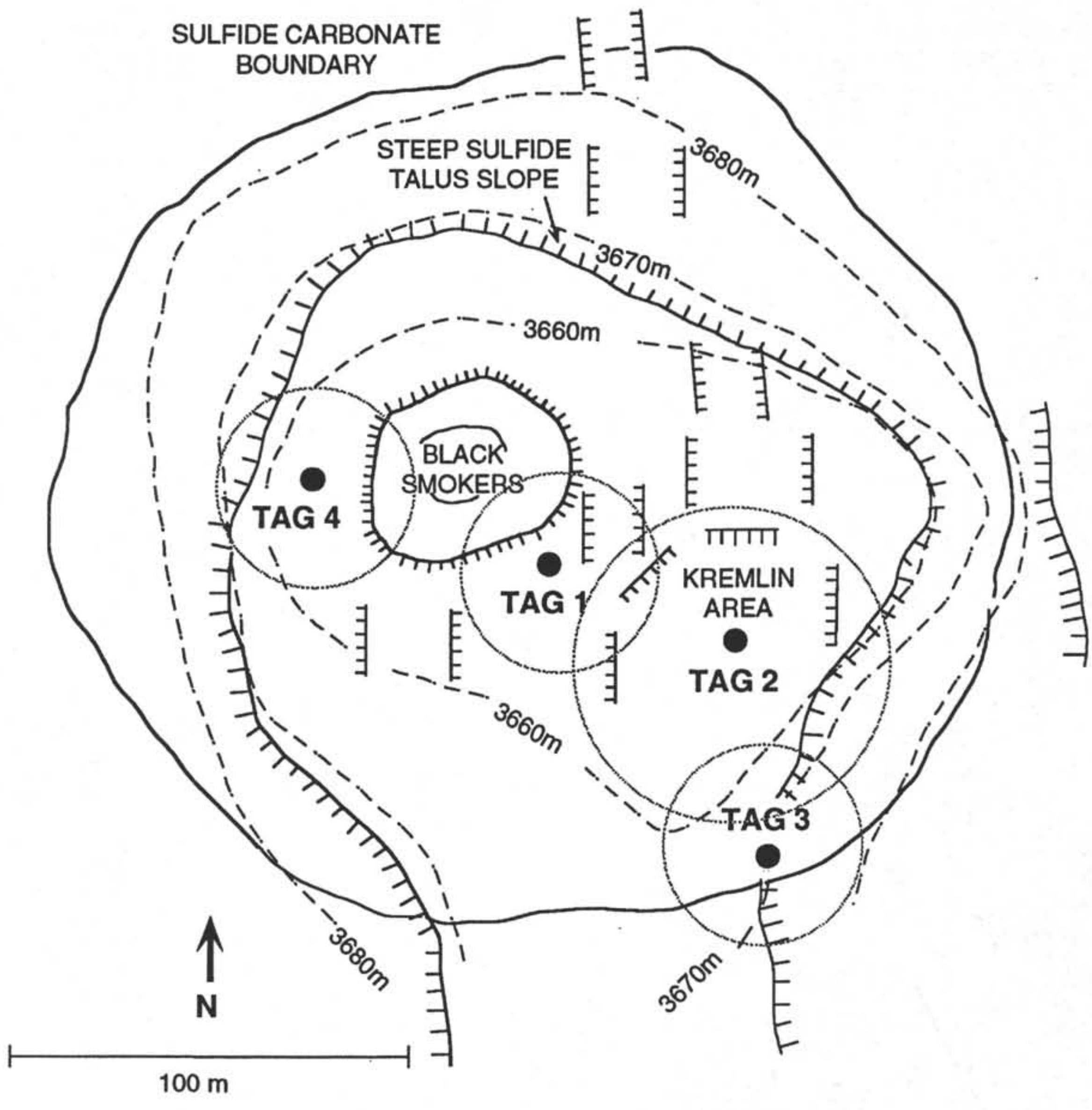

SULFIDE CARBONATE
BOUNDARY
STEEP SULFIDE
TALUS SLOPE
3680m
3670m
3660m
BLACK
SMOKERS
TAG 4
TAG 1
KREMLIN
AREA
TAG 2
3660m
TAG 3
3680m
3670m
N
100 m

Figure 5

HOLE: TAG-1

POSITION: 26°08'N, 44°49'W

PRIORITY: 2

WATER DEPTH: 3660 m

SULFIDE THICKNESS: 50-70 m

BASEMENT PENETRATION: ≥140 m

Objectives: Sample the entire section of the TAG hydrothermal mound near the black smokers where fluid flow is focused, and into the upper part of the highly altered crust.

Drilling Program: RCB coring.

Logging and Downhole Operations: Standard logs and specialty tools to measure sub-bottom formation temperatures, pore pressures and fluid fluxes, formation chemistry, sonic velocity porosity, resistivity, permeability, and stress.

Nature of Rock Anticipated: Massive sulfide deposits and hydrothermally altered and veined basalts.

HOLE: TAG-2

POSITION: 26°08'N, 44°49'W

PRIORITY: 1

WATER DEPTH: 3660 m

SULFIDE THICKNESS: 50-70 m

BASEMENT PENETRATION: ≥450 m

Objectives: Sample the section of the TAG hydrothermal mound in an area where fluids have undergone conductive cooling and mixing within the mound, and extend penetration into the underlying stockwork zone.

Drilling Program: RCB coring and reentry.

Logging and Downhole Operations: Standard logs and specialty tools to measure sub-bottom formation temperatures, pore pressures and fluid fluxes, formation chemistry, sonic velocity porosity, resistivity, permeability, and stress.

Nature of Rock Anticipated: Massive sulfide deposits, stockwork zone and hydrothermally altered basalts.

HOLE: TAG-3

POSITION: 26°08'N, 44°49'W

PRIORITY: 2

WATER DEPTH: 3680 m

SULFIDE THICKNESS: 20 m

BASEMENT PENETRATION: ≥180 m

Objectives: Drill through the older, weathered sulfides where there is diffuse flow and into the stockwork, the existence of which is suggested by the magnetization low.

Drilling Program: APC/XCB and RCB coring.

Logging and Downhole Operations: Standard logs and specialty tools to measure sub-bottom formation temperatures, pore pressures and fluid fluxes, formation chemistry, sonic velocity porosity, resistivity, permeability, and stress.

Nature of Rock Anticipated: Massive sulfide deposits, stockwork zone and hydrothermally altered basalts.

HOLE: TAG-4

POSITION: 26°08'N, 44°49'W

PRIORITY: 4

WATER DEPTH: 3660 m

SULFIDE THICKNESS: 50-70 m

BASEMENT PENETRATION: ≥140 m

Objectives: Sample the entire section of the TAG hydrothermal mound near the black smokers where fluid flow is focused, and into the upper part of the highly altered crust.

Drilling Program: RCB coring.

Logging and Downhole Operations: Standard low-temperature logs and specialty tools to measure sub-bottom formation temperatures, pore pressures and fluid fluxes, formation chemistry, sonic velocity porosity, resistivity, permeability, and stress.

Nature of Rock Anticipated: Massive sulfide deposits and hydrothermally altered and veined basalts.

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