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

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ABSTRACT

Leg 158 investigated 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 mid-ocean 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.

At Site 957, a northwest-southeast transect of holes in three major, distinct areas of the mound was drilled: the upper terrace east of the Black Smoker Complex (proposed TAG-1 area), the white smoker Kremlin area (proposed TAG-2 area), and the upper terrace west of the Black Smoker Complex (proposed TAG-4 area). In addition, holes were drilled on the south side of the lower terrace (proposed TAG-3 area) and on the northern edge of the upper terrace (proposed TAG-5 area) in an attempt to delineate lateral heterogeneity of the sulfide deposit, and the extent and nature of the underlying stockwork zone.

Breccias of various types dominate the stratigraphy of the entire mound, not only within the sulfide section but also extending into the upper part of the stockwork. Within the sulfide mound, these different types are distinguished primarily on the basis of the relative abundances of pyrite, anhydrite, and silica, and therefore reflect different degrees of brecciation, cementation, hydrothermal reworking, and replacement of preexisting sulfides.

Based on the sequence of rock types recovered from each area, four major lithologic types can be distinguished, all of which may or may not be present at a given location. Massive pyrites and pyrite breccias dominate the upper 10-20 m. This is followed by an anhydrite-rich zone, which is composed of matrix-supported pyrite-anhydrite breccias and pyrite-anhydrite-silica breccias. At depths of about 40-45 mbsf, the amount of quartz-pyrite mineralization and quartz veining increases and represents the top of the quartz-sulfide stockwork zone, which typically includes pyrite-silica breccias overlying silicified wall-rock breccias. A quartz-chlorite stockwork zone was sampled at depths greater than 100 mbsf in Hole 957E. This complex assemblage of rock types is a

product of the multistage development of the mound, and is reflected in the sequences of alteration and veining events that can be distinguished both in the sulfide breccias and in the silicified wall-rock and chloritized basalt breccias.

INTRODUCTION

Hydrothermal circulation is one of the fundamental processes associated with crustal accretion along oceanic spreading centers. Driven by heat from magmatic intrusion and emplacement of new crust, seawater circulates through the permeable portions of the crust and upper mantle, and discharges at the seafloor as both high-temperature (up to 400°C) focused and lower temperature (less than ~250°C) diffuse fluid flow. The circulating hydrothermal fluids interact with the oceanic basement in a complex series of water-rock reactions that not only influence the physical properties and composition of the crust (e.g., Thompson, 1983; Jacobson, 1992; Johnson and Semyan, 1994), but also give rise to the development of seafloor mineral deposits. These reactions result in changes in the chemistry of the material recycled into the mantle by subduction (e.g., Hoffmann and White, 1982; Hart and Staudigel, 1989), and also play a role in regulating the chemical composition of seawater (e.g., Edmond et al., 1979). However, the extent of alteration and its impact on global geochemical mass balances is still very poorly constrained.

Hydrothermal vent systems also provide unique habitats that support chemosynthetically based biological communities that are especially adapted to the physicochemical environment and ephemeral nature of vents. Reduced gases in the discharging fluids are converted into biochemical energy through microbially mediated oxidation. Most noteworthy are the free-living sulfide oxidizers and the sulfide oxidizing endosymbionts (Jannasch and Wirsen, 1985) associated with the vent invertebrates that obtain their energy through sulfide oxidation and their carbon through CO_2 fixation. These primary producers provide the basis of the trophic structure that supports the large biomass of macroinvertebrates endemic to deep-sea hydrothermal vents. Deep-sea hydrothermal vents also provide a unique environment for the study of the thermally restricted hyperthermophilic microorganisms -- organisms that grow optimally above 80°C (Baross and Deming, in press).

The surficial expression of submarine hydrothermal systems has now been investigated at fast-, intermediate-, and slow-spreading ridges, at intraplate volcanic centers, and in island arc settings, both in backarc basins and in forearc regions (Rona and Scott, 1993). However, our knowledge of the subsurface part of the hydrothermal system is indirect, and has been derived by combining studies of altered rocks recovered from oceanic spreading centers (e.g., Humphris and Thompson, 1978; Alt et al, 1986; Mével, 1987; Gillis and Thompson, 1993) and from ophiolites (e.g., Stern and Elthon, 1979; Harper et al., 1988; Nehlig and Juteau, 1988; Gillis and Robinson, 1990), with experimental work (reviewed in Saccocia et al., 1994) and theoretical modeling (e.g., Lowell et al., 1993; Lowell et al., in press; Rosenberg et al., 1993). All of these approaches have been combined into simple conceptual models of the progression of alteration reactions that occur within the oceanic crust (Gillis and Thompson, 1993; Alt, in press). However, many uncertainties remain about the nature of the subsurface part of an active system. These include (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) structural controls on the plumbing system within both the upflow and reaction zones, (5) the evolution of major black smoker systems, and (6) the existence, extent, and persistence of a subsurface biosphere.

ODP Leg 158 was designed to address these issues by investigating fluid flow, alteration and mineralization and associated geochemical fluxes, microbiological processes, and the subsurface nature of an active hydrothermal system on a slow-spreading, sediment-free mid-ocean ridge. Hydrothermal systems on unsedimented ridge axes dominate global hydrothermal activity, and hence are an important contributor to global mass and energy fluxes. The site chosen for this study was the active TAG hydrothermal mound (26°N on the Mid-Atlantic Ridge) - - a large, mature deposit composed of massive sulfides probably in excess of 5 N × 10^6 tons (Rona et al., 1986), making it equivalent in size to some of the ophiolite deposits in Cyprus, Oman, and elsewhere (e.g., Fouquet et al., 1988; Constantinou and Govett, 1973).

GEOLOGIC AND TECTONIC SETTING

The 40-km-long ridge segment in which the TAG hydrothermal field is located trends north-northeasterly, and is bounded by non-transform discontinuities to the south and north at 25°55'N and 26°17'N respectively (Purdy et al., 1990; Sempéré et al., 1990). Seafloor spreading has been asymmetric over the last 10 m.y., with half spreading rates of 13 mm/yr to the east and 11 mm/yr to the west (McGregor et al., 1977). At about 26°10'N -- approximately the middle of the segment -- the east wall forms a broad salient that reduces the width of the valley floor from about 9 to 6 km and rises from the valley floor, near 4000 m in depth, to a height of 2000 m through a series of steps formed by fault blocks (Temple et al., 1979).

The TAG hydrothermal field lies at the base of this salient and extends over an area of at least 5 × 5 km along the eastern median valley wall (Fig. 1). The 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 in depth on the east wall and includes massive, layered deposits of manganese oxide, amorphous iron oxide, and nontronite (Rona et al., 1984; Thompson et al., 1985). The two large relict zones occur on the lower east wall to the north of the active mound, and are believed to be associated with volcanic domes (Rona et al., 1993a, b). The 2-km-long *Alvin* hydrothermal zone lies between depths of 3400 and 3600 m and is composed of discontinuous sulfide deposits associated with several mound-like features with dimensions similar to those of the active mound, and separated by sediment and pillow-basalt flows. The *Mir* zone is south of the *Alvin* zone on the lower east wall about 2 km east-northeast of the active mound between 3430 and 3575 m. It consists of inactive deposits in various stages of weathering, situated on normal fault blocks, as well as areas of numerous standing and toppled sulfide chimneys, some up to 25 m in length and up to 3 m in diameter (Rona et al., 1993a).

The presently active black smoker system occurs at the juncture between the rift-valley floor and the east wall at approximately 26°08'N, 44°49'W, and at a depth of about 3620-3700 m (Fig. 1). The low-temperature field described above lies 3.7 km upslope to the east; the bathymetric axis of the rift valley is about 1.5-2 km to the west. The active high-temperature mound lies on oceanic crust at least 100,000 years old, based on present seafloor-spreading rates. Preliminary geochronological studies of samples recovered by dredging suggest that the mound is on the order of 40,000-50,000 years old (Lalou et al., 1990). More detailed studies of samples collected by submersible suggest that activity has been intermittent over the past 20,000 years, with a periodicity of 5000-6000 years (Lalou et al., 1993). Present activity commenced about 50 years ago after a hiatus of about 5000 years (Lalou et al., 1993).

A recent bathymetric map confirms that the mound is distinctly circular and measures 200 m in diameter and about 50 m in height (Fig. 2). It exhibits two distinct, flat platforms at depths of about 3650 and 3644 m, which may represent two phases of active growth (Humphris et al., 1994). The mound is surrounded by an apron dominated by carbonate and metalliferous sulfide-oxide sediment that ranges in width up to 100 m. A schematic cross section of the active TAG hydrothermal mound made during the 1990 *Alvin* dive series, and the inferred flow pattern within the mound, are shown in Figure 3. The mound is composed of massive sulfides and anhydrite, with distinct sample types being distributed from the inner to the outer parts of the mound (Rona et al., 1993a; Tivey et al., in press). A cluster of chalcopyrite-anhydrite-rich black smoker chimneys emitting fluids up to 363°C is northwest of the center of the mound. This chimney cluster sits on the top of a 10-15-m-high, 20-30-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 tops of both the upper and lower platforms of the mound are relatively flat with irregular surfaces. 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 parts of the mound (Tivey et al., in press). 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 (3 at 23°C) and lesser amounts of iron than the black smoker fluids (Edmond et al., in press). They are thought to be derived from the black smoker fluids by a combination of conductive cooling and mixing with seawater and precipitation of sulfides within the mound (Edmond et al., in press; Tivey et al., in press).

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: (1) pyrite-rich blocks with trace amounts of late-stage amorphous silica, quartz, goethite and with outer oxidized layers that include atacamite; and (2) deep-red to orange-brown blocks of amorphous Fe oxide, goethite, hematite, and silica (as both amorphous silica and quartz). Analogs 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).

Hydrothermal activity on the active TAG mound supports a productive chemosynthetic-based benthic community (Van Dover et al., 1988). The most abundant organisms over much of the mound surface where diffuse fluid flow is present are anemones, together with smaller numbers of inconspicuous tube-dwelling polychaetes and buccinid snails (Grassle et al., 1986; Galkin and Moskalev, 1990). In the immediate vicinity of the active black smokers, however, swarming shrimp (*Rimicaris exoculata*; Rona et al., 1986) that reach densities up to 1500 per m^2 are dominant (Van Dover et al., 1988), with two other shrimp species, a brachyuran crab, and a zoarcid fish (at densities of only a few per m^2) also present.

RESULTS

The major objective of Leg 158 was to investigate the subsurface nature of the active TAG hydrothermal system on the Mid-Atlantic Ridge at about 26°N. Unlike most other ODP legs, drilling was concentrated on a feature only 200 m in diameter. Consequently, all drilling locations were considered as one site, although holes were grouped in specific areas, each of which had distinctive objectives. Several holes in one location were often attempted in order to recover as much of the stratigraphic section as possible. It was originally planned that a full logging program would be run at each location and a CORK would be emplaced in one hole; however, due to very difficult drilling conditions that included hole instability and cleaning problems, we were unable to accomplish these particular objectives. However, a northwest-southeast transect of three major, distinct areas of the mound was successfully completed, as well as some additional holes that attempted to delineate lateral heterogeneity of the sulfide deposit, and the extent and nature of the underlying stockwork zone.

PROPOSED TAG-1 AREA (East of the Black Smoker Complex)

Holes 957C, 957E, 957F, and 957G were drilled on the upper terrace of the TAG active hydrothermal mound approximately 20 m southeast of the Black Smoker Complex. The objective of drilling at this location was to recover a stratigraphic section of hydrothermal deposits and underlying stockwork beneath the most active part of the mound. The two most complete sections through the mound were cored in Hole 957C (from 10 to 49 mbsf) and Hole 957E (from 30 to 125 mbsf) with recoveries of 44% and 4% respectively. The upper part of the section was cored in Hole 957F (from the surface to a depth of about 8 mbsf with recovery of 10.5%) and in Hole 957G (from 12 to 22 mbsf with recovery of 8.5%). Holes 957D and 957L were also drilled in this area, but had no recovery.

Since all the holes are within 10-15 m of each other, their stratigraphy is considered together to form a composite section through the hydrothermal mound and into the upper part of the stockwork zone (Fig. 4). Most of the sulfides occur in the upper part of the section, with pyrite making up between 50% and 80% of the rock by volume down to about 30 mbsf. Based on recovery from Holes 957F and 957G, the upper few meters of the section contains fragments of massive granular pyrite and chalcopyrite, which likely represent near-surface hydrothermal precipitates derived from sulfide crusts and chimney talus.

Massive pyrite breccias (from 0 to 15 mbsf) contain >75% pyrite and are largely clast-supported. These breccias consist of subrounded clasts of massive, granular pyrite in a porous, sandy pyrite matrix cemented by anhydrite. Clastic material in these breccias resembles porous and granular massive pyrite found in the sulfide talus from the surface of the mound. From 15 to 30 mbsf, a zone of pyrite-anhydrite-rich breccias, grades into pyrite-silica-anhydrite breccias that extend down to about 45 mbsf. These compose the bulk of the anhydrite-rich zone. The pyrite-anhydrite breccias typically consist of rounded pyrite clasts in a matrix of semi-massive anhydrite. The clasts (ranging in size from 0.5 to 2 cm) are composed of massive granular pyrite, but siliceous clasts, quartz-pyrite clasts, and altered basalt fragments become increasingly common with depth. The pyrite-silica-anhydrite breccias are intermediate in character between pyrite-anhydrite breccias above and pyrite-silica breccias below. Subangular to subrounded clasts consisting of siliceous pyritic material, quartz-pyrite aggregates, and massive granular pyrite, are cemented mainly by quartz, with most of the anhydrite in the form of crosscutting veins. The quartz appears dark gray due to inclusions of abundant, fine-grained disseminated pyrite.

Abundant quartz-pyrite mineralization and quartz veining immediately beneath the anhydrite-rich zone represent the top of the stockwork, suggesting that the thickness of the mound in this area is about 30 m. A quartz-rich zone composed mainly of pyrite-silica breccias near the top and silicified wall-rock breccias toward the bottom occurs between 45 and 100 mbsf. The pyrite-silica breccias consist of large (up to 10 cm) fragments of fine-grained, gray siliceous material and smaller fragments of quartz-pyrite set in a matrix of very fine-grained quartz. The gray siliceous clasts appear to be fragments of preexisting mineralized and silicified wall rock similar to that occurring deeper in the section, but the clasts generally have more diffuse boundaries and are partially replaced by the quartz matrix.

The silicified wall-rock breccias differ from the overlying pyrite-silica breccias in that they are dominantly clast-supported and contain significantly less pyrite. They consist of angular siliceous basalt fragments that are identical to the silicified clasts that occur higher in the stratigraphic column. They are 1-5 cm in size, totally recrystallized to quartz, pyrite, and clay, but locally they contain relict igneous textures, and are veined and cemented by white to gray quartz and pyrite.

Below about 100 mbsf, this quartz-rich zone grades downward into a chloritic stockwork where chloritized and weakly mineralized basalt is the dominant lithology. The rocks range from gray chloritized basalt breccias to green chloritized basalt fragments and glass shards cemented by quartz. The gray chloritized basalt breccias consist of 1-5-cm clasts of altered basalt in a fine-grained matrix of intergrown white to gray quartz and pyrite. The altered basalt clasts are softer and less silicified than those in the overlying silicified wall-rock breccias, and are pervasively altered to chlorite + pyrite + quartz.

Anhydrite veining is abundant throughout the vertical extent of the section, but is best developed in the pyrite-anhydrite and pyrite-silica breccias (15 to 50 mbsf), where veins up to 45 cm in width are present. These veins comprise complex, multistage fracture fillings and cavity linings, some of which include disseminated, fine-grained pyrite and chalcopyrite, and trace amounts of hematite. The occurrence and size of veins decrease downward and correspond to an increase in the amount of quartz cement. In the chloritized basalt breccias, veins of pyrite, quartz, and quartz + pyrite commonly cut the basalt clasts, and appear to follow a sequence from early pyrite and quartz + pyrite veins to later quartz veins that cut the earlier veins. There is some evidence for small, late anhydrite veins that cut other vein types, and some anhydrite also occurs as the last mineral to form at the center of sulfide veins.

Large ranges in the chemical compositions of different rock types reflect the extreme heterogeneity of the samples and the variable proportions of sulfides, anhydrite, and silica. The Fe contents of the samples range from 20.1 to 40.8 wt% and reflect the dominance of pyrite in the sulfide section. Cu contents are significantly lower, ranging from 0.01 to 6.0 wt%, and Zn concentrations are also generally low (<700 ppm). The most striking feature of the sulfides in the proposed TAG-1 area is their very low concentrations of Pb, Ag, and Cd, which are close to their detection limits.

Physical properties of sulfide samples from the proposed TAG-1 area are typical for this type of material and yielded bulk densities from 2.85 to 4.51 g/cm^3 and porosities ranging between 2.4 and 16.2%. Compressional (*P*)-wave velocities are generally high (4.85-5.66 km/s), and electrical resistivities are low (0.11-2.01 Ωm). Thermal conductivities generally range between 5.7 and 8.7 W/m K. In contrast, anhydrite samples have lower bulk densities (2.79 and 2.85 g/cm^3) and thermal conductivity (5.4 W/m K) and distinctly higher electrical resistivity (2.77 Ωm) than the sulfides, but porosities (4.9% and 9.6%) are similar.

Paleomagnetic measurements indicate that cores recovered from the upper part of the section (0 to 25 mbsf) have a low intensity of natural remanant magnetization, while those from depths of 30 to 35 mbsf have a stable component of magnetization consistent with the location of the TAG mound. Preliminary data from unblocking temperatures and coercivity determinations suggest that maghemite is the most likely magnetic carrier in these rocks.

Fluid sampling in Hole 957C indicates that borehole fluids were dominated by surface seawater introduced during the drilling processes, and there was no evidence for upflow of hydrothermal fluids. However, elevated concentrations of magnesium, calcium, and sulfate in the sample suggested that dissolution of calcium and magnesium sulfate solids may be occurring. This was most likely an artifact of the drilling process but could also be the result of an ongoing process in the mound.

PROPOSED TAG-2 AREA ("Kremlin" White Smoker)

Holes 957A, 957B, 957H, and 957N are within about 10-15 m of each other on the lower terrace of the active TAG mound in an area of white smoker chimneys (the Kremlin, or proposed TAG-2 area). Objectives of drilling at this location were to sample a section of the mound where discharging fluids have chemistries distinct from those of the black smokers, and have undergone conductive cooling and mixing within the mound.

The most complete section cored was Hole 957H (from 8.7 to 54.3 mbsf) with a recovery of 11.0%. Hole 957A was located about 5 m northwest of Hole 957H and sampled the upper 15.0 m with recovery of 1.7%. Hole 957B was cored with recovery of 5% to a depth of 29.6 m about 8-10 m southeast of Hole 957H and recovered a thick section of massive sulfides, with the hole ending in partly altered basalt. A single wash core covering the interval 0-42.2 mbsf was recovered from Hole 957N to the west of Hole 957A.

The stratigraphy of the sulfide section in the Kremlin area is similar for all the holes down to about 20 mbsf. Drill cuttings from the very top of the section in Hole 957B consist of red-brown, sulfide-rich sand and mud with abundant chert clasts and a few small pieces of porous massive sphalerite and massive granular pyrite. The sulfide-rich sand and mud contains up to 16 wt% combined Cu and Zn (1-3 wt% Zn and 8-13 wt% Cu), and may represent near-surface hydrothermal precipitates similar to those observed in Hole 957F east of the Black Smoker Complex (proposed TAG-1 area). A hard layer in the top few meters of each hole at the proposed TAG-2 area consists of mixed pyrite and chert clasts in a dominantly cherty matrix. Clasts of similar red and gray chert are also common in the underlying massive, porous pyrite to a depth of about 10 mbsf. Most of the sulfide material recovered from the proposed TAG-2 area occurs in the upper 20 m of the section as massive porous pyrite and porous, nodular pyrite breccias. These breccias have experienced less complex brecciation, cementation, and veining than similar rocks drilled in the other areas of the mound. The upper 10 m of the core in Holes 957A and 957H consists of massive, porous to granular pyrite with abundant red and gray chert. The massive pyrite is colloform-banded and exhibits primary depositional textures, with only limited replacement and local recrystallization to coarse, granular pyrite. Between 10 and 20 mbsf, a zone of massive, nodular pyrite breccias containing rounded clasts of pyrite in a sandy pyrite matrix is present. Although the breccias are dominantly matrix-supported, they contain only minor anhydrite cement.

Pyrite accounts for 80%-90% of the rock by volume in the upper 20 m, and chalcopyrite is locally abundant in the upper 15 m of the core as disseminated grains and clasts in the sandy pyrite matrix, replacing the colloform pyrite, and locally associated with anhydrite veins. Sphalerite occurs mainly as coatings on massive colloform pyrite and in late cavities or fluid channelways in the upper 5 m of core. A sample of nodular pyrite breccia from about 10 mbsf contains close to 7 wt% Cu. Zn contents are low in samples from Hole 957H below about 8 mbsf (<0.02 wt% compared with 1-3 wt% from the uppermost samples recovered in this area).

Between 20 and 30 mbsf in Hole 957H, massive pyrite breccias grade into pyrite-silica breccias, which consist of nodular clasts of quartz and pyrite in a quartz-rich matrix with anhydrite veining.

Silicified wall-rock fragments and altered hyaloclastite first occur at a depth of 27 mbsf, and the wallrock fragments become increasingly abundant deeper in the core. Below 27 mbsf, the fragments in the pyrite-silica breccias become coarser and more angular and are interspersed with sections of brecciated and silicified wall rock. At about 40 mbsf, the pyrite-silica breccias grade into more massive silicified wall-rock breccias, and chloritized basalt fragments are present locally among the clasts. The silicified wall-rock breccias represent the upper part of the stockwork zone below the massive sulfides. This stratigraphic sequence suggests that the thickness of the sulfide mound beneath the Kremlin area is only about 25 m.

The silicified basalt clasts in the pyrite-silica breccias of Holes 957H and 957N, and in the silicified wall-rock breccias of Hole 957H, are gray to buff, 2-mm to 3-cm rounded to angular fragments in a fine-grained matrix of gray quartz plus pyrite. Pyrite in the matrix is present as 0.1-1-cm grains and rounded aggregates. The basalt clasts themselves are composed of a buff phyllosilicate plus quartz, and contain variable amounts of fine-grained pyrite replacing plagioclase microlites and disseminated in the groundmass. The clasts are replaced by quartz to varying extents, with gray portions that are more intensively silicified. The silicified hyaloclastite from Hole 957H consists of 1-5-mm angular fragments of altered basaltic glass in a matrix of fine-grained gray quartz. The glass fragments are altered to green chlorite and a white phyllosilicate, commonly in concentric bands.

Anhydrite veins are less abundant in the recovered rocks from the proposed TAG-2 area than in rocks recovered from the proposed TAG-1 area. Late anhydrite veins, up to several centimeters in width, occur in the pyrite-silica breccias in Hole 957H. Quartz veining is abundant in pyrite-silica breccias below the massive sulfides, and small quartz-pyrite veins (up to 1 cm) are the dominant vein type in the silicified wall-rock breccias to a depth of 45 mbsf.

In Hole 957B, massive porous pyrite and pyrite breccias, similar in texture and mineralogy to those observed in Hole 957H, are present to a depth of about 20 mbsf. At the base of the massive sulfides in Hole 957B, a 30-cm section of pillow-rim breccia was recovered, which overlies partly altered basalt. This is interpreted to be the uppermost basement or a part of a basaltic flow. Centimeter-sized pieces of altered crystalline and glassy basalt occur in a matrix of red mud. The crystalline basalt fragments are grayish red and completely replaced by yellow phyllosilicates (smectite?) and iron oxides and/or oxyhydroxides. Basaltic glass fragments are blue and also completely altered to phyllosilicates (chlorite?). The strongly altered pillow-rim breccia at the contact between relatively fresh basalt and the base of the massive sulfides may indicate local hydrothermal flow along the contact or weathering of the basalts at the base of the sulfide breccias.

Fragments of red brown to dark gray, very fine-grained aphyric to sparsely phyric basalt occur in the lowermost part of Hole 957B. They exhibit rare olivine phenocrysts in a microcrystalline groundmass containing plagioclase microlites, and are slightly altered with olivine phenocrysts replaced by smectite and iron oxyhydroxides and/or oxides. Small rounded to elongated vesicles make up 1% to 2% of these samples.

Physical properties of sulfide specimens from the Kremlin area yielded a range of bulk densities from 2.61 to 4.33 g/cm^3 and porosities between 6.38% and 21.5%. Electrical resistivity measured on two sulfide minicores are low (0.07 and 0.58 Ωm). Compressional (*P*)-wave velocities of minicores vary between 5.4 and 6.7 km/s, and thermal conductivities between 8.0 and 10.4 W/m K. High porosities (15.7% and 18.6%) and low wet bulk densities (2.25 and 2.43 g/cm^3) reflect their altered character.

The cores recovered from Hole 957H displayed a multicomponent magnetization. The unstable viscous component is characterized by a higher magnetic susceptibility and a lower Koenigsberger ratio. This viscous magnetization can be removed by AF demagnetization. The downhole magnetic profile shows a trend of increasing intensity with depth, which coincides with the observed changes in lithology. No noticeable magnetic anisotropies were observed.

The core from the proposed TAG-2 area indicates that the massive sulfides at the eastern edge of the lower terrace comprise a 20-m-thick talus pile on the flanks of the mound. This material was presumably derived from the erosion of sulfide chimneys on top of a former mound/stockwork complex. As these breccias are presently at the edge of the main upflow zone, they exhibit only minor replacement, veining, and cementation by quartz and anhydrite. The upper 10 m of sulfides consists of massive colloform pyrite with minor late sphalerite lining cavities and fluid channelways. This sphalerite is probably related to the current white smoker activity at the surface of the mound. Massive, nodular pyrite breccias beneath the white smoker complex may represent an earlier generation of sulfide talus that accumulated on the eastern flanks of the growing sulfide mound.

PROPOSED TAG-3 AREA (South of the Black Smoker Complex)

Hole 957Q was drilled on the lower terrace of the mound about 55 m south of the Black Smoker Complex in a water depth of 3657 m. The objectives were to investigate the nature and degree of sulfide oxidation, and the vertical extent of the sulfide deposits in the southwestern quadrant of the mound. Hole 957Q was drilled to a total depth of 14.5 mbsf with 41% recovery.

The recovered cores consist of fine- to medium-grained drill cuttings and several small fragments of pyrite and chert. The drill cuttings are composed of silt- and sand-sized grains and fragments of pyrite, red chert, partially silicified Fe oxides, and trace amounts of chalcopyrite. Geochemical analyses of this material indicate that it is composed of 36.8 wt% S and 33.0 wt% Fe. It has a high Cu content (6.64 wt%), but low concentrations of Zn (0.42 wt%), Ag (5.1 ppm), and Cd (9.2 ppm). These drill cuttings are more pyrite-rich than those recovered from Hole 957B (proposed TAG-2 area -- Kremlin area) about 40 m to the east, and are enriched in Fe oxides and chert but depleted in anhydrite relative to the drill cuttings from Hole 957P on the upper terrace to the north of the Black Smoker Complex. Larger fragments of porous red chert, red and gray chert, and massive porous pyrite were recovered both embedded in the drill cuttings and stuck in the core catcher. Similar material was collected at all locations drilled on the mound, and corresponds to a hard layer of chert just beneath the seafloor. This most likely results from precipitation of silica from hydrothermal fluids diffusing through the mound and forming a silica cap.

Physical properties measurements were made on four sections of drill cuttings. Bulk densities range between 2.8 and 3.2 g/cm^2, with the top section exhibiting more variable values and very high magnetic susceptibility values (1200×10^{-5} SI). One partially silicified Fe oxide fragment showed a high total porosity of 18.1% and a bulk density of 2.60 g/cm^3.

PROPOSED TAG-4 AREA (West of the Black Smoker Complex)

Holes 957I, 957J, 957K, and 957M were drilled on the upper terrace on the western side of the mound (proposed TAG-4 area). The objectives of drilling at this location were to recover a section through the sulfides and into the stockwork zone in an area of low conductive heat flow (<20 mW/m^2), and to determine the extent of the sulfides and the stockwork on the western side of the deposit. Holes 957I, 957K, and 957M were drilled about 20 m west of the Black Smoker

Complex in a water depth of 3645 m. The most complete section was cored in Hole 957M (from 9.3 to 51.2 mbsf) with a recovery of 13.6%. Hole 957K was drilled approximately 5-8 m north of Hole 957M and sampled the section down to 20.0 mbsf with a recovery of 5.0%. Hole 957I was 10-15 m west of Hole 957K and drilled to 9.0 m before coring to 13.5 m with 17% recovery. Hole 957J was 25 m northeast of Hole 957I in a water depth of 3647 m, and only one core was retrieved with 1.0% recovery.

Core recovered from the proposed TAG-4 area indicates that the western side of the upper terrace consists mainly of massive sulfide crusts and sulfide-cemented breccias. In addition, there are significantly higher amounts of sphalerite, marcasite, and amorphous silica and lower amounts of anhydrite than in samples drilled elsewhere on the mound. The upper 10 m of the mound consists of porous colloform pyrite + marcasite with red and gray chert, below which is a 10-m-thick zone of massive pyrite and massive pyrite breccia with minor sphalerite. A few altered basalt clasts occur in this zone. Between 20 and 30 mbsf, massive pyrite grades downward into pyrite-silica breccia in which larger, silicified wall-rock fragments (up to 10 cm) are abundant. Silicified wall-rock breccias are the dominant lithology between 30 and 42 mbsf, followed by an abrupt transition into slightly to moderately altered basalt, which was drilled down to 51.2 mbsf.

In the top of Hole 957M, fine- to coarse-grained red-brown and orange Fe oxides and minor pyrite and silica were encountered as drill cuttings. Geochemical analyses of this material indicate high Fe contents (up to 52.4 wt%) but low S (4.7 wt%), Cu (up to 0.29 wt%) and Zn (0.28 wt%) contents compared with near-surface drill cuttings recovered from the proposed TAG-2 area indicative of the higher abundance of Fe oxides and Fe oxyhydroxides at the proposed TAG-4 location.

The dominant rock type in the upper 10 m of the section is porous massive pyrite that consists of variable proportions of pyrite + marcasite with colloform banded textures and a coarse vuggy porosity. The colloform texture commonly encloses zones of massive fine-grained pyrite and marcasite, or grades into dark gray pyrite-silica. Minor chalcopyrite occurs as 1-3-mm aggregates associated with silica-rich zones. Minor amounts of sphalerite are intergrown with pyrite and marcasite, and sphalerite is also present as overgrowths on the colloform pyrite. Geochemical analyses of four samples indicate high Fe (38.4-45.7 wt%) and S (41.0-50.8 wt%) contents. Zn concentrations range from 3.0 to 3.7 wt%, which are among the highest values determined, while Cu contents are only 0.05-0.13 wt%. The upper 10 m of core from Holes 957J, 957K, and 957M also contains clasts of red and gray chert, which consist of dark red Fe oxides intimately intergrown with silica, and are similar to those observed in the uppermost hard layer at other drilling locations.

Between 10 and 20 mbsf, porous massive pyrite and massive granular pyrite occur in Holes 957K and 957M. Massive granular pyrite consists almost entirely of granular aggregates of fine-grained pyrite with abundant colloform texture. This rock type seems to have formed by recrystallization of the porous massive marcasite + pyrite, but also incorporates pyritized silicified wall-rock fragments.

This lithology grades down into a pyrite-silica breccia that contains numerous silicified wall-rock fragments, that increase in abundance and size between 30 and 40 mbsf until they comprise more than 50 vol% of the rock. The pyrite-silica breccias are matrix-supported and consist of assemblages of different clasts derived from both surface hydrothermal processes (e.g., cherts) and subsurface alteration processes (e.g., silicified wall rock) in a dark gray pyrite-silica matrix.

Between 30 and 42 mbsf, silicified wall-rock breccias resemble those in the upper part of the quartz-rich stockwork in the proposed TAG-1 and TAG-2 areas, but are generally softer, have greater porosity, lack significant quartz veining, and contain greater quantities of massive pyrite. The breccias consist of angular to subrounded clasts of variably silicified and highly altered basalt enclosed in a matrix of pyrite-silica breccia or porous massive pyrite. The clasts are generally hard and silicified, and contain abundant pyrite disseminated in the matrix. The buff to gray color of the groundmass suggests replacement by chlorite. The siliceous wall-rock breccias are cut by several generations of quartz and pyrite veins. A few pieces of chloritized basalt breccia occur below 34 mbsf, where they are gradational from the silicified wall-rock breccias, and where there is less intensive silicification of the altered basalt material.

Below 42 mbsf, the silicified wall rock and chloritized basalt breccias are underlain by slightly to moderately altered basalts. These basalts are uniformly dark gray, but some have <1 mm red iron oxide/oxyhydroxide coatings on their outer surfaces or display various combinations of 1-5-mm-wide red, black, and green alteration halos around central parts of dark gray basalt. These sparsely olivine phyric basalts appear to be fragments of pillow basalts, as several of the pieces are rimmed with glassy rinds or are holohyaline. Textures range from intergranular to subvariolitic and variolitic. Olivine is partly altered to colorless to pale green to tan smectite, rarely with small amounts of accompanying red iron oxyhydroxide. The groundmass is composed of microcrystalline to cryptocrystalline plagioclase, clinopyroxene, small interstices of variably altered glass, and granular fine-grained titanomagnetite. Vesicles are filled with a light green smectite. Small (10 μm) veinlets of tan smectite are also present in some samples.

Physical properties measurements on sulfides from the proposed TAG-5 area indicate that the porous massive pyrites exhibit a narrow range of high values of bulk density (4.34-4.50 g/cm^3) combined with high values of porosity (8.22%-11.53%). Pyrite-silica breccias have lower bulk densities (3.46-4.38 g/cm^3), which are similar to those of silicified wall-rock breccias (3.51-4.65 g/cm^3). Porosities for these two rock types are in the range 2.86%-9.09%. The slightly altered basalts have typical bulk densities of 2.88-2.90 g/cm^3, porosities of <2%, and compressional (*P*) - wave velocities of 6.09-6.13 km/s.

Paleomagnetic measurements were conducted on two basalt samples and indicated NRM intensities ($\sim 4 \times 10^3$ mA/m) much stronger than those typical of oceanic basalts. Based on the magnetic behavior during AF demagnetization, the magnetic carrier is speculated to be titanomagnetite. The stable component of magnetization for both samples has a much shallower inclination (14°) compared with the expected inclination (55°) at this site, suggesting that the magnetization is unlikely to have been acquired during cooling of the basalt but may be related to the pervasive hydrothermal alteration that has affected the TAG hydrothermal mound.

Core recovered from the proposed TAG-4 area indicates that the western side of the upper terrace consists mainly of massive sulfide crusts and sulfide-cemented breccias. Although abundant wall-rock clasts were recovered, the framework-supported nature of the breccias, the absence of pervasive quartz and anhydrite cement, and the presence of relatively unaltered basaltic basement at the bottom of Hole 957M suggest that this is not part of the high-temperature stockwork. Instead, these breccias appear to be part of a thick talus pile adjacent to the main upflow zone. Measured from the basalt basement, the mineralized talus is at least 20 m thick and is capped by a 10- to 15-m-thick carapace of massive pyrite. This carapace may be either an in situ hydrothermal precipitate, composed mainly of porous and colloform pyrite-marcasite crusts, or primary precipitates that originate from the Black Smoker Complex.

PROPOSED TAG-5 AREA (Northeast of the Black Smoker Complex)

Holes 957O and 957P are about 15 m apart and are near the margin of the upper terrace on the north side of the mound about 20-30 m north-northeast of the Black Smoker Complex (this area is designated as the proposed TAG-5 area). The objectives of drilling at this location were to determine the lateral heterogeneity of the sulfide mineralization and to delineate the northern extent of the underlying stockwork zone. The upper part of the section from 0 to 20.5 mbsf was cored at Hole 957O, although material was recovered only from 7.9 to 20.5 mbsf. The overall recovery for the entire 20.5-m section was 6.2%; however, between 7.9 and 20.5 m, recovery of 10.1% was achieved. Hole 957P is 15 m west of Hole 957O, and was cored from 0 to 59.4 mbsf with a recovery of 12%.

The overall stratigraphy inferred from core recovered from Holes 957O and 957P is similar to that observed in Holes 957E, 957F, and 957G in the proposed TAG-1 area to the east of the Black Smoker Complex. Massive pyrite and semi-massive pyrite-anhydrite breccias make up the dominant lithology from the surface down to a depth of about 10 mbsf, below which there is a 20-m-thick zone of massive granular and brecciated pyrite and massive pyrite-anhydrite breccias. Between 30 and 45 mbsf, this zone grades into pyrite-silica breccias that contain fragments of silicified basalt and extend down to about 55 m. Silicified wall-rock breccias make up the lower part of the cored section. The last two cores from Hole 957P consisted of sand-sized fragments of pyrite, quartz, anhydrite and Fe oxide, which represent drill cuttings. Embedded within them are large fragments of massive granular pyrite, pyrite-silica breccia, and silicified wall-rock breccia.

The upper part of the section is composed dominantly of nodular pyrite and pyrite-anhydrite breccia, similar to those in the anhydrite-rich zone in the proposed TAG-1 area. The hard, cherty layer encountered in the upper few meters in the other proposed areas (TAG-2, TAG-3, and TAG-4) was not recovered at the proposed TAG-5 area. Nodular pyrite breccias are composed of nodular pyrite clasts and angular aggregates about 1 cm in diameter in a matrix of fine sandy pyrite and anhydrite (up to 20 vol%). Geochemical analyses indicate S and Fe concentrations of 45.1 and 33.0 wt% respectively. The Cu content is high (3.7 wt%), but the Zn content is low (0.03 wt%). The analyzed sample contains 4.5 ppm Ag, but the concentration of Cd was below the detection limit. The Fe, Zn, Cu, and S contents are within the range of similar samples of the proposed TAG-1 and TAG-2 areas. The pyrite-anhydrite breccias contain nodular to angular clasts of pyrite (as large as 2 cm in diameter) and smaller (<3 mm in diameter) aggregates of chalcopyrite in a matrix of fine- to medium-grained pyrite and anhydrite. Anhydrite composes up to 60 vol% of the rock and occurs in vugs as irregular veins and as matrix.

There is an increase in the proportion of anhydrite and vein-related mineralization below 10 mbsf. Vein-related pyrite-anhydrite breccias have a banded texture and are characterized by fine- to coarse-grained pyrite and chalcopyrite disseminated in anhydrite. Massive granular pyrite is also present associated with the anhydrite veining and pyrite-anhydrite breccias, and consists of pyrite as granular or crustiform banded aggregates and intergrown with chalcopyrite.

Below 30 mbsf, massive, coarse-grained granular pyrite is associated with the pyrite-silica breccias and contains significant amounts of silica. Remnant patches of chert, dark gray silica, and silicified altered basalt material are commonly included within the massive pyrite, suggesting that the rock formed by pyritization of an existing pyrite-silica or silicified wallrock breccia. The pyrite-silica breccia consists of coarse, poorly sorted pyrite aggregates in a matrix of fine-grained dark gray silica with coarse disseminated pyrite. Anhydrite is common, but is confined to vugs and late veining. These breccias contain clasts of an earlier generation of pale-gray, fine-grained pyrite-silica breccia, indicating at least two stages of brecciation.

In Hole 957P, 1-mm to 5-cm round to angular to irregularly shaped clasts of silicified wall rock occur in pyrite-silica breccias from 35 mbsf to the bottom of the core at 59.4 mbsf. The clasts are replaced by quartz, gray chlorite(?), and 0.1-1-mm pyrite grains and aggregates, and they commonly have 0.5-3-mm rims of pyrite. The matrix is white to dark gray quartz + pyrite. Silicified basalt clasts are also common in massive pyrite matrix at depths greater than 45 mbsf in Hole 957P. These basalt clasts are more intensively replaced by pyrite than those in the pyrite-silica breccias. The breccias and massive pyrite containing silicified basalt clasts in Hole 957P contain numerous veins, indicating multiple stages of veining, brecciation, and cementation.

Physical properties measurements were made on 11 sulfide samples from Holes 957O and 957P. Bulk densities range from 3.37 to 5.19 g/cm^3 and porosities from 3.8% to 11.2%, similar to the values measured on samples from the proposed TAG-1 and TAG-2 areas. Electrical resistivities measured on two sulfide minicores are low (0.13 and 0.19 Ωm) and show the same inverse relationship to porosity as found in samples from the proposed TAG-1 and TAG-2 areas.

Compressional (*P*)-wave velocities measured on the same minicores are 5.4 and 5.8 km/s. Thermal conductivities measured on half-round slabs are relatively high (10.2 and 10.5 W/m K) and comparable to similar measurements made on cores from the eastern side of the mound in the proposed TAG-1 and TAG-2 areas.

Paleomagnetic measurements were completed on two pyrite-rich samples from Hole 957O. The NRM intensities of these two samples are comparable with those of samples recovered from the proposed TAG-1 and TAG-2 areas, although the Koenigsberger ratios and the initial magnetic susceptibilities are higher. The anisotropy of magnetic susceptibility (AMS) is similar to that of samples recovered from the proposed TAG-1 and TAG-2 areas as well as the basalt samples from the proposed TAG-4 area, suggesting no significant magnetic anisotropy in these samples. Vertically directed, drilling-induced magnetization could be removed relatively easily from the nodular pyrite breccia by AF demagnetization. However, AF demagnetization was not sufficient to completely remove this overprint from the pyrite-anhydrite breccia. Similar examples of this behavior are also seen in samples from other TAG areas, and the more heavily overprinted samples are often associated with the presence of anhydrite and also come from relatively deeper sections in the mound. This suggests that the hydrothermal processes that have produced the entire TAG mound may have resulted in distinct zones where precipitates have their own characteristic magnetic properties. These zones are likely to reflect different mineralogical and chemical compositions and hence variable abilities to acquire and maintain magnetic overprints.

The section of the mound cored in Holes 957O and 957P most closely resembles that of Holes 957E, 957F, and 957G in the proposed TAG-1 area. Although the top of the stockwork could not be precisely determined from the core recovered in Hole 957P, the presence of numerous altered basalt clasts and silicified wall-rock fragments below 45 mbsf suggests that a part of the stockwork zone occurs at the bottom of the hole. This is close to the depth at the top of the quartz stockwork in Hole 957E, and suggests that the thickness of the mound beneath the northern part of the upper terrace may be similar to that in the proposed TAG-1 area. The abundance of pyrite as cement and vein material in the lower part of the section at the proposed TAG-5 area suggests that this part of the mound may be underlain by pyritic stockwork and that the sulfide-rich portion of the stockwork zone extends at least to the northern edge of the upper terrace.

SUMMARY AND CONCLUSIONS

The complex assemblage of rock types that result in the overall stratigraphy of the sulfide mound is a product of its multistage development, and is reflected in the sequences of alteration and veining events that can be distinguished both in the sulfide breccias and in the silicified wall rock and chloritized basalt breccias. Sulfide breccias that are now at the base of the mound were formed at the seafloor during an earlier stage of deposit growth and have since been buried and overprinted by later hydrothermal events. The sulfide breccias likely accumulated at the seafloor through the collapse of large sulfide chimneys and by dissection of massive sulfides along active fault scarps. This debris has been overgrown by later generations of chimneys and progressively cemented or replaced by quartz, sulfides, and sulfates. The presence of altered basalt clasts from the base of the mound higher up in the section may indicate periodic dislocation and partial erosion of the mound/stockwork complex by faults during the growth of the deposit. Alternatively, the basalt clasts may be remnants of lava flows that partially buried the deposit early in its development, or relics of the original pillow talus on top of which the sulfides accumulated.

Results from drilling have enabled some constraints to be placed on the vertical and lateral extent of the stockwork beneath the TAG mound. Although the extent of the stockwork zone beneath the Kremlin area (proposed TAG-2 area) could not be determined, the presence of chloritized basalt fragments in the lower part of the core suggests proximity to a chloritic alteration zone at depth or at the outer margins of the quartz stockwork. On the western part of the mound (proposed TAG-4 area), the outer margin of the stockwork zone may be somewhere between this area and the Black Smoker Complex, and within about 5-10 m of the present high-temperature upflow. Despite their proximity to the present Black Smoker Complex, the wall-rock breccias in this area exhibit only minor replacement or veining by quartz and anhydrite, consistent with having been outside the main upflow zone throughout most of their history. In comparison to the breccias in the proposed TAG-1 area, where the original fragments of basalt have been almost completely replaced, the wall-rock fragments recovered in the proposed TAG-4 area are reasonably intact. However, abundant colloform pyrite and late-stage sphalerite in cavities and veins suggest that low-temperature upflow, possibly originating from beneath the present Black Smoker Complex, has occurred through the flanks of mound and was likely responsible for cementing the breccias in this area.

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FIGURE CAPTIONS

Figure 1. SeaBeam bathymetry (50-m contour interval) of the TAG hydrothermal field, showing volcanic domes, the active TAG hydrothermal mound, the low-temperature hydrothermal field up on the eastern rift-valley wall, and the *Alvin* and *Mir* relict hydrothermal zones (modified from Rona et al., 1993b).

Figure 2. Bathymetry (5-m contour) of the active TAG mound showing major morphologic features and the Leg 158 drill sites (Kleinrock and Humphris, unpublished data).

Figure 3. Schematic cross section of the active TAG mound from northwest to southeast. The flow patterns within the mound are derived from the mineralogy and chemistry of the deposits and the chemistry of white smoker and black smoker fluids (from Tivey et al., in press).

Figure 4. Schematic stratigraphic section of the mound in the proposed TAG-1 area showing the distribution of the principal rock types in cores from Holes 957C, 957E, 957F, and 957G.

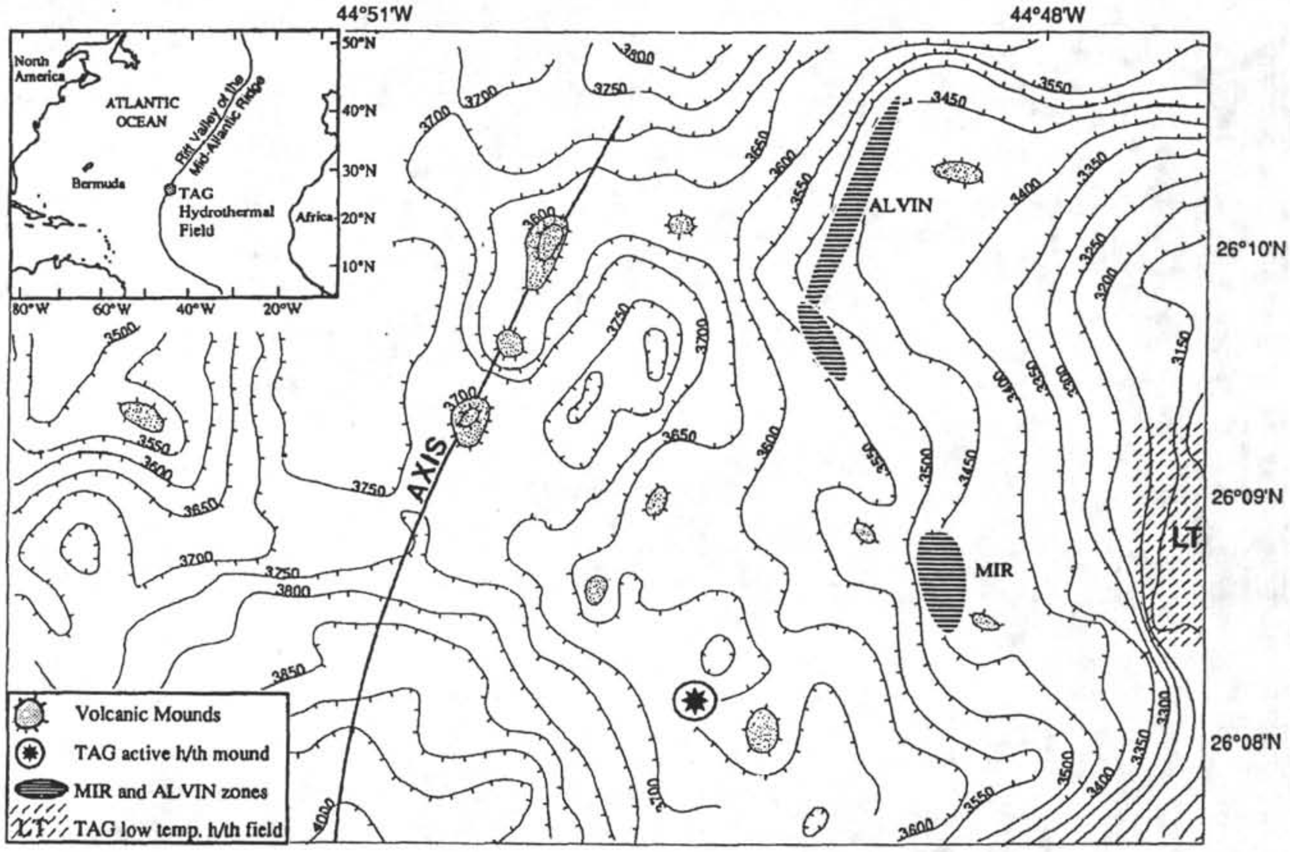

44°51'W
44°48'W
26°10'N
26°09'N
26°08'N
North America
ATLANTIC OCEAN
Rift Valley of the Mid-Atlantic Ridge
Bermuda
TAG Hydrothermal Field
Africa
50°N
40°N
30°N
20°N
10°N
80°W
60°W
40°W
20°W
AXIS
ALVIN
MIR
LT
3150
3200
3250
3300
3350
3400
3450
3500
3550
3600
3650
3700
3750
3800
3850
4000
Volcanic Mounds
TAG active h/th mound
MIR and ALVIN zones
LT TAG low temp. h/th field

Figure 1

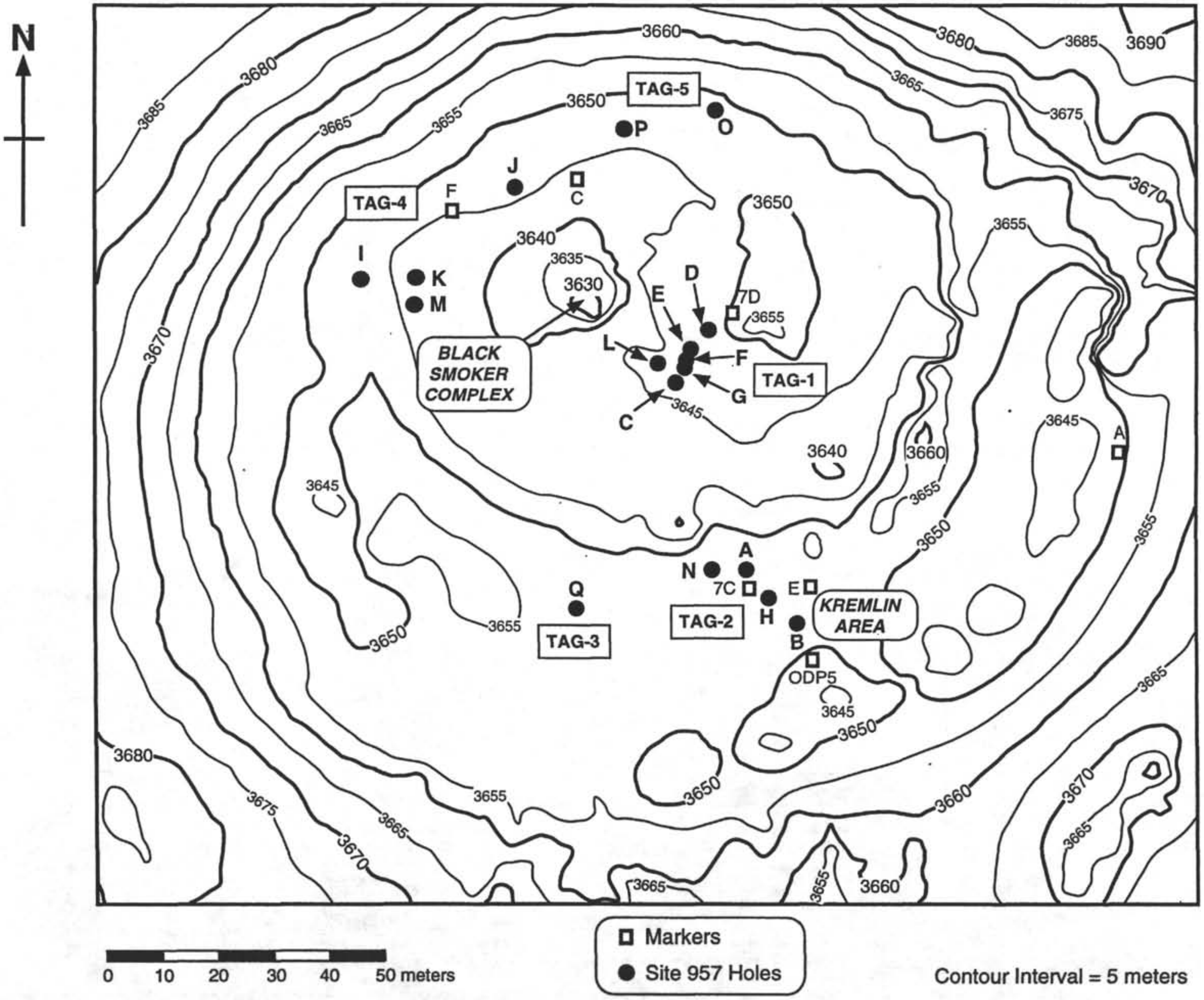

N
3660
3680
3685
3690
3680
3685
3665
3655
3650
TAG-5
3665
3675
P
O
3670
J
C
F
TAG-4
3650
3640
3655
I
K
M
3635
3630
D
E
7D
3655
3670
L
F
BLACK SMOKER COMPLEX
TAG-1
G
C
3645
3645
A
3640
3660
3645
3655
3650
3655
A
N
7C
E
Q
H
KREMLIN AREA
3655
TAG-2
3650
TAG-3
B
ODP5
3665
3645
3650
3680
3655
3650
3660
3670
3675
3665
3670
3665
3665
3655
3660
0
10
20
30
40
50 meters
Markers
Site 957 Holes
Contour Interval = 5 meters

Figure 2

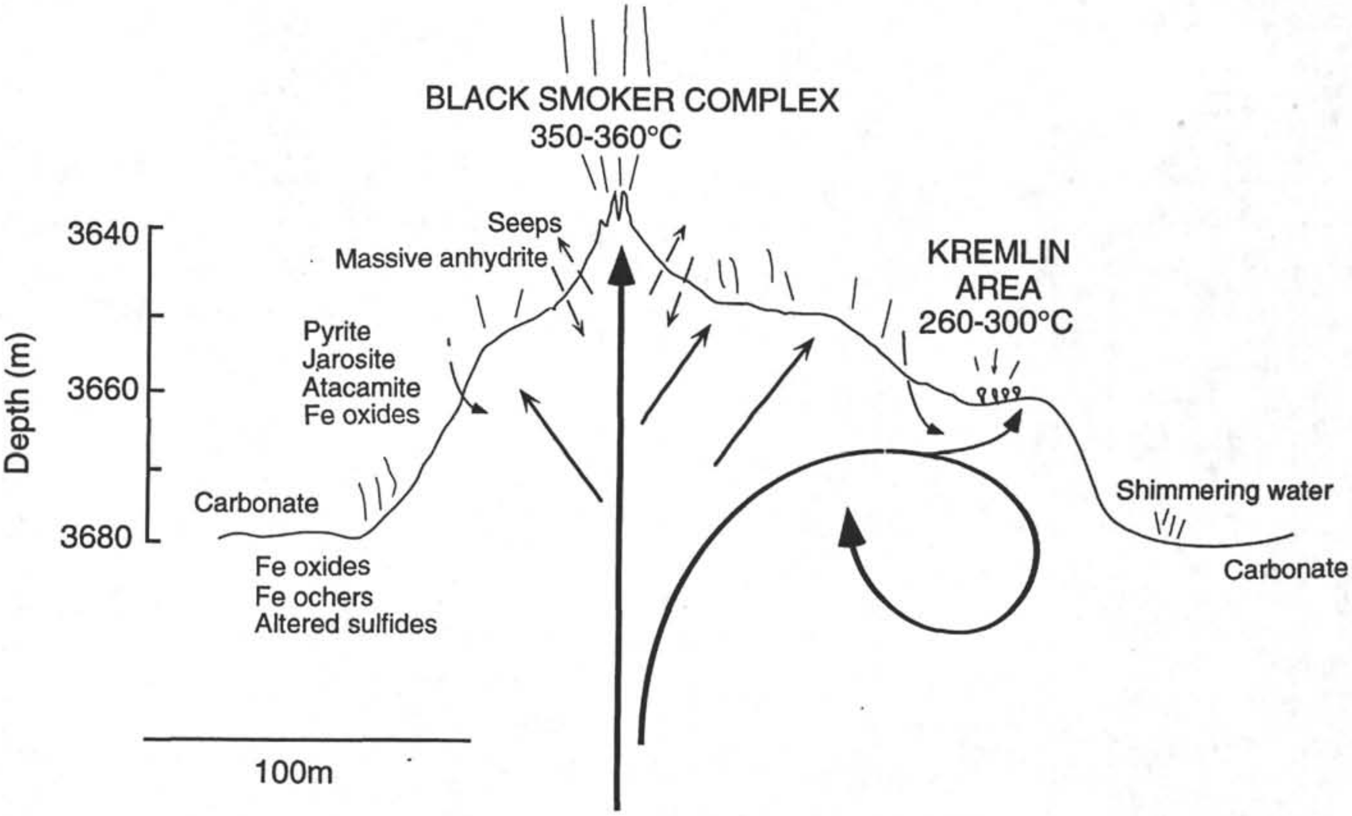

BLACK SMOKER COMPLEX
350-360°C
Seeps
Massive anhydrite
KREMLIN
AREA
260-300°C
3640
3660
3680
Depth (m)
Pyrite
Jarosite
Atacamite
Fe oxides
Carbonate
Fe oxides
Fe ochers
Altered sulfides
Shimmering water
Carbonate
100m

Figure 3

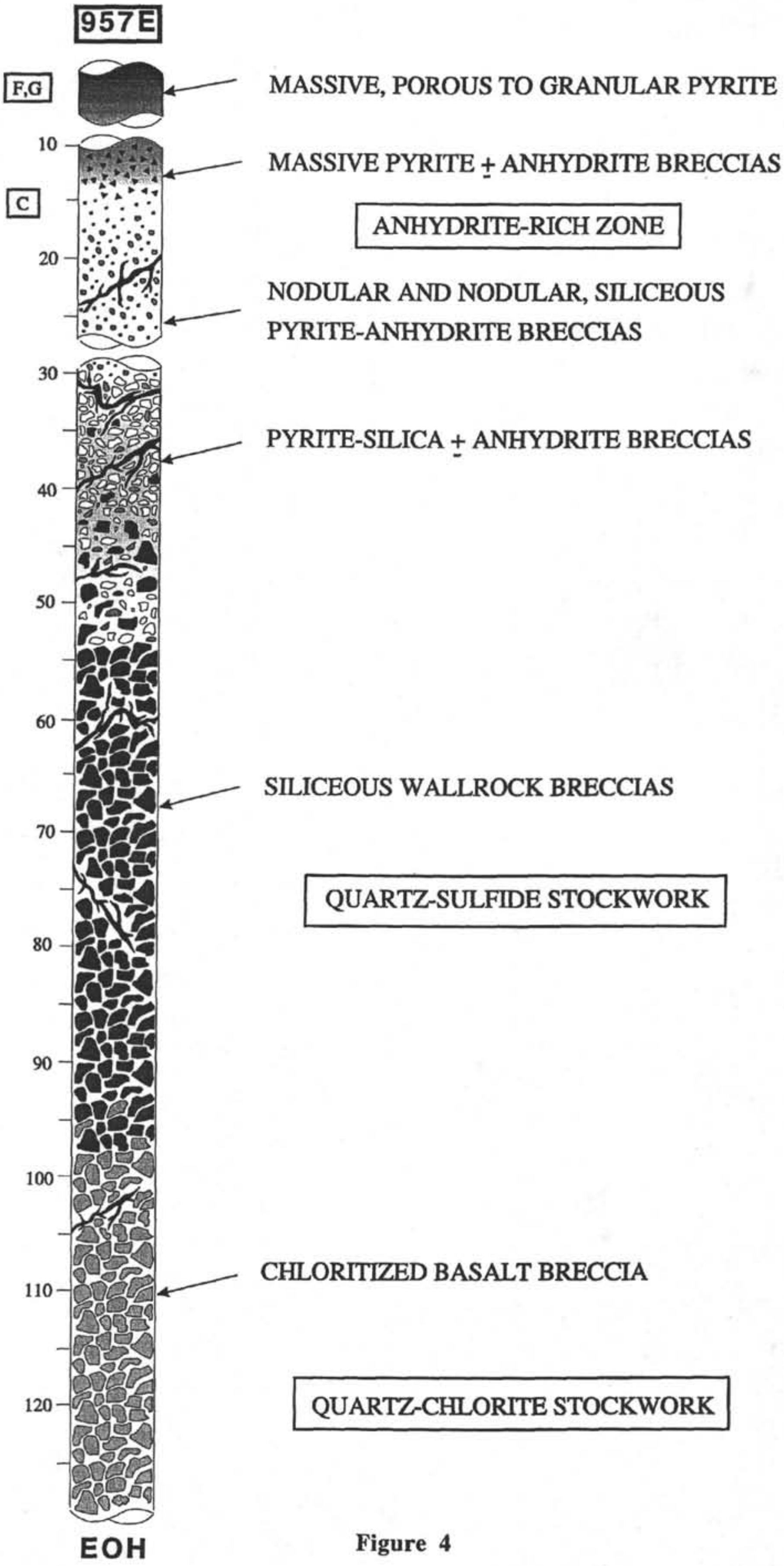

957E
F,G
C
10
20
30
40
50
60
70
80
90
100
110
120
EOH
MASSIVE, POROUS TO GRANULAR PYRITE
MASSIVE PYRITE ± ANHYDRITE BRECCIAS
ANHYDRITE-RICH ZONE
NODULAR AND NODULAR, SILICEOUS PYRITE-ANHYDRITE BRECCIAS
PYRITE-SILICA ± ANHYDRITE BRECCIAS
SILICEOUS WALLROCK BRECCIAS
QUARTZ-SULFIDE STOCKWORK
CHLORITIZED BASALT BRECCIA
QUARTZ-CHLORITE STOCKWORK

Figure 4

OPERATIONS REPORT

The ODP Operations and Engineering personnel aboard *JOIDES Resolution* for Leg 158 were:

Operations Manager:	Gene Pollard
Development Engineer:	Scott McGrath
Schlumberger Wireline Logging Engineer:	Richard Sammy
Special Tools Engineer:	Volker Boehm
LDEO Logging Technician:	Erich Scholz
JAMSTEC Engineering Observer:	Eigo Miyazaki

OVERVIEW

The TAG area had been extensively surveyed prior to the leg with submersible dives, Sea Beam and high-resolution deep-towed side-scan sonar bathymetric surveys (1990 and 1993), a photo mosaic (1994), and a 120-kHz side scan with co-registered bathymetry (July 1994). The following markers and sensor arrays have been deployed on and near the mound:

1. Three 60-m-high vertical temperature sensor arrays (GK-4 to -6) and a high-temperature probe were deployed in the Black Smoker Complex in August 1994.
2. A Japanese horizontal heat probe array (H-1 to -6) called "Daibutu," with eight cables up to 50 m long and a data logger, was installed in August 1994.
3. Two Japanese OBS's (HDJ-1,-2) failed acoustic recall.
4. Lettered markers (A to F) deployed by *Alvin* in 1993.
5. Funnel marker (No. 4) deployed by *Alvin* in 1993.
6. Markers (No. N-1, -3, -4) were deployed by *Shinkai* in August 1994.
7. ODP syntactic foam markers with stripes (No. 2, 5, 6) deployed in August 1994.
8. ODP Datasonics 354M commandable recall beacon (S/N 750) deployed in July 1994.
9. Other markers (No. 2, 3, 4, 5, 6, 7) deployed by *Alvin* in 1990.
10. British markers (AL, AJ, AF, AE, AA, AC, BX15, BX08, BX09) deployed in September 1994 by *Mir*.
11. British "Medusa" water sampler ("1,""2,""3") deployed in September 1995 by *Mir*. Medusa 1 and a gamma spectrometer were deployed near Diabutu.; Medusa 2 and 3 and DSPL camera were deployed near ODP marker "6."

A considerable operations and engineering effort and investment was required for Leg 158 because of the unknown drilling conditions, including the potential of low pH and high H_2S concentrations, and potential temperature extremes of 40°F (4°C) at the surface (downflow zone) to bottom-hole temperatures exceeding 750°F (400°C). Extensive cement testing was done at the Halliburton lab in Tulsa on experimental very high (differential) temperature retarders. Rock Bit Industries in Fort Worth performed extensive materials testing to extend rollercone bit seal and lubricant operating temperatures to prolong bit life. Two reentry cones, two hard-rock guide bases (HRB), and two CORKs were built, and rental hole openers, underreamers, and mud motors were obtained. High-temperature casing-hanger seals were developed to prevent annular flow behind the casing, a 16" HRB centralizer was developed to permit centralized coring, the first HRB CORK was developed, and a tapered drill collar was developed to reduce drill-collar failures when spudding in hard rock. ODP personnel took an H_2S safety training course, additional gas masks and detectors were ordered, and the shipboard detectors were serviced.

PORT CALL IN LAS PALMAS

ODP Leg 158 began with the first line ashore at Quaya La Luz Naciamiento in Las Palmas, Gran Canaria, at 0630 hr on 23 September. The SMP panel visited the rig. Departure was delayed two days because most of the sea-freight shipment, consisting of an ODP flatbed and container and three ODL containers, did not arrive until 1400 hr on 28 September. Colmek and Mesotech service calls were completed on the TV and sonar systems. The 2-G Co. serviced and performed maintenance on the cryomagnetometer. The lab stack core-splitting table was replaced. ODL replaced three crown bearings, changed the logging sheave in the derrick, replaced cementing and kelly hoses, and performed routine rig maintenance. Two ODL containers that were required for dry dock preparations were welded in place.

One sample box was taken from the Leg 157 air-freight shipment when it was positioned on the dock. The box was later found ripped open in a nearby dumpster. The last line was on board at 0800 hr on 29 September, and the *JOIDES Resolution* departed for TAG.

The shipboard clocks were retarded 1 hr on 25 September to match the daylight savings time (DST) change on Gran Canaria. In this report all times refer to ship time which remained the same for the entire leg (i.e., ship time = UTC + zero hr = College Station + 5 hr (or + 6 hr for daylight savings time). In this report, all depth measurements are based on drill-pipe measurements (DPM), which are referenced to the top of the dual elevator stool (DES) about 1 ft above the rig floor and designated by "m." Hole depths are given in meters below seafloor (mbsf), which are referenced to the mud line as determined visually, from the initial core recovery, or from bottom contact. "Mean sea level" (msl) references are not used unless otherwise indicated (see "depth" spreadsheet for m to msl corrections); however, the distance from sea level to the top of the DES depends on the variable ship's draft, which averages about 11.5 m.

LAS PALMAS TO TAG SITE 957

The 1614-nmi sea voyage from Las Palmas to the proposed TAG-2 area required 135 hr at an average speed of 11.96 kt. The weather was fair and clear, with air temperatures of 19° to 24°C, a 1-kt current, seas 1-2 ft, and a quartering 10-14-kt wind. The H_2S detectors and monitoring system were tested, the science party received H_2S training, and H_2S contingency plans were reviewed. A reentry cone was bolted together in the moonpool.

SITE 957

As part of the preparations for Leg 158, a beacon supplied by ODP (Datasonics 354M beacon, S/N 750, 15.5 kHz) was deployed 100 m east of the mound in August 1994. In September 1994 the Japanese *Shinkai* submersible deployed three ODP syntactic foam markers during a mapping dive. The *JOIDES Resolution* arrived at the GPS coordinates of the TAG site beacon at latitude 26°08.164'N, longitude 44°49.461'W, at 2230 hr on 4 October. The pre-positioned Datasonics 354M beacon (S/N 750, 15.5 kHz) was commanded but did not respond. A Datasonics 354M beacon (S/N 1240, 14.5 kHz) was deployed at 2336 hr on 4 October at 26°08.164'N, 44°49.408'W. The beacon landed about 280 m east of the mound; therefore, it is assumed that the beacon was dropped on a bad GPS fix. The ship moved 80 m south and 400 m west to 26°08.140'N, 44°49.525'W. A backup Datasonics 354M beacon (S/N 1245, 17.0 kHz) was dropped as a precaution at 0153 on 5 October. The beacon landed 81 m southeast of the drop point, and was about 100 m south of the mound as intended. A wiper pig was pumped to clean rust from the drill string off the mound. The VIT frame was run with the TV, sonar, VIT beacon, and a marker float. At 2214 hr on 5 October the survey proceeded northeast from the backup beacon drop point, and in 20 m the edge of the mound was encountered. The survey proceeded east of the Kremlin white smoker area to the northeast edge of the mound, and continued generally north-south and east-west until the Black Smoker Complex, Kremlin white smoker area, and numerous other features were clearly identified. Marker floats proved elusive to find; however, marker "A" was clearly identified on the eastern edge of the mound. At 2045 hr on 5 October, the VIT marker float "7C" was deployed at 26°08.217'N, 44°49.569'W, in a 3651-m water depth in the white smoker Kremlin area. On 6 October, *Alvin* marker "E" was identified about 10 m north of ODP marker "7C."*Alvin* marker "E" had been dropped on an earlier *Alvin* dive by Keir

Becker in the proposed TAG-2 area. At 2200 hr on 5 October a bottom-water sample was obtained near the Kremlin white smoker. The water sampler was positioned 0.5 m off bottom at 3650.5 m, and a good bottom-water sample was obtained.

The bit was positioned 10 m west of VIT marker "7C,"and at 0030 hr on 6 October a penetration/jet-in test was performed. The mound surface was at 3651.0 m. The bit penetrated 0.75 m with 5000-10000 lb WOB without circulation. The bit was jetted-in an additional 0.5 m in 10 min circulating at 200 gpm; however, the bit could not be washed below 1.25 mbsf with 300 gpm. The XCB core barrel was recovered with no recovery. The ship was moved 5 m west of ODP marker "7C," and a second penetration/jet-in test was performed. The mound surface was at 3652.0 m. The bit penetrated 0.5 m in 15 min with 5000-10000 lb WOB without circulation; however, the bit could not be washed below 0.5 mbsf with 500 gpm. The XCB core barrel was circulated clear.

Hole 957A (Proposed TAG-2 Area)

The objective of the hole was to obtain cores through the upper part of the mound and to determine hole conditions in preparation for a deeper cased hole. The ship was moved 2 m northwest of marker "7C," and Hole 957A (proposed TAG-2 area) was spudded at 0400 hr on 6 October at 26°08.196'N, 44°49.552'W. The mound surface was at 3653.2 m. A punch core was taken with the XCB core barrel and penetrated 2.0 mbsf with 5000-10000 lb WOB; however, the bit could not be washed below 2.0 mbsf without rotation while circulating at up to 200 gpm. XCB Cores 957A-1X to -3X were taken from 3653.2 to 3668.2 m (0 to 15.0 mbsf). Recovery was 0.25 m of broken heavy sulfide fragments. The operating parameters were: 5000-10000 lb WOB, 20-30 rpm, and 120 gpm. The formation was very hard from 2 to 5 mbsf, but 5 to 15.0 mbsf was very soft (cored 10 m in 20 min). The rotary stalled at 10 mbsf with 30000 overpull and 3 m fill on the connection. A 10-bbl bentonite mud pill was pumped with good effect. An APC core was attempted following Core 3X at 3668.2 m (15.0 mbsf) in an effort to recover some of the soft material; however, only a trace of pyrite sand was recovered, and there was no advancement. The TV was run to observe the hole,which appeared to be static. A slump was noted upslope of the hole, which might explain the tight hole incident.

Proposed TAG-2 Area (APC Attempt)

An APC core barrel was run to obtain a surface sample. *Alvin* marker "E" was found on the Kremlin white smoker about 10 m east of marker "7C." The bit was positioned 1 m from the white smoker mound surface at 3651.5 m. The APC core barrel did not penetrate the surface. Trapped pressure stroked out the APC core barrel downslope,which pushed the BHA aside and bent the barrel. The bit cleared the rotary table at 2400 hr on 6 October. There was no APC recovery, and therefore there is no hole designation.

Hole 957B (Proposed TAG-2 Area)

The objective of this hole was to obtain a section through the sulfide mound and penetrate the stockwork and footwall alteration zone to a depth of 500 m. The original operations plan was to run a reentry cone with three casing strings; however, the penetration/jet-in tests indicated that 0.5 to 2.0 m of sulfide sediment covered a hard, massive sulfide layer. It would be very difficult to wash in the 2+ m-long 26"-diameter transition pipe (even without casing) below the reentry cone. Water-depth measurements with the drill string indicated slopes of 10° to 30° in the Kremlin area; reentry cones were not designed to be used on a slope. A reentry cone had been bolted together in the moonpool on the sea voyage to TAG; however, it was removed, and an HRB was assembled. The HRB assembly was run with the following BHA: Reentry/logging bit, 9-7/8"stabilizer, 16" Dril-Quip running tool (with the CADA feature locked out), one stand of drill collars (DC), crossover, and two stands of 5-1/2" drill pipe. A 7-1/4" transition DC was not run due to a weak connection. The HRB was set down in the Kremlin white smoker area (proposed TAG-2 area) twice, but the slope exceeded 20°. The HRB was set down a third time on top of an active white smoker with a slope of about 15°. The running tool was torqued to 3000 ft-lb at neutral tension, where it spun into the release position; however, it would not come free. Additional torque was applied, but the tool had already rotated the required 3.5 turns. The intention was to move the base to a more level site; therefore, the tool was reengaged, requiring 12000 ft-lb of torque to initiate left-hand rotation. The HRB was repositioned and was nearly level; however, the tool would not release at up to 25000 ft-lb torque at various tensions. Rather than perform a string shot-release and risk dropping the HRB, it was pulled back to the surface, clearing the moonpool at 2315 hr on 8 October. A torque of 40000 ft-lb was required to break out the 16" D-Q running tool. No damage was noted to the CADA tool except that the torque-ring had slipped; therefore, the tool was rerun with the HRB.

At 1000 hr on 8 October, the HRB was reset in the Kremlin white smoker (proposed TAG-2 area) between ODP marker "5" and *Alvin* marker "E." ODP marker "7C" was near Hole 957A about 10 m west of marker "E." The HRB was set without problems on an 8° slope in a 3655.0-m water depth at 1000 hr on 8 October. The running tool was pulled and disassembled. The lugs that lock out the drill-ahead feature were badly brinelled. The actuating ring and pins were brinelled. An RCB coring BHA was run, and Hole 957B (proposed TAG-2 area) was spudded at 0230 hr on 9 October at 26°08.193'N, 44°49.546'W. RCB Cores 957B-1R to -4R were taken from 3655.0 to 3684.6 m (0 to 29.6 mbsf) with 29.6 m cored and 1.62 m recovered (5.5% recovery). High torque to 400 amps and 4 m of hole fill were noted at 29.6 m after the connection, and the hole could not be cleaned out in 2 hr of washing with two 20-barrel-high viscosity bentonite mud sweeps. The core barrel was recovered with 0.01 m recovery, which was archived as bit sample 957B-5B from 0 to 29.6 mbsf. Core 4R recovered relatively fresh basalt and red clay with no evidence of hydrothermal alteration; therefore, the alteration zone might not be below Hole 957B. The bit was pulled out of the HRB at 1630 hr on 9 October to survey for a better HRB site.

Moving the HRB

The area northwest of the proposed TAG-2 area was surveyed, and an alternate drill site was located. Several penetration tests with the 9-7/8" RCB bit identified an area of 0.5-m penetration with 10,000 lb WOB near the Black Smoker Complex. Marker "7D" was deployed with the VIT at 26°08.225'N, 44°49.565'W, in a water depth of 3648 m. The RCB bit with centering bushing was pulled out, and an HRB running-tool assembly was run as follows: 16" Dril-Quip running tool, 17-1/2" stabilizer, reentry/logging bit. The ship was positioned on the beacon/VIT offset coordinates, and Hole 957B was reentered in 15 min. The HRB had muddy water in the cone, but no flow in/out of hole; therefore, it was not plugged. The HRB was engaged easily, picked up, and moved to the proposed TAG-1 area. The HRB was landed three times with an angle exceeding 20° and picked back up. The HRB was finally landed about 15 m southeast of the Black Smoker Complex. The angle was 8°, and the water depth was 3648 m. The HRB was released easily and checked, and the area around it was surveyed. The HRB was about 8 m south of marker "7D." The running tool was on deck at 1630 hr 10 October.

Hole 957C (Proposed TAG-1 Area)

The initial objective was to core deep enough to get a good casing seat. The subs required for the motor driven core barrel (MDCB) were included in the normal APC/XCB BHA in case recovery was still poor in what was thought to be the more silicified portion of the mound. The MDCB was spaced out and function tested, and the BHA was run with an 11-7/16" RBI S86F bit (S/N 478454). After a 2-hr TV survey, a good WSTP bottom-water sample was taken up-current from the HRB in the proposed TAG-1 area; however, the temperature reading was not good. There appeared to be black smoke emanating from beneath the HRB, and the HRB was initially obscured by black smoke coming through the reentry cone and out from under the base. The HRB was reentered, and Hole 957C was spudded at 1000 hr on 11 October in a water depth of 3648.0 m at 26°08.226'N, 44°49.555'W. The HRB angle was about 6°. XCB Cores 957C-1X to -2X were taken from 3648.0 to 3658.5 m (0 to 10.5 mbsf) with 10.5 m cored but no recovery. Fine sulfide grit was noted in the 8- and 10-finger core catchers. The MDCB core barrel was dropped with a piloted diamond-impregnated MDCB bit, and Core 957C-3N was taken from 3658.5 to 3663.0 m (10.5 to 15.0 mbsf) with 4.5 m cored but no recovery. Fine sulfide grit was noted again in the core catcher. An XCB core barrel was run as a wash barrel to clean out 4 m of fill on bottom. The 11-7/16" hole was reamed from 3658.0 to 3663.2 m with high torque. The pipe stuck and was worked free. The hole was circulated and conditioned by reaming back to bottom with 5 m of fill. A 20-bbl high-viscosity mud pill was circulated. Wash barrel 957C-4W recovered two pieces (0.12 m) of friable anhydrite-cemented sulfides. A 50-bbl mud pill was circulated, and the hole was cleaned. Core 957C-5N was taken from 3663.0 to 3667.5 m (15.0-19.5 mbsf) with 0.50 m recovery. XCB wash barrel 957C-6W was reamed in from 3663.2 to 3667.5 m (19.5 mbsf). The bit was reamed to bottom (in 5 m of fill), and a 30-bbl high-viscosity mud pill was circulated. Recovery was 0.02 m. MDCB Core 957C-7N from 3667.5 to 3672.0 m (19.5-24.0 mbsf) was advanced 4.5 m and recovered 3.60 of massive sulfide and anhydrite. XCB wash barrel 957C-8W was run to condition the hole, and recovery was 0.05 m. An MDCB barrel was dropped, but the tool never seated and the piston stuck; therefore, there was no advance and no recovery. An XCB core (957C-9X) was taken from 3672.0 to 3676.7 m (24.0 to 28.7 mbsf), with 4.7 m cored and 0.06 m recovered (core-catcher jammed). MDCB Core 957C-10N was taken from 3676.7 to 3678.7 m (28.7 to 30.7 mbsf) with 2.0 m advance and 0.15 m recovery (the core-catcher jammed). A WSTP was run into 3676.6 m (28.6 mbsf), and a good water sample was obtained with a bottom temperature of 15°C. The hole was reamed from 28.7 to 30.7 mbsf. MDCB Core 957C-11N was taken from 3678.7 to 3683.2 m (30.7 to 35.2 mbsf) and advanced 4.5 m with 4.07 m recovered. A good casing seat had been found; therefore, coring was terminated in preparation for opening the hole and setting casing.

The bit was pulled up to 3.5 mbsf, and preparations were made to take a seafloor APC and pull out for casing. The HRB was observed to have an angle of about 18°-20° (the original angle was about 6°), and some seafloor scour was noted. There was no obvious bending or damage to the BHA or centering bushing. Hole conditions were good; therefore, a decision was made to continue coring. MDCB Core 957C-13N was taken from 3685.2 to 3688.2 m (37.5 to 40.2 mbsf) with 3.0 m advancement and 1.69 m recovery. A Totco survey showed the average hole angle to be 6-3/4°. If the HRB remained stable, the plan was to core as deep as 70 mbsf (top of DC) and attempt to run 13-3/8" casing with a 17-1/2" underreamer. An XCB core barrel was run with a center bit, and 4 m of fill was reamed out. The core barrel was stuck while being pulled out at 494 m when the coring wireline operator made a quick stop to re-spool the wireline and the XCB dogs set. The barrel was freed by jarring down. MDCB cores 957C-12N to 16N were taken from 3083.2 to 3697.2 m (35.2 to 49.2 mbsf) with 14.0 m advancement and 13.31 m recovery in friable granular anhydrite. Recovery averaged 64% (using the "advance by recovery" method in some cases); however, apparent recovery was enhanced when the granular pyrite core fell apart in handling. Bit advancement was based on the apparent stroke (wear on a paint mark) on the MDCB kelly and recovery. XCB core barrels with center bits were dropped between MDCB core runs to condition the bottom of the hole for diamond coring. The bit stroked at 600 psi. Thruster nozzle sizes ranging from 10/11 to 12/12 were used to provide 4000 to 8000 lb WOB, and bit-nozzle sizes from 2/3 to 3/3 were used to provide about 21 to 28 gpm through the bit. Circulating pressure was about 1500 psi at a constant 38 spm (190 gpm). Calculated pressures were about 350 psi lower than actual pressures. Bit speed was 260 to 270 rpm. The drill string was rotated at 20 rpm with 150 amps of torque to monitor hole conditions. Most 4-m cores were cut in 20 to 25 min. WOB was reduced when pressures increased, indicating a motor stall. End-of-stroke pressure drops were sometimes evident. The 3-3/4" piloted diamond-impregnated bits were used for most of the MDCB cores. Repairs were made to the upper section of the MDCB following Core 12N. An XCB wash barrel with a center bit was dropped following Core 12N, but it stuck and the bit plugged. Attempts to retrieve the stuck wash barrel were unsuccessful, and the bit was pulled to the HRB throat to determine if the HRB could be reentered. The HRB appeared to have an angle in excess of 20°; therefore, an attempt was made to reenter (to verify the ability to do so). The HRB tipped up on its edge; therefore, the BHA was picked up to allow the HRB to set back down. An attempt was made to move the ship to improve the cone angle for reentry: however, the bit slid to the edge of the cone and the HRB fell over. The HRB was lying on its side about 2 m from Hole

957C. Circulation under the HRB appears to have undercut the legs. The BHA was relatively undamaged, but the center bit would not retract through the SBDC due to a connection that had been swollen by over torque (when the MDCB hex froze). The bit cleared the rotary table at 1245 hr on 14 October. The bit shirttail was badly worn, which had caused the seals to fail and lock three of cones. The hole penetrated through the mound into the stockwork zone. Most of the material recovered was a pyrite, anhydrite, and silica breccia.

Hole 957D (Proposed TAG-1 Area)

The repeated instability of the HRB when spudding with even a moderate 8° angle forced reconsideration of a means to run a casing string with a reentry cone and a Dril-Quip casing hanger system for the CORK. A drill-ahead casing system could be run with an underreamer to advance the casing and a reentry cone for the hanger system. The reentry cone was built during the pipe trip out. The horizontal top rim is striped, and "ODP 957" is in the black panel. The heavy sulfides had been difficult to clean out even in smaller holes with high annular velocities; therefore, it was not considered advisable to attempt to underream ahead of a 16" casing in a 22" hole. To improve chances for success in running a surface casing, 27.97 m (two joints) of 13-3/8" casing was run on a 16" Dril-Quip casing hanger and latched into the transition pipe (reentry cone). A 12-1/4" Smith Q7J 3-cone drill bit (S/N BH46684), a 17-1/2" Servco series 11700 underreamer, a Drilex mud motor, and two 8-1/4" DC (31.36 m) were run inside the 13-3/8" casing on the 16" Dril-Quip running tool. The tools were function tested.

The ship was positioned on beacon offset coordinates twice before a suitable water depth was located at 3648.5 m. Hole 957D was spudded at 0730 hr on 15 October about 10 m from Hole 957C. The 13-3/8" casing and reentry cone were drilled ahead with a 12-1/4" bit and a 17-1/2" underreamer from 3648.5 to 3678.0 m (0-29.5 mbsf) in 4.5 hr. The CADA tool was rotated 3.5 turns but failed to release. The tool was rotated back to the engaged position, the ship was moved off the mound in case the casing was dropped, and the assembly was pulled. The reentry cone was in the moonpool at 2230 hr 15 October. The initial attempt to release the running tool in the moonpool was not successful because the casing hanger was rotating on the hanger lock down ring in the transition pipe. The ring was released, and the running tool/hanger/casing was pulled to the rotary, where a second release attempt was unsuccessful. The running tool was finally released in the rotary after the top was removed, and the sulfide grit was washed out of the area behind the split retainer ring so it could retract. The tool was packed internally with sulfide grit. One bottom o-ring had evidently failed in the running tool, allowing fine sulfide sand to enter the tool and lock it up.

Hole 957E (Proposed TAG-1 Area)

The 16" Dril-Quip running tool was cleaned and rebuilt, the bottom seals were tested, and the top was sealed with Aqualube. The mud motor and underreamer were function tested. There was negligible wear on the bit and underreamer. The bolt holes in the transition pipe were closed, and holes were cut in the reentry-cone base to ensure the flow of cuttings up the annulus. Holes in the cone base were patched to reduce the flow of cuttings back into the hanger. The running tool was function tested and torqued to 2,500 ft-lb excess left-hand torque to counter left-hand mud-motor rotation at stall-out. The same casing and BHA were rerun. The ship was positioned three times on beacon offset coordinates (positioning beacon to ship and ship to VIT beacon) before a suitable water depth was located at 3648.6 m at 2245 hr on 16 October. The motor stalled out when an attempt was made to drill ahead with the 13-3/8" casing. When the bit was picked up off bottom to free the motor, back torque apparently caused the reentry cone to spin to the left and released the running tool. An attempt was made to drill down a 12-1/4" hole using low circulation to allow the underreamer arms to close (so the running tool could be reset). The motor continually stalled when attempting to advance the underreamer, and the reentry cone was picked up off bottom with the pump on (which left the casing weight supported on the open underreamer arms). A piston locks the arms in the open position, and the weight could not be removed by drilling ahead. The ship was moved off the mound, and the assembly was tripped. The reentry cone and casing were riding on the underreamer arms; therefore, the reentry cone was set on the moonpool doors, and the underreamer was lowered 2 m allowing the arms to close. The BHA was retrieved, and the bit cleared the rotary at 0530 hr on 17 October. No damage was noted to the tools or casing. The running tool was rerun with a new underreamer, new mud motor, and the same bit. The tools were function tested. The reentry cone transition pipe was modified with two angle-iron spikes on the side and four bars on the bottom (like a castle nut) to bite into the seafloor to stop rotation. The ship was moved back over the mound, positioned on beacon offset coordinates, and moved once.

Hole 957E (proposed TAG-1 area) was spudded at 1800 hr on 17 October in a water depth of 3646.0 m within 5-10 m of Hole 957C. A hard layer from 0 to 8 m and 12 to 18 m reduced the ROP from 3.2 to 2 m/hr, and drilling was much slower than in Hole 957D (8 to 12 m/hr). The new underreamer had mill tooth cones (instead of tungsten carbide insert cones); however, the cones had moderate wear and would not explain the slow ROP. It is assumed that the massive sulfides were harder in Hole 957E than in Hole 957D. The 13-3/8" casing was drilled ahead with the 17-1/2" underreamer and 12-1/4"bit to 3677.3 m in 8 hr. The 13-3/8" casing shoe was at 3675.10 m (29.1 mbsf), and the top of the cone was at 3643.6 m. An attempt was made to release the reentry cone; however, the 16" D-Q running tool rotated but did not come free. The pipe and casing became stuck and could not be freed with 50,000 lb overpull. The mud motor was restarted in tight hole; however, the reentry cone was rotating, indicating that the casing was being carried on the (then open) underreamer arms. The casing was worked back to 3674 m with the underreamer arms open. The hole was reamed back to 3677.3 m TD with high torque. Circulation was reduced to close the underreamer arms and advance the 12-1/4" bit. The running tool popped out of the reentry cone throat, the underreaming BHA was free, and the reentry cone and 13-3/8" casing were set. The underreaming BHA was pulled. The underreamer and bit had some shirttail wear but were reusable. The 16" D-Q running tool could not be detorqued on the rig floor. The torque stop ring was cut off, and the tool was disassembled. Sulfide grit had packed in the area behind the split retainer ring so it could not retract, and marks on the running-tool body indicated that it was in a bind in the hanger due to a ship/cone misalignment. The support lugs were sheared in half, and the split ring was also bent. The bit cleared the rotary at 1215 hr 18 October. Heavy shirttail wear was noted on the bit and underreamer.

The 12-1/4" bit was rerun without nozzles, and 5 m of fill was tagged at 3632 m. The hole was cleaned out to TD, and cemented with 18 sacks of 16.0 ppg Class "G"cement with 50% SSA-1 (silica flour). The 10-m-high plug of cement was set from 1 m below the casing shoe. After circulating the hanger area for 2 hr, a 4-hr TV survey was conducted while waiting on cement. The hole was reentered, and the bit tagged cement at 3668.5 m (6.6 m above the shoe). Two meters of soft cement and 5 m of hard cement were drilled, and an additional 0.2 m of new hole was drilled to 3677.5 m to prepare for RCB coring. An RCB BHA was run with a 9-7/8" PDC bit in an effort to increase RCB recovery. RCB Cores 957E-1R to -2R were cut from 3677.5 to 3687.7 m (31.5-41.7 mbsf) with 10.2 m cored and 0.50 m recovered (5% recovery). After the connection, the pipe stuck while circulating a 30-bbl high-viscosity mud sweep. The pipe was worked at up to 120,000 lb overpull, and the rotary was stalled at 700 amps. The pipe came free in 15 min; however, the PDC coring was canceled because of the poor recovery and the stuck pipe problem with a near gauge PDC bit. The bit cleared the rotary at 1445 hr on 20 October.

Hole 957F (Proposed TAG-1 Area)

Good core recovery in the mound had been achieved only with the MDCB, but a critical upper 0 to 20 mbsf section had been missed at the proposed TAG-1 and TAG-2 areas. It was decided that, before deepening Hole 957E, the MDCB should first be used to get the upper section cores in both areas. An APC/XCB/MDCB BHA was run, and Hole 957F was spudded at 2345 hr on 20 October in a 3648.6-m water depth. The hole is between Holes 957E and 957C (about 4 m from both). The bit penetrated from 3648.6 to 3649.6 m (0-1.0 mbsf) when it was set on the seafloor to take the first MDCB core. MDCB Cores 957F-1N to -2N were taken from 3649.6 to 3654.1 m (1.0-10.0 mbsf) with 9.0 m cored and 0.95 m recovered. The core barrel stuck, and the bit was pulled clear of the seafloor at 0500 hr on 21 October. The bit moved laterally when the MDCB came free, and the barrel was bent.

Hole 957G (Proposed TAG-1 Area)

Another hole was required to complete the upper section; therefore, Hole 957G was spudded at 0715 hr on 21 October about 2 m north of Hole 957C (HRB) and 2 m south of Hole 957F. The bit was drilled in from 3646.0 to 3658.0 m (0 to 12.0 mbsf). MDCB cores were taken from 957G-1N to 3N, 3658.0-3671.5 m (12.0 to 25.5 mbsf), with 13.5 m cored and 1.12 m recovered. The hole was reamed with a center bit between MDCB runs to provide a clean bottom for the diamond-impregnated bit on the MDCB. Following Core 957G-2N, the seals on the locking piston assembly were replaced and pyrite was washed out of the thruster barrel. The pipe stuck at 3667 m (21 mbsf) following Core 957G-3N. The pipe was worked to 700,000 lb (440,000 lb string wt and 260,000 lb overpull) without success. The rotary stalled with 700 amps (17,000 ft-lb of torque). Two 30-bbl high-viscosity mud sweeps were circulated, which reduced the circulating pressure moderately. The McCullough jars could not be used because almost the entire BHA was unsupported. There was no room to retrieve the MDCB (to improve circulation) through the top of the string, and the tool joint was below the rotary. The tool joint was eventually worked to the floor with 700,000 lb of tension and set in the 500-ton elevators. The MDCB was retrieved and circulation was increased to 1000 gpm. The pipe was finally worked free at 0015 hr on 22 October. The seafloor was cleared at 0030 hr, and the bit cleared the rotary at 0700 hr. The MDCB was function tested to determine its availability for further use; however, it would not stroke out and was laid down to work on the thruster section. The BHA was inspected (no problems), and the packing gland nut on the jars was tightened.

Return to Proposed TAG-1 Area (Hole 957E)

Based on the poor performance of the MDCB in coring the shallow portion of the mound, and the need to work on the core barrel, it was decided to return to RCB coring. An RCB BHA was run with a 9-7/8" RBI C-7 (S/N BF844), and Hole 957E was reentered in 45 min at 2230 hr on 22 October. One meter of fill was cleaned out, and RCB Cores 957E-3R to -5R were taken from 3687.7 to 3709.3 m (41.7 to 63.3 mbsf) with 21.6 m cored and 0.56 m recovered. The two hard and medium formation fingered core catchers were jammed with pyrite-silica breccias and siliceous wall-rock fragments to 3 cm. Coring parameters were 15,000 lb WOB at 30-70 rpm with 150 amps torque, circulating 180 gpm at 500 psi. The pipe stuck while retrieving core barrel 5R. The bit was at 58 mbsf, and the pipe was worked to 240,000 lb overpull. The rotary stalled at 700 amps (18,000 ft-lb torque). High-viscosity mud sweeps were pumped. The McCullough jars were used for 9 hr to hit ±200 blows at 150,000-180,000 lb (200,000 lb maximum) on the BHA. The BHA was moving at about 0.5 m/hr; however, the pressure increased from 700 to 1700 psi at 650 gpm and progress slowed. A total of 260 bbl of very high viscosity mud sweeps and 30 bbl of 13.2-ppg mud were circulated to clear out the heavy sulfide cuttings. Progress slowed, and the pipe was worked to 3700 m (where there was a tool joint in the rotary). Preparations were made to sever the BHA, and the pipe was set in the 500-ton elevators. While laying out excess drill pipe, the circulating press decreased, and the pipe came free. The pipe was pulled to inspect the jars and upper unsupported BHA. The seafloor was cleared at 2015 hr on 23 October. The inspection revealed no problems, and the jars were in excellent shape. The bit was changed because one cone appeared to be locked; however, later inspection found a broken tooth lodged between the cone and core guide. A total of 30.75 hr was lost in the stuck-pipe incident.

A decision was made to continue coring in spite of the hole problems, and Hole 957E was reentered at 0930 hr on 24 October. About 7 m of fill was cleaned out to 3709.2 m TD. RCB Cores 957E-6R to -8R were taken from 3709.3 to 3723.8 m (63.3 to 77.8 mbsf) with 14.5 m cored and 0.68 m recovered. Coring parameters were 12,000-15,000 lb WOB at 60 to 50 rpm with 150 amps torque, circulating 400 gpm at 800 psi. A precautionary short trip was made into the casing shoe to allow small cobbles and loose material from the walls to fall below the bit. About 3 m of fill was encountered on bottom. RCB Core 957E-13R was taken from 3723.8 to 3747.5 m (77.8 to 101.5 mbsf) with 23.7 m cored and 0.84 m recovered. While retrieving Core 13R at 0800 hr on 25 October, the pipe stuck with the bit 5 m off bottom, and the rotary stalled at 700 amps.

Two 30 bbl sepiolite sweeps were pumped, rotation was restored, and the pipe was reamed upward to 3732 m. A wiper trip was made to the casing shoe, and 1.5 m of fill was encountered on bottom. The scientific party elected not to set casing despite the stuck-pipe problems because the object was to get a deep penetration. RCB Cores 957E-14R to -18R were taken from 3747.5 to 3771.7 m (101.5 to 125.7 mbsf) with 24.2 m cored and 1.45 m recovered. Although recovery was low, the sequence included massive granular pyrite, pyrite-silica breccias, and silicified and chloritized basalt breccias.

The pipe stuck at 0200 hr on 26 October with the bit at 3764 m while dropping the next core barrel. The jars could not be set (evidently stuck above the jars), the rotary stalled, and the hole was packing off. Rotation was reestablished by bumping down, and two 50-bbl high viscosity mud sweeps were circulated. The bit was pulled to 3752.9 m with 240,000 lb overpull, and a single was laid out. The pipe was worked with up to 240,000 lb overpull, and numerous mud sweeps were circulated; however, the hole had evidently fallen in above the jars. No progress was being made; therefore, a decision was made to attempt to sever the pipe at the bit to salvage a loggable 77-m hole. A stop collar was welded on the outside of the charge to position it exactly. The severing tool was fired in the bit sub at 3751 m at 0700 hr on 27 October. The pipe did not come free, and the sinker bars stuck at 3722 m. The weak point in the head was pulled out at 0800 hr, leaving the only two 1-1/16" sinker bars and a collar locator tool in the hole. The wireline tools may have been blown up the hole because of the stop collar and close proximity to a stuck and packed-off bit. A second severing charge was shot in the bottom joint of 5-1/2"transition pipe at 3660.6 m. The pipe had 60,000 lb overpull and 200 amps torque, but it did not part. The torque was increased to 400 amps, and the pipe parted at 1245 hr. The severed pipe was on deck at 2145 hr on 27 October. A total of 43.75 hr of leg time was lost in addition to $49,275 worth of drilling tools and $8,400 worth of Schlumberger tools.

Hole 957H (Proposed TAG-2 Area)

A decision was made to drill the shallow holes necessary to complete the leg objectives in the near-surface part of the hydrothermal mound before attempting another deep hole. The object of the hole was to obtain a detailed section of the mound in the Kremlin area, where the discharging fluid chemistries are distinct from black smokers. An SBDC with MDCB subs and an 11-7/16" Security S86F bit (S/N 478543) were picked up to test the MDCB, which stroked out and rotated properly. After a short survey, Hole 957H was spudded at 0830 hr on 28 October in the proposed TAG-2 area (Kremlin white smoker area) within 8 m of Holes 957A and 957B. The seafloor was at 3655.0 m, and there was no bit penetration when it contacted bottom. An 11-7/16" hole was drilled from 3655.0 to 3663.6 m (0 to 8.6 mbsf) with a center bit. MDCB Core 957H-1N to -2N 3663.7-3672.7 m (8.7-17.7 mbsf) cored 9.0 m, and 0.84 m was recovered. Tight hole was encountered at 17.7 mbsf after a connection. MDCB Core 957H-3N was taken from 3672.7 to 3681.7 m (17.7-26.7 mbsf) with 9.0 m cored and 0.81 m recovered. Core 4N had no recovery. The polypak seals were changed in the MDCB, and it was dropped again. The MDCB had the wrong pressure when it landed; therefore, it was retrieved. A missing shuttle valve was replaced, and the MDCB was rerun.

MDCB Cores 957H-5N to -8N were taken from 3681.7 to 3699.7 m (26.7 to 44.7 mbsf) with 18.0 m cored and 3.22 m recovered. A precautionary wiper trip was taken following Core 6N from 3690.7 to 3661.7 m, and 1 m of soft fill was found. MDCB core barrels were dropped twice, but attempts to core were unsuccessful because the drill string could not be worked to bottom. Mud sweeps were not effective in cleaning out a constant 3 to 4 m of soft fill. Continuous pumping was required to keep the string relatively free; therefore, it was not possible to core with the MDCB. XCB Core 957H-9X was taken from 3699.7 to 3709.5 m (44.7-54.5 mbsf) with 9.89 m cored and 0.14 m recovered. The hole was abandoned due to hole instability. The VIT was run to determine Hole 957H coordinates, and to survey for a site in the proposed TAG-4 area. An attempt to drop a marker was unsuccessful because the marker would not release (a motor connection pulled apart).

Hole 957I (Proposed TAG-4 Area)

The Diabutu temperature probes were in the proposed TAG-4 area west of the black smoker mound about 20 m northwest of their expected location. A small terrace to the west of the Black Smoker Complex was selected with the objective of recovering a section through the sulfides in an area of low conductive heat flow. After a short TV survey, the bit was set down in 3645 m water depth at 1520 hr on 30 October to spud Hole 957I. The site was on a slope in chimney rubble. An 11-7/16"hole was drilled from 3645.0 to 3654.0 in 2.75 hr. The formation was very hard and unstable with high torque and pressure from debris falling in from upslope. MDCB Core 957I-1N was taken from 3654.0 to 3658.5 m (9.0-13.5 mbsf) with 4.5 m cored and 0.77 m recovered. A center bit was run to clean out the 4.5 m advance to 3658.5 m; however, the XCB shoe and extension sub were destroyed, and the hole was junked. The center bit had gauge wear from the very hard and abrasive massive sulfide boulders. The hole could not be cleaned out with mud sweeps. The 11-7/16" Security S86F bit (S/N 478543) was pulled for examination after 3 rotating hr and had heavy gauge wear and shirttail wear, with the seals exposed on all 4 cones.

Hole 957J (Proposed TAG-4 Area)

An 11-7/16" RBI C-4 bit was run, and the area northwest of the black smoker in the proposed TAG-4 area was surveyed. At 2100 on 31 October the seafloor was tagged at 3647.0 m to spud Hole 957J (proposed TAG-4 area). The GPS location of Hole 957J was 26°08.238'N, 44°49.590'W. A force 8 storm had moved in with rain and wind to 35-43 kt (50 kt gusts), seas 8 ft, swell 12 ft, pitch and roll 3°, and heave 2-3 m. When the bit set down on the steep slope at the base of the chimney it hit very hard (at least 40,000 lb) and slid down and sideways before heave compensation reduced the pounding. It is probable that the main bit and XCB shoe were damaged in that incident. XCB Core 957J-1X was taken from 3647.0 to 3656.0 m (0-9.0 mbsf) with 9.0 m cored and 0.08 m recovered. The formation was hard red and gray chert, and the XCB shoe was destroyed. The hole was falling in, and the core barrel could not be retrieved. The hole could not be cleaned out, and Hole 957J was abandoned at 0030 hr on 1 November.

Hole 957K (Proposed TAG-4 Area)

Hole 957K (proposed TAG-4 area) was spudded in 20 m west of the black smoker at 0415 hr on 1 November at 26°08.239'N, 44°49.583'W. The seafloor was at a depth of 3644.0 m. XCB Core 957K-1X was taken from 3644.0 to 3654.0 m (0-9.0 mbsf) with 0.28 m recovered. The XCB shoe was destroyed. The hole was unstable and falling in. The hole was cleaned out, and mud sweeps were circulated. MDCB Core 957K-2N was taken from 3654.0 to 3658.5 m (9.0-13.5 mbsf) with 0.40 m recovered. The MDCB barrel had some bit tooth marks, which inferred that the bit was pinching in and failing. The hole was cleaned out four times, and high-viscosity mud sweeps were circulated; however, 3 m of fill remained, and MDCB coring could not be continued. XCB Core 957K-3X was taken from 3658.5 to 3664.0 m (13.5-19.0 mbsf) with 0.31 m recovered. The XCB shoe was destroyed, and the sub had bit tooth drag marks, implying bit failure. The formation was massive granular pyrite and sulfides. The bit cleared the seafloor at 2245 hr on 1 November.

A survey was conducted to locate a site for a deep cased hole near the proposed TAG-1 area and verify beacon offset coordinates. The bit cleared the rotary at 0900 hr on 2 November. The 11-

7/16" RBI C-4 bit had lost all 4 legs (welds failed), had severe wear on the body, and the pads were worn off completely. The failure is attributed to the very hard chert and probable damage sustained when the bit pounded bottom when spudding Hole 957J.

Hole 957L (Proposed TAG-1 Area)

Hole 957L was a final attempt to penetrate deep into the stockwork zone and produce a loggable hole by drilling without coring through the upper unstable part of the mound. The area close to Hole 957E was chosen because the stratigraphy of the mound was known, based on offset holes. A reentry cone was moved to the moonpool, and one joint of 16" casing was run with a 13-3/8" adapter, a 16" pup joint, and a 16" D-Q hanger. The 16" D-Q running tool was made up, and the casing was landed in the reentry cone. The Drilex mud motor, 17-1/2" Servco Series 11700 Underreamer, and 14-3/4" Smith 4JS 3-cone drill bit (S/N LZ3045), were function tested and run inside the casing on the running tool. Straps were welded to the bit and underreamer to prevent the connections from breaking if the motor stalled. The running tool was torqued to 2000 ft-lb excess left-hand torque to counter the left-hand rotation of a stalled mud motor. The horizontal top surface of the cone is plain (the reentry cone on Hole 957E is striped on top), and there is no writing inside.

Hole 957L was spudded at 0045 hr on 3 November. The 16" casing was drilled in from 3645.0 to 3664.5 m (0-19.5 mbsf) with the Drilex mud motor, 17-1/2" underreamer, and 14-3/4" bit. The top-drive rotary was left unlocked, and the left-hand mud-motor torque rotated the casing at about 6 rpm counterclockwise. The rotary required 600 amps counter torque to stop cone rotation. The reentry cone was landed on the seafloor at 3645.0 m. Hole 957L is 5 m west-northwest of Hole 957C and 10 m south of Hole 957E. Four hours was spent attempting to release the running tool with up to 25,000 ft-lb of torque. When the running tool finally released, it fell on the open underreamer arms. Additional rat hole was made with the bit and underreamer using the mud motor, and then the pump rate was reduced to 25 gpm to close the underreamer arms while operating the mud motor and bit. The bit and underreamer assembly were pulled clear of the seafloor at 1015 hr. The top of the reentry cone is at 3642.6 m, the seafloor 3645.0 m, the 13-3/8" adapter 3648.0 m (3.0 mbsf), the 16" shoe 3661.4 m (16.4 mbsf), and TD 3664.5 m (19.5 mbsf). The bit cleared the rotary at 1645 hr. The bit and underreamer showed minor abrasion. The 16" running tool was detorqued (normal torque) and laid out. It was packed with sulfide grit between the actuating pins and split ring, but was completely retracted. The lockout support lugs were brinelled into the inner body again. The torque weldment could not be removed from the inner body, and the two pieces were left together. The tool was reassembled and used to retrieve the HRB from Hole 957D at the end of the leg.

9-7/8" Hole

A 9-7/8" HTC J55R 3-cone drill bit (S/N B10HC) was run in an attempt to drill a hole to 100 m for logging. A 9-7/8" hole was drilled from 3664.5 to 3711.6 m (19.5-66.6 mbsf) in 16.0 rotating hr; however, drilling progress was halted at 37.3, 45.0, 57.0, and 66.6 mbsf by continuous hole problems. High torque (rotary stalled at 700 amps), high overpull (to 70,000 lb), and high pump pressure (to 2700 psi at 500 gpm) indicated that the hole was packing off. High-viscosity mud sweeps were circulated in an attempt to lift the cuttings out of the hole; however, hole-cleaning attempts were largely unsuccessful in reducing the depth of fill. Ledges were contacted running in and pulling out of the hole even after repeated reaming. The pipe went on vacuum (sucked) when the pipe connections were broken, possibly inferring that flow channels or porosity were taking fluid and thwarting circulation to the surface. The hole was not open after reaming several times to bottom; therefore, the attempt to deepen the hole was abandoned in favor of setting casing. The bit cleared the seafloor at 0215 hr and cleared the rotary at 0715 hr on 5 November. The lower BHA was severely worn, and the upsets for the DC slip recesses were nearly gone. The underreamer body was 7-3/4" diameter (8-1/4" new), and the bit had two missing grease reservoir caps and one cone locked. The teeth had been flattened by cone skidding (locked by pyrite gravel). The bit reservoirs were filled with 1- to 10-mm pyrite gravel, but the bit seals were still effective.

A 12-1/4" bit and a 17-1/2" underreamer were run in an attempt to open the 9-7/8" hole (with the rotary) to run 13-3/8" casing. Hole 957L was reentered at 1515 on 5 November. The hole was opened with a 17-1/2" underreamer and a 12-1/4" bit from 3661.4 to 3705.0 m (16.4-60.0 mbsf). The pipe stuck at 3695 m, and the rotary stalled. The pipe was worked up to 160,000 lb overpull. The hole was packing off, and 120 bbl of high viscosity mud sweeps was circulated; however, the pyrite gravel could not be cleaned out. Circulation was regained, and the pipe was free. The pipe was back reamed to 3659 m (16" shoe). Fill was tagged at 3675 m (13.6 m below the shoe). Attempts to wash-in without rotation were not successful. An attempt to ream back to bottom was abandoned when the torque increased and the hole started packing off. The 13-3/8" adapter was flushed before pulling out. The bit cleared the seafloor at 1100 hr on 6 November and cleared the rotary at 1630 hr. The 17-1/2" Servco underreamer had severe body abrasion. The 12-1/4" Smith

Q7J 3-cone bit (S/N 46684) had severe body and shirttail abrasion, and had lost three grease reservoir caps. The 13-3/8" casing was run as follows: Texas pattern shoe, four joints 13-3/8" casing, and D-Q casing hanger (54.42 m length). The casing was landed in the moonpool, and a drilling stinger was run as follows: Drilex mud motor, 17-1/2" underreamer, and 12-1/4" bit. The motor turned at 10 spm, and the underreamer opened at 43 spm. Hole 957L was reentered at 0700 hr on 7 November (the reentry cone was initially obscured by black smoke). The casing was run in to the 16" shoe at 3661 m, where the mud motor stalled out repeatedly. After 1 hour, the casing went into open hole and was washed in from 3661 to 3698.7 m (16.0 to 53.7 mbsf) in 9.75 hr (12-1/4" bit at 3701.2 m. The mud motor torqued and stalled out repeatedly from the shoe to TD, indicating that it was drilling most of the time. Underreaming parameters were: 4000-10,000 lb WOB circulating with 600 gpm at 1500-2000 psi. The 13-3/8" hanger was landed three times about 1.2 m low to the supplemental adapter, and 20,000 lb was set down. A 20,000 lb overpull was applied in an attempt to verify what appeared to be a successful latch-in. While running the motor to close the underreamer arms, the TV showed that the hanger was out of sight; however, the reentry cone was half full of grit. The running tool was rotated 3.5 right-hand turns but did not come free. A 40,000 lb overpull was not successful in removing the tool. The mud motor stalled, and the hole started packing off. Increasing the release torque to 15,000 ft-lb produced no further running-tool rotation. The string was pulled to 60,000 lb overpull and came free. An inspection with the TV indicated that the casing had pulled out; however, it was not clear whether the hanger had sheared out (set at 60,000 lb) or had never been set. Nevertheless, the pipe was plugged and could not be circulated with 2500 psi; therefore, it was not possible to underream back to bottom. It was also possible that the running tool might be jammed and inoperable (i.e., packed with grit) whether engaged or not. The bit cleared the seafloor at 1900 hr on 7 November. The ship was moved off the mound, and the casing was pulled. The running tool had operated, but sulfide grit had packed in behind the split ring, kept it extended, and held the 13-3/8" casing. The hanger had not set or sheared out, and there was no damage to the casing or shoe.

There was no effective method of preventing sulfide grit from jamming the running tool if the 13-3/8" casing was drilled in again and hole conditions appeared to be worse; therefore, the casing attempt was terminated. The bit cleared the rotary at 0330 hr on 8 November. The 12-1/4" RBI C-3 3-cone drill bit (S/N BD004) had all three grease reservoir caps worn off, and the shirttail was badly worn. The 17-1/2" Servco Series 11700 underreamer had a worn body, and wear on the arms had exposed the seals on the cones.

Hole 957M (Proposed TAG-4 Area)

A 9-7/8" RBI C-7 RCB bit (S/N BF844) was run with an RCB BHA, and a site 5 m south of Hole 957K was selected in a water depth of 3648.0 m. Hole 957M (proposed TAG-4 area) was spudded at 1430 hr on 8 November at 26°08.222'N, 44°49.588'W. The bit penetrated 1 m when set down. RCB Cores 957M-1R to 10R were taken from 3648.0 to 3699.2 m (0-51.2 mbsf) with 51.2 m cored and 6.95 m recovered. Coring proceeded cautiously, and a 20- to 30-bbl mud sweep was circulated each connection; nevertheless, the pipe was stuck at 19.3 and 29.3 m. A wiper trip was made at 38.3 mbsf, and a 30-bbl mud sweep was circulated. Core barrel 10R was retrieved on the second try with bad hole conditions. The next core barrel did not land (low pressure), and the pin sheared on the overshot in an attempt to retrieve it. The core barrel was retrieved, and the bit deplugger was dropped. The deplugger was jarred down four times, but the pressure was still low. The deplugger engaged but dropped off when the wireline rams were closed to circulate. The pipe was pulled, clearing the seafloor at 0530 hr on 10 November and the rotary at 1030 hr. The MBR had failed, leaving the bit, the bottom half of the MBR, and the RCB core barrel with a deplugger in the hole. A considerable amount of reaming was required due to persistent tight hole, and that may have resulted in metal loss and ultimate failure of the lower (outer) MBR. The pipe was being worked in tight hole at the time; therefore, the bit loss may have been initiated by a stuck pipe event.

Hole 957N (Proposed TAG-2 Area)

Hole 957N was a last attempt to produce a loggable 100-m deep-hole, and the most stable area near the proposed TAG-2 area was chosen for the attempt. A 9-7/8" RBI C-7 (S/N BH207) was run with the RCB BHA to test the new hot hole sealed friction bearing bits. After a short survey in the proposed TAG-2 area, the bit was set down on bottom at 1745 hr on 10 November in a 3652.0-m water depth at 26°08.197'N, 44°49.553'W. Hole 957N is 10 m northwest of Hole 957H. A 9-7/8" hole was drilled from 3652.0 to 3694.0 m (0 to 42.2 mbsf) with a wash barrel in place. A 20-bbl high-viscosity mud sweep was circulated each connection, and the hole was reamed twice; nevertheless, the torque increased, finally stalling the rotary. The pipe was stuck at 40.0 mbsf, and it could not be freed. Wash barrel 957N-1W from 3652.0 to 3694.2 m (0-42.2 mbsf) was retrieved through the top of the top drive with 0.50 m recovered. The connection was 2 m above the rig floor, and it was considered dangerous to run explosives through the top drive; therefore, the ship was offset 100 m (1.5°) to lower the connection, and 160,000 lb overpull was applied. A severing charge was fired in the top sub/head sub (thinnest wall) in an effort to recover as much BHA as possible and leave the top of the pipe below the mound surface for future submersible work. The pipe was worked to 260,000 lb overpull, but the first severing shot was unsuccessful. Two severing charges were run with the plugs welded together to form a double charge, and they were fired with 210,000 lb overpull in the same area as the first shot. The second charge was not successful. The *Alvin* submersible operators advised that a pipe sticking above the seafloor may inhibit sub work but would probably prevent deep towed work; therefore, leaving a clean seafloor was considered a priority. A severing charge was shot just below the seafloor between the second and third drill coillars at 3652.3 m with 25,000 lb overpull and 600 amps (15,000 ft-lb left-hand torque). The string was pulled out of the hole, and the severed drill collar (DC) was on the deck at 1400 hr. One good DC was salvaged. Lost in the hole was a bit, a bit sub, 5 X CLDC (including the severed joint), a top sub, and a head sub.

Return to Hole 957C (Proposed TAG-1 Area)

A 16" CADA running tool and a 17-1/2" centralizer/jet sub was run on 5-1/2" DP, and the ship was positioned to retrieve the HRB on Hole 957C at 2100 hr on 12 November. The tool was stabbed on the first attempt and engaged without problems in 15 min. The HRB was landed on the moonpool doors at 0300 hr on 13 November. The legs were retracted, sediment samples were collected from the base, and the one good DC and crossover were inspected. The HRB was moved intact to the deck so operations could continue.

Hole 957O (Proposed TAG-5 Area)

A standard 6 DC RCB BHA was made up, and the ship was moved to the proposed TAG-5 area (north part of the mound and northeast of the Black Smoker Complex). The bottom was tagged at 1515 hr in a 3649.0-m water depth at 26°08.241'N, 44°49.545'W. The weather turned bad with rain, winds to 40 kt, and 2 m of heave. RCB Cores 957O-1R to 4R at 3649.0-3669.5 m depth (0-20.9 mbsf) with 20.9 m cored and 1.27 m recovered. Hole problems were encountered following Core 3R, and the hole packed off on the connection at 20.9 mbsf. The pipe was pulled up to 9 mbsf and circulation was regained; however, the pipe stuck and the rotary stalled. The pipe was worked with 260,000 lb overpull without success. Mud pills were circulated at 1000 gpm, and the pipe was pulled with 240,000 lb overpull. The bit cleared the seafloor at 0545 hr on 14 November.

Hole 957P (Proposed TAG-5 Area)

A 2-hr survey was conducted for a new site in the proposed TAG-5 area. Hole 957P (proposed TAG-5 area) was spudded at 0915 hr on 14 November in a 3649.0-m water depth at 26°08.236'N, 44°49.558'W. RCB Cores 957P-1R to 6R were taken from 3649.0 to 3679.1 m (0 to 30.1 mbsf) with 30.1 m cored and 1.06 m recovered. A 20-bbl high-viscosity mud sweep was circulated after every core, and half cores were taken to improve interval recovery. Tight hole was encountered at 30.1 mbsf with high torque and with the hole packing off. Circulation and rotation were regained and coring continued. RCB Cores 957P-7R to -12R were taken from 3679.1 to 3708.4 m (30.1 to 59.4 mbsf) with 29.3 m cored and 3.64 m recovered. Hole conditions remained unstable for the rest of the hole. The hole could not be cleaned out, and it packed-off despite circulation of 130 bbl of high-viscosity mud sweeps. Each core required back-reaming to get out of the pack-off, and the bit had to be reamed back to bottom through about 3 m of fill, despite circulating 20-bbl high-viscosity mud sweeps. A core barrel was dropped following Core 12R, but the bit could not be worked past 3683.0 m; therefore, wash barrel 957P-13W was retrieved with 2.51 m of granular pyrite recovered. The bit cleared the seafloor at 1800 hr on 15 November.

Hole 957Q (Proposed TAG-3 Area)

A TV survey was conducted from the proposed TAG-5 area to the proposed TAG-3 area (50 m south of the black smoker chimney). The seafloor was tagged at 2145 hr in 3657.0 m water depth for Hole 957Q (proposed TAG-3 area). The VIT coaxial cable was coated with corrosion inhibitor. RCB Core 957Q-1R was taken from 3657.0 to 3666.5 m (0-9.5 mbsf). The core barrel could not be retrieved due to tight hole, and the hole packed off with no circulation and 50,000 lb overpull. The bit was pulled up to the seafloor to clear the pipe. Granular pyrite and crushed red chert were recovered. A high-viscosity mud sweep was circulated, but 3 m of fill was encountered. RCB Core 957Q-2R was taken from 3666.5 to 3671.5 m (9.5-14.5 mbsf), but the hole remained unstable with 7 m of fill. The bit could not be advanced due to inability to clean the hole. The aft coring wireline was coated with corrosion inhibitor. The bit cleared the seafloor at 0600 hr on 16 November. The pipe was coated with corrosion inhibitor. The bit was on deck at 1230, and graded 2, 3, I, SD, HP. The metal around the wear buttons was heavily abraded, but negligible bit damage was noted. Two positioning beacons were recovered, but the pre-positioned beacon did not respond.

SEA VOYAGE TO LAS PALMAS

The ship departed for Las Palmas, Gran Canaria, at 1400 hr on 16 November. The sea voyage to Las Palmas covered 1598 nmi in 145.5 hr at an 11.0-kt average speed. The first line ashore in Las Palmas was at 1530 hr on 22 November.

SUMMARY OF CORING OPERATIONS

The unusual combination of surface and formation problems encountered at the TAG mound determined the operational choices available to meet leg objectives. Various combinations of operating techniques and drilling tools were used to combat the problems; however, no one technique was successful in overcoming all of the handicaps.

Mound Surface

The following problems were noted:

1. The seafloor around the mound consists of pillow basalts with a thin 1-2-m-thick covering of pelagic carbonates. Scattered fractures were evident on the seafloor and mound.
2. The circular 200-m-diameter mound surface consists of two roughly symmetrical circular 5-10-m-high terraces dominated by a 10-15 m-high Black Smoker Complex in the northwest quadrant. The small mound, the even smaller areas of interest, and the location of pre-leg instrumentation forced us to concentrate the holes within 10-20 m of each other; therefore, lost circulation and drilling-affected zones between holes was a potential problem.
3. The topography varies from 3670-3680 m on the seafloor to 3650 m on the first terrace (proposed TAG-1 and 2 areas), to 3628 m at the top of the Black Smoker Complex. TV surveys and guide-base experience indicate a general slope of 8° to 35°. Only two of eight HRB placement attempts indicated less than 20° slopes.
4. The high slope angle preempted setting a reentry cone on bottom, and the shallow sediment cover/massive pyrite top prevented penetration of the transition pipe or washing in casing. The HRB was used because of the slope; however, the shallow sediment cover was unstable, and the HRB's angle changed from 8° to 20°. The mound surface was therefore unsuitable for either base system.

Formation Problems

Many formation problems were encountered when penetrating the mound:

1. The mound surface is covered by a 1-2-m thick veneer of sulfide silts over what appeared to be 15-50-cm-wide boulders of chimney debris composed of massive sulfides and scattered anhydrites. The surface boulders and silt must be stabilized with casing before drilling can proceed safely.
2. At about 2 mbsf a very hard massive-pyrite and chert layer 3 to 8 m thick covers certain parts of the mound. Silica cementation increased on the west side of the black smoker chimney.
3. From 5 to 8 mbsf down to 15 to 20 mbsf, a porous, loosely cemented granular pyrite breccia with varying anhydrite cementation was noted. Nodules of very hard massive pyrite/sulfide and chalcopyrite 1-5 cm in diameter are interspersed in the granular pyrite matrix. The nodules piled up above the bit like gravel and pebbles and had to be dropped back under the bit by rotating with low circulation. The gravel could be broken up below the bit for circulation out of the hole.
4. From 15 to 20 mbsf to 20 to 25 mbsf the granular to massive pyrites/sulfides are cemented with anhydrite in certain parts of the mound. Anhydrite dissolves under contact with cold seawater, and lost circulation from problem holes may have affected later formation stability in offset holes. A minimal number of holes should be drilled, or holes should be widely spaced.
5. From 20 to 25 mbsf down to 100 mbsf, porous, loosely cemented granular pyrite formed cavities, alternating with hard and abrasive ledges of massive pyrites/sulfides .
6. The porous, loosely cemented granular pyrite had well-developed porosity and permeability. Low pressure fluid channels (lost circulation zones) are implied by the following observations:
    a. The hole could not be cleaned out below a certain depth, no matter how much viscous mud and water was circulated,
    b. Standing fluid level drops (suction) of 125 to 160 psi were noted when breaking the pipe, and
    c. Up to 1000 gpm could be pumped into the formation at low pressures below annular pack-offs.
7. The specific gravity of the formation ranges from 2.6 to 5.0. The dense, angular pyrites are very difficult to carry out of the hole, and they packed off with high torque and drag.

8. High circulation rates (600 to 1000 gpm) and high pressures (2000 to 3000 psi) were required to clean the hole at times; however, pump pressure packed off and compacted the cuttings in the annulus, which stalled the rotary and stuck the pipe.

Coring Practices

Coring practices generally consisted of running low (5000 to 10000 lb) weight on bit (WOB) at 50 to 100 revolutions per minute (rpm) while circulating at 300 to 500 gallons per minute (gpm) at 350 to 1000 psi. The large cuttings, nodules, and unstable formation debris (fill) in the hole were often circulated above the bit before being finely crushed. Loose debris accumulated in the annulus above the bit until pump pressure packed it off, stalled the rotary, and stuck the pipe. Lowering the pump rate to 150 to 250 gpm (or shutting off the pump) and working the pipe down would usually allow the loose debris to fall under the bit and restore rotation. If the packed-off material would not fall below the bit, the best technique was to ream up at 100 rpm with the compensator open at 2000 to 4000 lb and low circulation rates of 150 gpm. Once above the fill, the pipe was reamed back down with full circulation using mud sweeps.

RCB core recovery was very poor (about 4%-12%), and hole cleaning was very difficult; therefore, half cores (4 to 5 m) were cut to improve recovery and reduce the accumulation of cuttings between cores. To reduce packing off and high torque problems (generally on connections), 20-bbl high-viscosity mud sweeps (35 ppb bentonite clay in fresh water viscosified with 1/2 quart of Baroid VR-310 metal silicate) were pumped every 5 m of core. Also, 20 bbl of Sepiolite mud (22 ppb sepiolite in seawater) was pumped at times with about the same effect. The viscosity was as high as the pump suction would take. When hole-cleaning problems were evident, 30- to 50-bbl high-viscosity gel sweeps (enhanced with 1/2 quart of Baroid VR-310) were pumped at 500 to 1000 gpm. Connection problems (banging bottom) were reduced by increasing the rathole from 2 to 4 m and resuming circulation and rotation as quickly as possible after connections. The pipe stuck frequently while retrieving the core barrel, dropping the next core barrel, and pulling the sinker bars; therefore, circulation and rotation were restored quickly.

No H_2S was detected on the drill floor or in the core during the leg; however, an H_2S odor was evident in the core barrel when it was washed out with fresh water.

Deep Penetrations

One of the Leg 158 objectives was to obtain a deep section through the sulfide mound and penetrate the stockwork and footwall alteration zone to a depth of 500 m. The original operations plan was to run a reentry cone with 16", 13-3/8", and 103/4" casing strings; however, the shallow sediment was not deep enough for washing in casing, and the hard massive pyrite layer would not allow transition pipe to penetrate.

The HRB was designed for hard rock (not sediment) slopes up to 20°. TAG mound surface conditions did not fit either base; however, the HRB assembly was run because it could be used on a slope. The HRB was run using the 16" Dril-Quip running tool (with the CADA feature locked out) with the objective of setting the base and checking the area before drilling. Two tapered drill collars made for Leg 158 had been lost on Leg 157. A 7-1/4" transition DC was not run due to the weak connection. After several attempts to set the base in which the angle exceeded 20°, the HRB was set with an 8° angle at Hole 957B, which was cored to 29.6 mbsf and terminated in basalt. The HRB was easily engaged and moved to Hole 957C, which was cored to 49.2 m; however, the HRB tipped over at about a 45° angle on the unstable sediment slope.

The repeated instability of the HRB when spudding with even a moderate 8° angle forced reconsideration of a means to run a casing string with a reentry cone and Dril-Quip casing hanger system for the CORK experiment. A casing/hanger/reentry cone system could be run with an underreamer to advance the casing. The reentry cone would sit on the casing stem (even if it did not contact the sloping bottom) and provide a casing hanger/CORK seat.

Heavy sulfides were difficult to clean out even in a smaller 9-7/8" × 8-1/4" annulus with high annular velocities (to 80 m/min); therefore, it was not considered advisable to attempt to underream ahead of a 16" casing in a 22" hole. To improve chances for success in running a surface casing, two joints of 13-3/8" casing were run on a 16" Dril-Quip casing hanger and latched into the reentry cone. A 12-1/4" 3-cone drill bit, a 17-1/2" Servco series 11700 underreamer, a Drilex D-775 mud motor, and space-out collars were run inside the 13-3/8" casing on the 16" Dril-Quip running tool. The 13-3/8" casing was drilled in with the 17-1/2" underreamer in Holes 957D and 957E before it was successfully released. At Hole 957L, a single joint of 16" casing (i.e., without a 17" -diameter casing coupling) was drilled in with a 17-1/2" underreamer and released with some difficulty.

Multi-Use Bases

The technique of underreaming ahead of casing with a hanger/reentry cone attached has tremendous potential for establishing cased holes on unconsolidated sloping sites; however, the running tool must be redesigned to reduce jamming problems. This might be accomplished by removing the split ring and using spring loaded actuator pins to contact the hanger.

A reentry cone with a shorter transition pipe would be an advantage in setting the base in shallow-sediment cover over hard surfaces (Hole 957L). A shorter transition pipe throat would also facilitate removal of the running tool (Hole 957L). A flow pipe coming out of the lower base would improve the removal of cuttings from the annulus. Narrow horizontal slots 1 m up in the cone would drop cuttings outside the cone before they fell back downhole. The generic base should have a lock ring (snap-in) transition pipe and lock ring (snap-in) reentry funnel for easier assembly and disassembly.

Mud Motors and Underreamers

The Drilex Series D-775 mud motor started rotation at 10 spm (50 gpm) even after repeated use. It was normally operated at 400 gpm at 1500 psi, and the pressure increased to about 400 to 700 psi at stall-out. No problems were noted with operation, and the motor had sufficient torque to restart even under packed-hole conditions.

The Servco Series 11700 underreamers opened with 35 to 43 spm (165 to 215 gpm) even after repeated use. The body was worn about 1/2" on the OD. The nozzle area had to be protected with a ring of hard facing to reduce abrasion from rotation. A lift nubbin with threads in the top would allow underreamers and motors to be tested and cleaned out with a circulating hose to avoid picking up the top drive. The Servco Series 11700 underreamer needs to have 19" arms developed for underreaming ahead of 16" casing.

16" Dril-Quip Running Tool and Hanger

The 16" Dril-Quip running tool was jammed by heavy sulfide grit behind the split ring, which prevented the ring from collapsing for release. The split ring could be eliminated by putting the hanger profile on a lengthened actuator pin and providing an internal retraction spring. The tool needs to be sealed and filled with oil to prevent sulfide grit from penetrating into the tool. The hangers need anti-rotation dogs to prevent casing/base rotation when underreaming ahead of casing to prevent overtorquing the running tool.

Drilling Jars and Fishing Tools

The McCullough drilling jars proved their worth in Hole 957E, and were effective in jarring pipe free until the drill collars entered open hole. The tapered joints will reduce the stress at the drill-collar/drill-pipe transition. A field-serviceable fishing jar (such as a Tri-State Super Jar) and accelerator should be available to work on stuck pipe. A free point indicator should be available to back off (as opposed to sever) drill collars so they can be screwed back into with a fishing jar and accelerator assembly.

Hot Hole Bits

Bottom-hole static temperatures exceeding 750°F (400°C) were possible on Leg 158. Normal oil-field bit seals (elastomers) are effective to about 400°F (200°C); therefore, tests were conducted at RBI to find a suitable elastomer for the high-temperature seal system and grease reservoir diaphragm and to determine the effect of bi-metallic expansion on tooth retention. Five bits were made with nonsealed roller bearings, and five bits were made with sealed friction bearings. The bits were the standard spiral stabilizer type (with the addition of eight upreaming buttons), close catch, C-7 (IADC 6) tooth design with less abrasive resistant/more ductile tungsten carbide teeth. We anticipated getting about 30 rotating hr with the non-sealed bits and 50 rotating hr with the sealed bits. The bits all have 14/32-in. nozzles.

Aflas O-ring/Vespel sliding plastic seals were developed and survived a 475°F (245°C) heat test for 90 hr; however, they had hairline cracks after 28 hr at 700°F (370°C). The high-temperature grease lubricant lost its viscosity at 450°F (230°C), but remained a lubricating liquid up to 700°F (370°C). The Aflas grease reservoir compensators allow for a calculated 3% thermal expansion in grease volume. The assumption was that bearing life would be improved as long as circulation kept the operating temperature below about 300°C.

Tests and tungsten carbide vs. steel expansion calculations indicated that cone expansion could result in tooth loss. The bits had reduced tooth extension (for greater grip length) and higher tooth squeeze (press-in pressure to counteract the greater bi-metallic thermal expansion). The bits would not be run with an MBR because of the danger of inadvertently shifting the sleeve in hard, unstable granular sediments. One 9-7/8" sealed friction bearing hot hole bit (S/N BH207) was used in Hole 957N, cutting 42.2 m in 7.0 hr with a wash barrel; however, the bit was lost when the drill string became stuck and was severed.

Cement

Leg 158 could have required cement with temperature extremes of 40°F (4°C) at the surface (downflow zone) to bottom-hole temperatures exceeding 750°F (400°C). Normal oil-field cementing additives are effective to about 300°F (150°C), and cement can be dispersed for use at up to 400°F (200°C); however, existing retarders do not work well at high-temperature differentials. Extensive cement testing was done at the Halliburton lab in Tulsa, using a sample of the actual cement we would use.

The Class "G" cement was preblended with 50% by-weight-of-cement (BWOC) SSA-1 (silica flour). At temperatures up to 100°F (40°C) Class "G" cement with 50% SSA-1 would be mixed with fresh water without retarders. SCR-100 (a low-temperature synthetic polymer retarder) would be added from 0.2%-1.0% BWOC in the temperature range from 150° to 250°F (65°-120°C). Above 300°F (150°C), HR-25 (high-temperature organic carboxylate acid retarder) would be added from 0.54.0% BWOC, and SCR-100 would be increased from 1.0% to 4.0% BWOC. The additives would be mixed in the fresh mix water before the job. The additives should be mixed slowly because they are acidic and cement tends to gel initially until more cement is added to dilute pH.

Mud

The Baroid VR-310 viscosifier was effective in increasing bentonite mud viscosity as high as it could be pumped. Attempts to increase viscosity by adding additional clay resulted in unpumpable gels. The use of a weighted 10.2-ppg sweep to decrease the relative density of the cuttings/nodules was not successful. A lost-circulation material such as cellophane or kevlar fibers (for high temperature) should be available to combat lost circulation.

CORING TOOLS

APC/XCB/RCB Systems

The APC was not successful in penetrating or recovering surface or downhole samples of unconsolidated granular sulfides. A few 11-7/16" APC/XCB 4-cone core bits need shirttail armor to protect against severe gauge wear in abrasive formations in which the XCB/MDCB may be used in the future. A few XCB core bits need to be built with diamond-impregnated cutters and improved flow channels to withstand use in the abrasive massive sulfide/pyrite/chert zones in conjunction with the MDCB. A stronger (harder formation) center bit is also required.

The RCB coring system was strong enough to handle the very hard and abrasive massive sulfides and pyrite; however, recovery was very poor in granular pyrites. The RCB C-7 and C-9 core bits with gauge armor and upreaming buttons were well suited to the formation.

Motor Driven Core Barrel (MDCB)

The MDCB was very successful in granular pyrite with good anhydrite cementation, but did poorly in unconsolidated granular pyrites. The plastic liners for the MDCB appeared to be so thin and fragile that they would hinder recovery; therefore, the MDCB was run without liners. Some core disturbance was obvious in beating the core out of the steel core barrel (which also damaged the core barrel). Single hard-formation (short-finger) core catchers were judged more effective because some core was clearly jammed between catchers.

Diamond Core Barrel and Diamond Coring System (DCS)

It might be possible in shallow core holes to use a 30-ft diamond core barrel to cut a 4" diameter core; however, the 1/32" clearance on the core-bit diameter would be a problem in tight hole (similar to the PDC bit in Hole 957E). The requirement to trip the drill string for every core would slow penetration. The formation has shown a definite tendency to fracture and jam core catchers (which was the reason to take half cores); therefore, a jam could potentially lose large sections of core.

The DCS should improve core recovery in the sulfide mound if it becomes operational; however, the sulfide mound is a very hostile and unstable environment, and even the DCS's ability to get deep penetrations would be questionable.

Optimum Casing Design for Deep Penetration

Experience on Leg 158 suggests that the optimum three-string casing program for a deep penetration would be to underream a 19" hole ahead of 30 m of 16" casing. Then a 17-1/2" hole would be underreamed ahead of 60 to 100 m of 13-3/8" casing and cemented. Finally a 15" hole would be underreamed ahead of 10-3/4" casing to about 200 to 300 m (or as deep as possible). All casings would be cemented by the circulation method for a high-cement column. The cement would have lost circulation material in it.

BHA length should be increased to prevent drill collars from entering open hole where loose boulders can fall in on top of the smaller drill pipe. Tapered crossovers would also reduce horizontal shoulders on the drill string. All drilling tools should be protected against abrasion and equipped with back-reaming teeth looking up.

OCEAN DRILLING PROGRAM
TIME DISTRIBUTION
LEG 158

OCEAN DRILLING PROGRAM
LEG 158
OPERATIONS RESUME

	days
Total Days (23-SEPT-94 to 22-NOV-94)	60.4
Total Days in Port	6.1
Total Days Underway	13.3
Total Days on Site	41.0

	days
Stuck Pipe/Downhole Trouble	5.7
Repair Time (ODP)	1.4
Tripping	11.8
Drilling	1.7
Coring	10.9
Logging/Downhole Science	0.2
Re-Entry	3.5
Other	0.5
Casing and Cementing	4.8
Development Engineering	0.5
Fishing & Remedial	0.0
Repair Time (Contractor)	0.0
W.O.W.	0.0

Total Distance Traveled (nautical miles)	3228.0
Total Miles Transited:	0.0
Average Speed Transit (knots):	10.9
Total Miles Surveyed:	0.0
Average Speed Survey (knots):	0.0
Number of Sites	1.0
Number of Holes	17.0
Total Interval Cored (m)	435.8
Total Core Recovery (m)	51.6
% Core Recovery	11.8
Total Interval Drilled (m)	200.5
Total Penetration	565.1
Maximum Penetration (m)	125.7
Maximum Water Depth (m from drilling datum)	3657.0
Minimum Water Depth (m from drilling datum)	3644.0

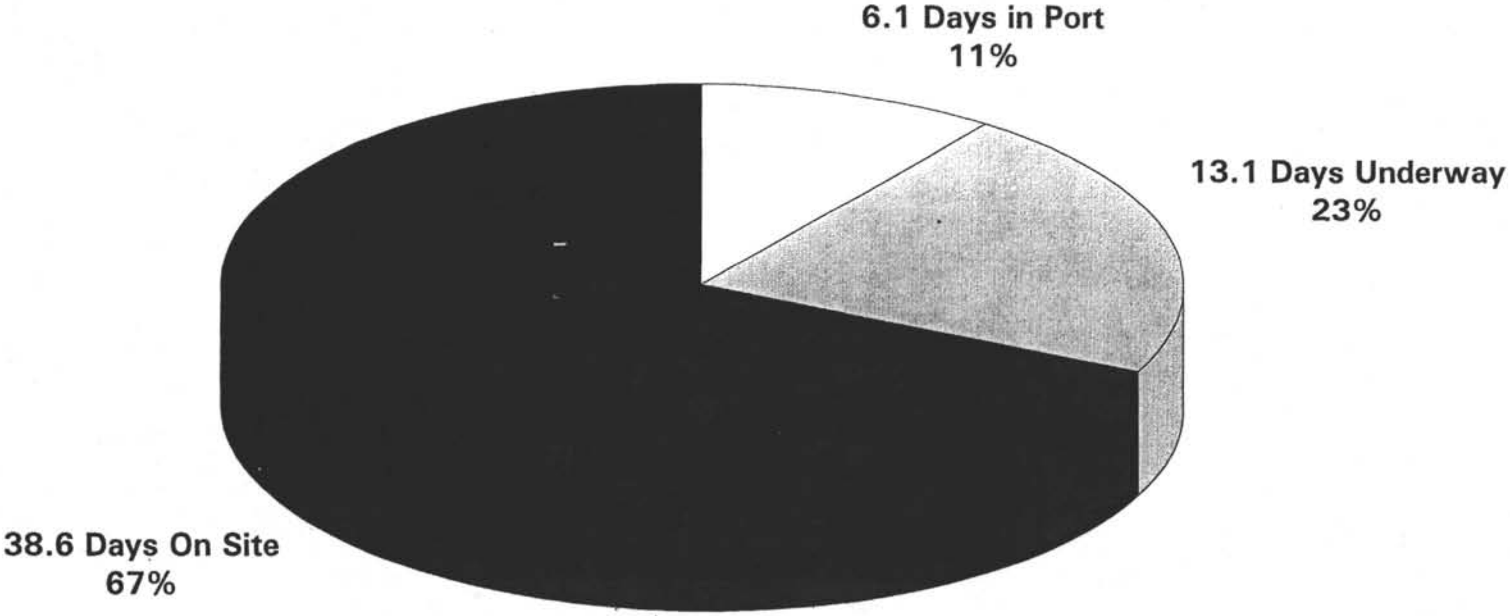
OCEAN DRILLING PROGRAM

SITE SUMMARY

LEG 158

HOLE	LATITUDE	LONGITUDE	WATER DEPTH (meters)	NUMBER OF CORES	INTERVAL CORED (meters)	CORE RECOVERED (meters)	PERCENT RECOVERED (percent)	DRILLED (meters)	TOTAL PENETRATION (meters)	TIME ON HOLE (hours)	TIME ON SITE (days)
957A	6°08.196'	44°49.552'W	3653.2	3	15.0	0.25	1.7%	0.0	15.0	25.50	1.06
957B	6°08.193'	44°49.546'W	3655.0	4	29.6	1.62	5.5%	0.0	29.6	72.25	3.01
957H	6°08.195'	44°49.555'W	3655.0	9	45.8	5.01	10.9%	8.7	54.5	63.50	2.65
957N	6°08.197'	44°49.553'W	3652.0	0	0.0	0.50	0.0%	42.2	42.2	51.50	2.15
		TAG-2 TOTALS		**16**	**90.4**	**7.38**	**8.2%**	**50.9**	**141.3**	**212.75**	**8.86**
957C	6°08.226'	44°49.555'W	3648.0	16	49.2	21.88	44.5%	0.0	49.2	108.00	4.50
957D	6°08.220'	44°49.562'W	3648.5	0	0.0	0.00	0.0%	29.5	29.5	33.75	1.41
957E	6°08.219'	44°49.560'W	3646.0	18	94.2	4.03	4.3%	31.5	125.7	246.50	10.27
957F	6°08.212'	44°49.564'W	3648.6	2	9.0	0.95	10.6%	1.0	10.0	14.75	0.61
957G	6°08.213'	44°49.558'W	3646.0	3	13.5	1.12	8.3%	12.0	25.5	26.00	1.08
957L	6°08.215'	44°49.565'W	3645.0	0	0.0	0.00	0.0%	66.6	66.6	138.50	5.77
		TAG-1 TOTALS:		**39**	**165.9**	**27.98**	**16.9%**	**140.6**	**306.5**	**567.50**	**23.65**
957I	6°08.226'	44°49.585'W	3645.0	1	4.5	0.77	17.1%	9.0	13.5	18.00	0.75
957J	6°08.238'	44°49.590'W	3647.0	1	9.0	0.08	0.9%	0.0	9.0	17.25	0.72
957K	6°08.239'	44°49.583'W	3644.0	3	20.0	0.99	5.0%	0.0	20.0	32.50	1.35
957M	6°08.222'	44°49.588'W	3648.0	10	51.2	6.95	13.6%	0.0	51.2	55.00	2.29
		TAG-4 TOTALS:		**15**	**84.7**	**1.84**	**2.2%**	**9.0**	**22.5**	**122.75**	**5.11**
957O	6°08.241'	44°49.545'W	3649.0	4	20.9	1.27	6.1%	0.0	20.9	24.75	1.03
957P	6°08.236'	44°49.558'W	3649.0	12	59.4	7.21	12.1%	0.0	59.4	36.25	1.51
		TAG-5 TOTALS:		**16**	**80.3**	**8.48**	**10.6%**	**0.0**	**80.3**	**61.00**	**2.54**
957Q	6°08.198'	44°49.570'W	3657.0	2	14.5	5.91	0.0%	0.0	14.5	18.50	0.77
		TAG-3 TOTALS:		**2**	**14.5**	**5.91**	**0.0%**	**0.0**	**14.5**	**18.50**	**0.77**
		LEG 158 TOTAL		**88**	**435.8**	**51.59**	**11.8%**	**200.5**	**565.1**	**982.50**	**40.94**

LEG 158
TOTAL TIME DISTRIBUTION



Total days of leg = 61.0

TECHNICAL REPORT

The ODP Technical and Logistics personnel aboard *JOIDES Resolution* for Leg 158 were:

Lab Officer:	Brad Julson
Marine Lab Specialist (Photography):	Roy Davis
Marine Lab Specialist (Storekeeper):	John Dyke
Marine Computer Specialist:	John Eastlund
Marine Lab Specialist:	Jorge Estrada
Marine Lab Specialist (Paleomagnetics):	Edwin Garrett
Assistant Lab Officer (U/W Lab):	Dennis Graham
Marine Lab Specialist (Thin Section):	"Gus" Gustafson
Marine Lab Specialist (Yeoperson):	Michiko Hitchcox
Marine Lab Specialist (Physical Properties):	Taku Kimura
Marine Electronics Specialist:	Eric Meissner
Marine Electronics Specialist:	Dwight Mossman
Marine Lab Specialist (Chemistry):	Chieh Peng
Marine Lab Specialist (Chemistry):	Phil Rumford
Marine Lab Specialist (X-ray):	Don Sims
Marine Lab Specialist (Curatorial):	Lorraine Southey
Marine Lab Specialist (X-ray):	Joel Sparks
Marine Computer Specialist:	Barry Weber

PORT CALL

On the morning of the 23rd of September 1994, the *JOIDES Resolution* docked in Las Palmas, Canary Islands, ending leg 157.

Offgoing cores were unloaded into two refrigerated vans and shipped to the Bremen Core Repository in Germany.

The Shipboard Measurements Panel toured the ship and met with individual technicians in their labs. Their meeting continued for the next 3 days in a hotel in Las Palmas.

Colmek and Mesotek representatives visited the ship and worked on the reentry camera. They fixed the problems, and the camera worked well during the leg.

The ship sailed on the morning of 29 September 1994.

H_2S PRECAUTIONS

Because we were drilling in an area of H_2S presence, several steps were taken for the quick detection of high levels of hydrogen sulfide (H_2S). H_2S detectors and sensors were installed throughout the ship. Fixed sensors were deployed on the drill floor, the catwalk, air intakes to the quarters, the core lab, the refrigerated storage space, and at the base of the stairwell and elevators. Each of these had two sensors and communicated remotely with the central unit that was on the bridge. The detectors send out a radio frequency to the bridge unit that will sound an alarm. The individual detectors also have local flashing lights and alarms that will go off if H_2S is detected. In addition, portable H_2S sensing units were stationed around the drill floor and lab stack in case H_2S levels are encountered. A Geiger counter was available in case radium is encountered.

All scientists and technicians were given H_2S training during the initial transit to the site. This included discussions about the physical properties of the gas as well as hands-on training such as donning the self-contained breathing apparatus (SCBA) and trying out the portable detectors. In addition, most individuals had their ear drums tested during their physicals before the leg. We received six new SCBA's for the leg.

LABORATORIES

Underway Lab

The lab was not used much this leg. Magnetic, navigation, and bathymetric data were collected on the transit to and from the TAG site. There was not a seismic survey at the site.

The starboard magnetometer sensor was out of service this leg. Both the magnetic strip chart recorder and the magnetometer deck unit are old and in need of replacement. A new digital depth reader was installed. In the future this will allow the watch stander to enter the depth digitally into the computer file, and then it will be merged with the navigation file. Two of the MASSCOMP computers were cannibalized to make one working computer. This should be replaced officially next leg with the Sun computers. The gun booms were stripped and repainted in preparation for dry dock.

During port call, a NOAA expendable bathythermograph (XBT) computer ceased functioning because of a regulated power failure. A replacement will be sent to dry dock.

Physical Properties Lab

The multi sensor track (MST) worked very well, though it was not used much this leg. The new sprinkler system installed on the *P*-wave logger worked well. Thermal-Conductivity measurements were taken during the leg. Only one needle, with the best calibration, was used for the half-space measurements. A problem arose because we do not have standards with thermal values of around 10. We do not core this type of material often, and we are looking for standards back on the shore.

Index properties were determined for the minicores and the rock fragments. The velocity, strength, and resistivity (VSR) program worked well, and the calibration procedure is more efficient. Resistance measurements were made for all the minicores using the two-electrode method at 50 kHz, 5 VAC. Resistivity for these minicores was calculated with area/length parameters obtained from the actual dimensions of the samples.

Core Lab

The new core-splitter table was installed during the beginning of the leg. The old table will be sent back to be used with the old core splitter. The capstan motor was also replaced during the table installation. Blue plastic mats were installed on the splitting-room floor to prevent personnel from slipping.

Four new low-voltage halogen lights were installed above the description table, resulting in light that is more dispersed than the previous lights. This type of light also produces less heat and thus should result in reduced desiccation of the cores.

Paleomagnetics Lab

This leg began with a successful liquid helium refill during the port call. Bill Goree of the 2G Co. performed the refill and other service items. Only one liquid helium dewar arrived, so we were able only to fill the cryogenic magnetometer with 57 L. The cold head refrigeration unit was replaced, and the boil-off rate decreased to a "normal" level. After the refill, the field was trapped. This trapped field showed much less deviation in the measuring range than the last time the field was trapped.

One axis of the cryomagnetometer could not be calibrated. We received a note from the manufacturer to change a resistor in one of the amps to calibrate this sensor properly. This increased the quality of the signal. Since we recovered very little basalt, we did not have many of the anticipated problems associated with high-intensity basalt.

Chemistry Lab

The lab was not heavily used this leg. Most of the analyses were either atomic-absorption spectrophotometer work on digested sulfide samples, or elemental analysis of pyrite for sulfur content using a CHNS instrument.

The lab received a HP5890 gas chromatograph (GC) to replace the aging Carle GC. The new GC is used for quick analysis of low-molecular-weight natural gas and is equipped with an electronic pressure control (EPC) device. EPC capabilities were also added to the other two GC's. EPC allows digital programmatic control of gas pressure and flow during GC analysis. This programming control can be stored and recalled to optimize and reproduce operational parameters. This allows for better reproducibility from run to run and enhances the ability to recreate the conditions in which a sample was previously analyzed. On the new GC, EPC will be used to increase the gas flow, which will result in a reduction of the time it will take to perform an analysis. Consequently, more samples can be run in a given time. The other two GC's received EPC channels to control the split ratios during a capillary analysis. The EPC also can be used to reduce flow during non-use periods, which will reduce carrier gas usage (helium) during a leg. A new non-septum type of injection port was installed on the GC2 to reduce the down time and other problems associated with changing septums.

A series of analyses for reproducibility and precision was conducted on the GHM and Rock-Eval instruments for comparative purposes. A new version of the EAGER software for the CHNS was also loaded.

New portable chemistry tables were built for the lab. These have locking wheels and can be stored under the counter and out of the way.

X-ray Lab

This lab was hardly used during the leg.

The XRF sulfide standards that one of the co-chiefs tried to send from his lab in Germany did not arrive in time to make the leg. Consequently, the XRF was used only on two basalt samples. Both were analyzed for trace and major elements.

As soon as we reached our first site, the XRD tube died. This tube was replaced with the spare but the machine still would not come up. After a technical discussion with the company's representatives on shore and a subsequent lengthy troubleshooting session, it was concluded that the spare tube was also bad, so the instrument was down for the rest of the leg.

Thin-section Lab

The lab was quite busy producing polished thin sections of metalliferous deposits of pyrite and sulfides and also breccias, silica, anhydrides, cherts, clay, and basalts. Due to the nature of the material, impregnations were necessary on most thin sections.

Computers

The system managers had time to upgrade the most popular PC and Mac workstation software to current versions. New versions of EXCEL, Word, WordPerfect, and Canvas were installed, and there were the usual problems of bugs with new software to sort through. An IRIS database on Microsoft Access is being used to keep track of the software types and versions on individual computers.

Digital communication over the satellite to the beach continued to be slow this leg with a lot of dead time over the Marisat line. We hope the new Multiware and Multinet versions will increase our throughput in ship-to-shore communications to cut down on communication costs.

A new 1.7-GB drive was installed on the ODP file server. The Schlumberger Maxis Vax system was connected to our network, using their Multinet software. Exodus, an E-Windows program for the Mac, was tested during this leg.

The Domain Name Server (DNS) database on Balboa was updated to include all the Internet Protocol (IP) addresses. IP addresses have been assigned to all the Mac's, PC's, and other computers on the Ethernet.

The question arose about long-term Halon replacement. This is being addressed on shore and will affect us in the future. The database group on shore developed an official convention for naming the XRD data files.

A new Mitsubishi VCR and TV were received and installed as a center for the many training videos we now have, allowing people to view computer and safety films at their leisure.

Many of our PC's and Mac's are getting quite old, and SMP has recommended replacing them with new, more powerful models.

A management guide was started for the Sun computers. The Cyberex regulated power conditioner was down at the beginning of the leg and broke down twice during the leg.

Curation

Special extruded anodized aluminum core liners and high-temperature plastic core liners were on board to help protect the cores from the expected high temperatures. We never encountered any temperatures hot enough to melt the butyrate core liners, so consequently we never had to use the high-temperature liners.

Because sulfide cores oxidize over time, the archive sections of the cores were stored in special tri-laminated foil bags. A vacuum pump was used to remove the air from around the cores, which was replaced with nitrogen. The bags were sealed and stuffed in the D-tubes. This was done only to the archive halves; the working halves will be processed at the Bremen Core Repository.

Because the XRD was down, the XRD samples will be sent to be analyzed by a member of the scientific party. Microbiological samples were taken from the cores. These were frozen in liquid nitrogen and will be used for identification of high-temperature thermophilic bacteria.

Site 957 had the most holes we have ever cored at a single site, and many of the ODP written programs would not accept a "Q" hole. These were modified to accommodate the holes beyond "N."

Downhole Tools

The water-sampler/heat-flow tool was run only three times. The special high/low-temperature dual thermistor array built for this leg did not work well. In the end, only low-temperature thermistors were needed because the water in the hole had been cooled by drill-pipe circulation. A new pressure case was also received.

Paleontology Lab/Microscopes

The Axioplan and Akioscope microscopes were heavily used by the sulfide petrologists. Most of their work was done in reflected light.

One petrologist set up a portable digital voltameter in the lab. Gold content was determined in selected samples by means of anodic stripping voltammetry (ASV). ASV is an electro-analytical method in which gold is plated from solution onto a working electrode by applying a negative potential and subsequently stripped from the electrode by applying a reverse potential. The concentration of gold in the solution is determined by measuring the current produced by stripping the gold off the electrode.

A microbiologist also set up her sampling equipment in the lab.

Photo Lab

The photo lab developed many close-ups of the sulfide cores. There were also many rolls of microscope micrographs developed for the petrologists. A new core-photo policy was received.

Miscellaneous

The Marine Emergency Technical Squad (METS) trained every week with the SEDCO fire fighting crew. Drills consisting of simulated emergencies were held in various parts of the ship.

The Cyberex regulated power conditioner ceased to function a number of times during this leg. Maintenance is becoming more frequent, and when the device goes down, it sends a large spike of electricity over the regulated power lines.

Lock washers were put on the handles of the outside doors to reduce accidents to fingers caused by the falling handles.

LAB STATISTICS: LEG 158

General Statistics:

Sites:	1
Holes:	17
Cored Interval (M):	435.8
Core Recovered (M):	51.59
Percent Recovered:	11.8
Total Penetration (M):	565.1
Time on Site (Days):	40.17
Number of Cores:	88
Number of Samples:	1,451

Samples Analyzed:

Inorganic Carbon($CaCO_3$):	0
Total Carbon (NCHS):	50
Water Chemistry (the suite includes pH, Alkalinity, Sulfate, Calcium, Magnesium, Chlorinity, Potassium, Silica, Salinity):	3
Atomic Absorption on Sulfides/Pyrite:	48
Pyrolysis Evaluation (Rock Eval and GHM):	0
Gas Samples:	0
Extractions:	0
Thin Sections:	61
XRF:	2
XRD:	0
MST Runs:	28
Cryomagnetometer Runs:	12
Cubes:	16
Oriented Cores:	0
Physical Properties Velocity:	165
Thermal Conductivity:	107
Index Properties:	59
Resistivity:	24
Shear Strength:	0
Velocity:	18

Underway Geophysics:

Bathymetry (NM):	3,000
Magnetics (NM):	3,000
Seismic Survey (NM):	0
XBT's launched:	0

Downhole Tools:

WSTP:	3
ADARA:	0

Additional:

Close-up Photos:	235
Whole Core Photographs:	72
Rolls of Photomicrographs:	20