

# First observations of high-temperature submarine hydrothermal vents and massive anhydrite deposits off the north coast of Iceland

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## Abstract

High-temperature (250°C) hydrothermal vents and massive anhydrite deposits have been found in a shallow water, sediment-filled graben near 66°36'N in the Tjornes Fracture Zone north of Iceland. The site is located about 30 km offshore, near the small island of Grimsey. The main vent field occurs at a depth of 400 m and consists of about 20 large-diameter (up to 10 m) mounds and 1–3 m chimneys and spires of anhydrite and talc. A north–south alignment of the mounds over a 1-km strike length of the valley floor suggests that their distribution is controlled by a buried fault. Widespread shimmering water and extensive white patches of anhydrite in the sediment between the mounds indicates that the entire 1-km<sup>2</sup> area occupied by the vents is thermally active. A 2-man research submersible *JAGO* was used to map the area and to sample vent waters, gases, and chimneys. Actively boiling hydrothermal vents occur on most of the mounds, and extensive two-phase venting indicates that the field is underlain by a large boiling zone (200 × 300 m). The presence of boiling fluids in shallow aquifers beneath the deposits was confirmed by sediment coring. The highest-temperature pore fluids were encountered in talc- and anhydrite-rich sedimentary layers that occur up to 7 m below the mounds. Baked muds underlie the talc and anhydrite layers, and pyrite is common in stockwork-like fractures and veins in the hydrothermally altered sediments. However, massive sulfides (pyrite–marcasite crusts) were found in only one relict mound. Seafloor boiling has likely affected the metal-carrying capacity of the hydrothermal fluids, and deposition of sulfides may be occurring at greater depth. Although the mounds and chimneys at Grimsey resemble other deposits at sedimented ridges (e.g. Middle Valley, Escanaba Trough, Guaymas Basin), the shallow water setting and extensive boiling of the hydrothermal fluids represent a distinctive new type of seafloor hydrothermal system. © 2001 Elsevier Science B.V. All rights reserved.

**Keywords:** Tjornes Fracture Zone; Boiling hydrothermal vents; Anhydrite; Talc

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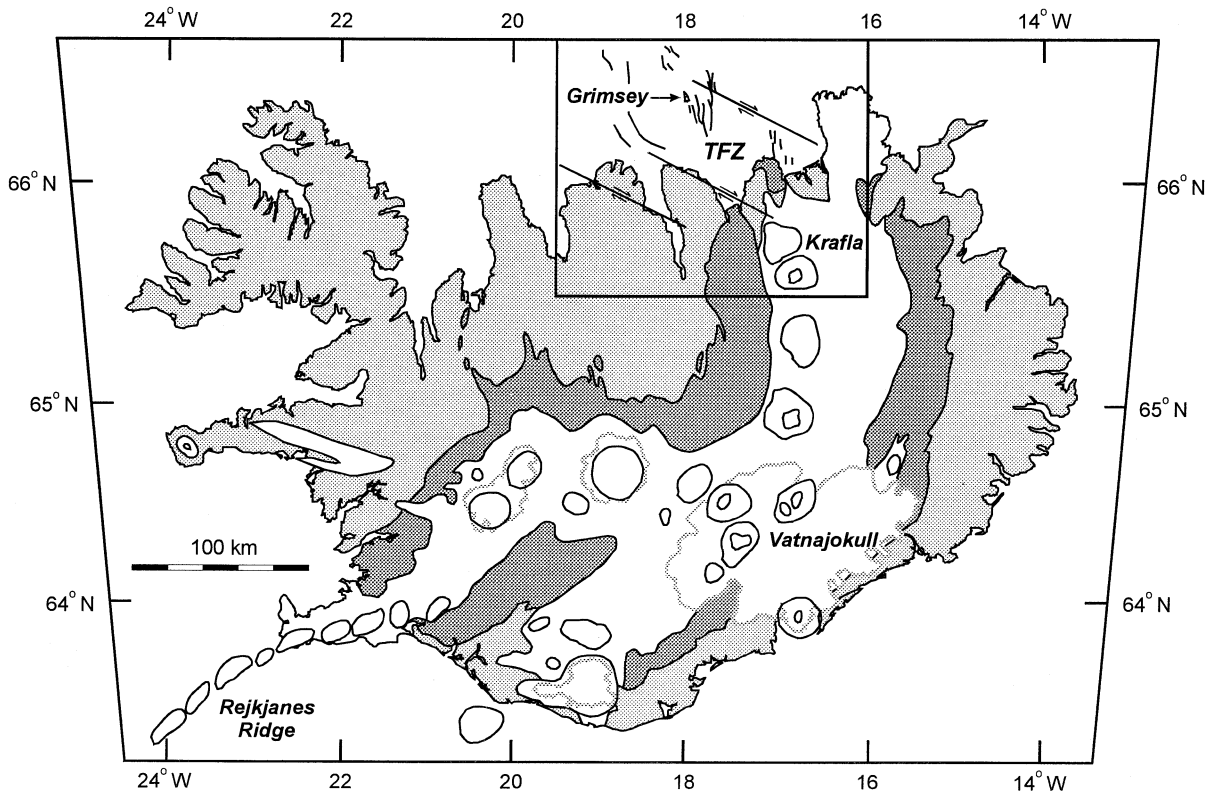


Fig. 1. Neovolcanic Zone of Iceland (white) showing the location of the offshore extensions along the Reykjanes and Kolbeinsey Ridges and the Tjornes Fracture Zone (after Pálmason, 1974). Central volcanic complexes within the neovolcanic zone are outlined in black (major glaciers are outlined by gray lines). The location of the main study area is indicated by the box.

## 1. Introduction

The neovolcanic zone in central Iceland is an expression of the Mid-Atlantic Rift system where it crosses the Iceland hot spot (Fig. 1). The South Rift of the neovolcanic zone is continuous with the Reykjanes Ridge offshore, and the Northeast Rift is linked to the Kolbeinsey Ridge by a series of short spreading segments. Active spreading in this area is split along several submarine valleys within a 75-km-wide zone of extensional grabens and transform faulting known as the Tjornes Fracture Zone (Fig. 2). Magnetic anomalies and ages of volcanic activity indicate that the offset between Kolbeinsey Ridge and the Northeast Rift has existed for about 5 Ma (Saemundsson, 1979; Jonsson et al., 1991).

Although this is one of the most volcanically active regions on Earth, relatively little is known about volcanic and geothermal activity offshore. Submarine

hydrothermal vents have been documented on the Kolbeinsey and Reykjanes Ridges, north and south of Iceland (Fricke et al., 1989; Olafsson et al., 1989; German et al., 1994; Botz et al., 1999), and some shallow water hot springs are known where land-based geothermal systems discharge offshore (Benjaminsson, 1988). However, no significant seafloor hydrothermal deposits have been found in any of these areas. Prior to 1997, the existence of hydrothermal activity in the Tjornes Fracture Zone was known only from a few reports of hydrothermal material being recovered in fishing nets. Several large blocks of anhydrite, weighing 300–500 kg, were inadvertently collected by trawlers working in the area east of Grimsey Island, and based on these reports, a number of different possible vent sites were thought to exist (Fig. 3). In 1987, a likely source for the anhydrite was located by the Marine Research Institute of Iceland at a depth of 400 m in the deep graben

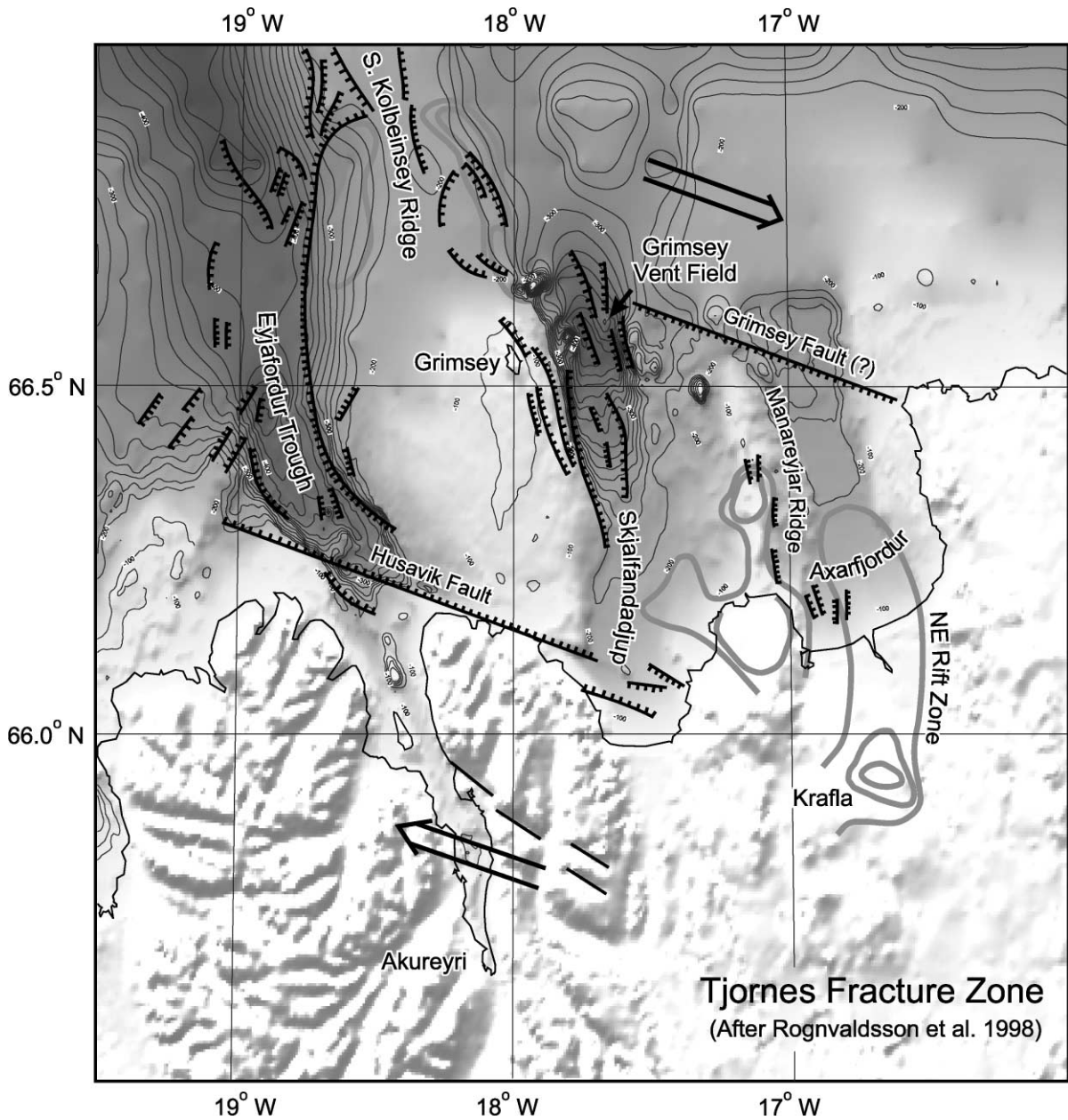


Fig. 2. Crustal rifting of the north Iceland platform (after Gudmundsson et al., 1993; Saemundsson, 1974; McMaster et al., 1977). The Northeast Rift Zone and Kolbeinsey Ridge are propagating towards each other, and the oblique right-lateral offset (so-called underlapping) is accommodated by the Tjornes Fracture Zone (TFZ). Spreading within the TFZ is segmented into a series of short, en echelon grabens or subsiding troughs. The zone of active rifting passes through the Grimsey area and joins with the Kolbeinsey Ridge about 75 km to the west. Although direct evidence for volcanic activity in the troughs is lacking, the location of offshore seismic activity suggests that submarine volcanism likely continues within the Axarfjörður and Skjalfandadjúp Troughs. The age difference of rocks on opposite sides of the Husavík Fault is approximately 5 Ma, corresponding to the interpreted age of the TFZ. The Grimsey Fault lies entirely offshore, and its location is inferred from seismic records. 25-m contour bathymetry is from Rögnvaldsson et al. (1998). Contours of major magnetic anomalies (shaded isolines) are interpreted to mark the locations of subsurface magma, as at Krafla (Meyer et al., 1972; Jonsson et al., 1991).

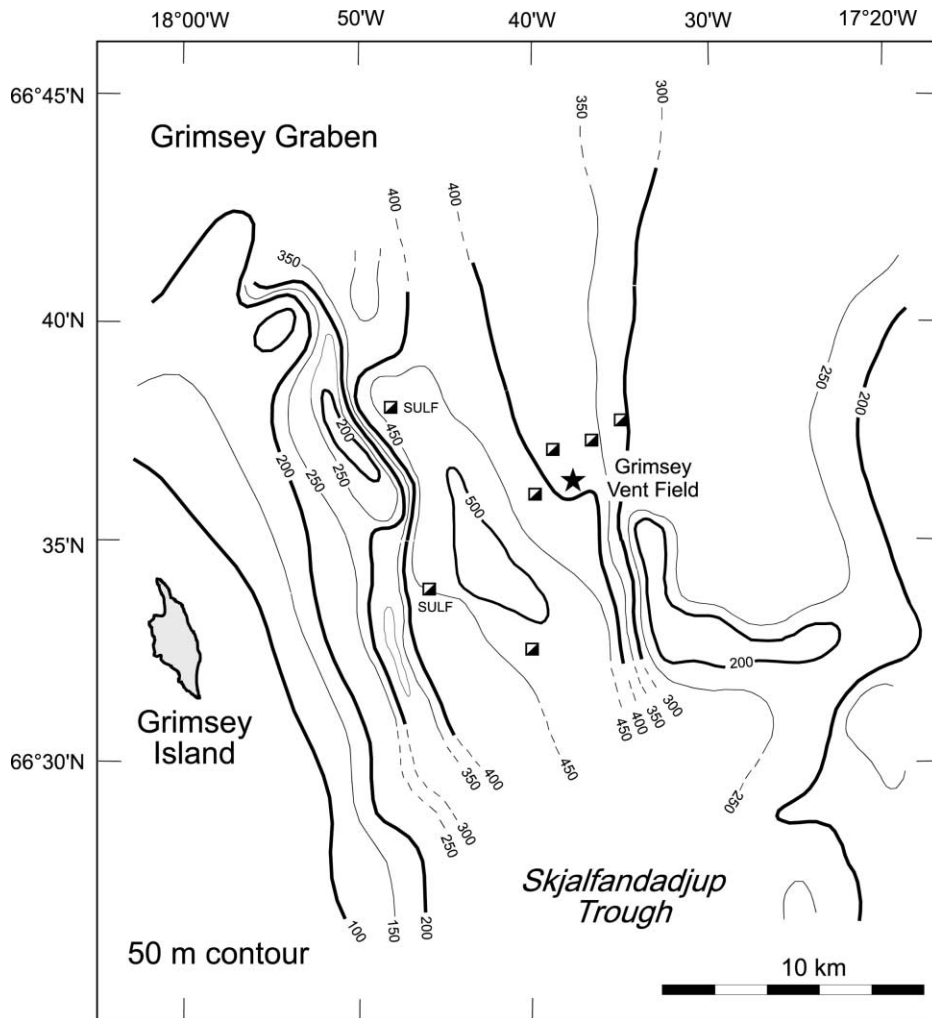


Fig. 3. Detailed bathymetry of the Tjornes Fracture Zone in the area east of Grimsey Island, reconstructed from 140 line-kilometers of 18 kHz echo-sounding. The main study area was a deep graben or pull-apart basin immediately east of Grimsey Island. The surveyed area is indicated by the star; other known or suspected sites of hydrothermal activity are also indicated. Pyritic sulfides were recovered in fishing nets from two locations; other occurrences are mainly anhydrite deposits.

adjacent to the island (J. Olafsson, personal communication). Several small samples of Fe-sulfides were also recovered at about 500 m depth. However, the extent and nature of the associated hydrothermal activity was unknown.

In 1997 and 1999, two research cruises aboard the German *R/V Poseidon* (229 and 253) were conducted in the Grimsey area by the University of Kiel, Freiberg University, the Geological Survey of Canada and the Iceland Technological Institute. Submersible operations were carried out at a maximum depth of

400 m using the research submarine *JAGO* from the Max Planck Institute in Seewiesen, Germany. This paper describes the first observations of high-temperature vents in the Grimsey graben and compares the geological setting of the massive anhydrite deposits with other known sediment-hosted submarine hydrothermal systems. The Grimsey vent field is the first known occurrence of significant hydrothermal activity in the North Atlantic, inside the Arctic circle, and one of the largest documented sites of high-temperature boiling at the seafloor.

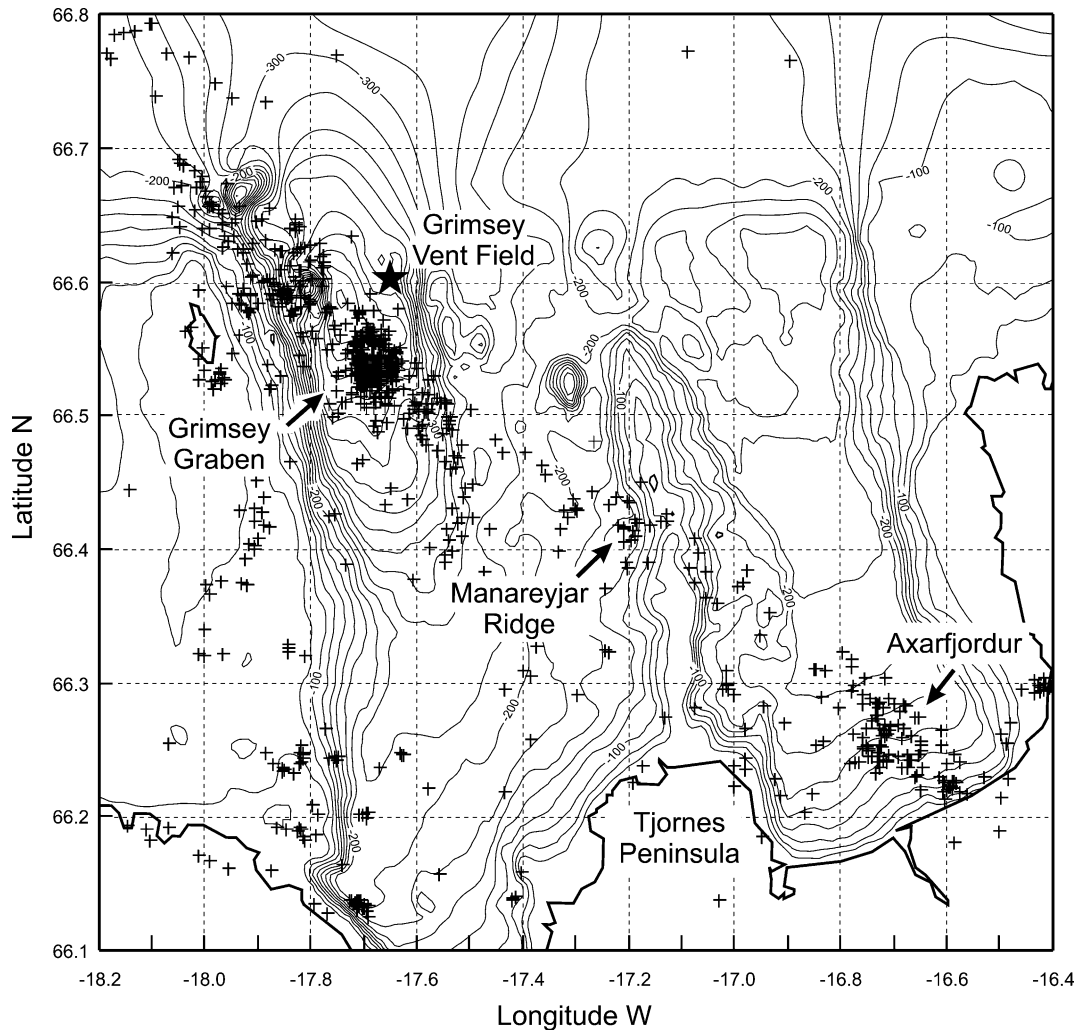


Fig. 4. Locations of earthquake epicenters in the Tjornes Fracture Zone for the year 1998–99 (from the database of the Icelandic Meteorological Office, Geophysics Department). All earthquakes with magnitude greater than 1 are shown. In recent years, the most intense seismic activity has occurred at the intersection of the Grimsey Fault and the northern Skjalfandadjup Trough. The earthquakes are associated with movement on NNW trending normal faults such as those within the Grimsey graben. Several magnitude 7 earthquakes have occurred in the Grimsey area since 1700 A.D., and a major earthquake swarm was recorded just four days before the rifting episode that led to the 1975–1984 Krafla eruptions (Einarsson, 1991; Rögnvaldsson et al., 1998). A more detailed analysis of earthquake swarms in the TVZ during 1994–1998 is provided by Rögnvaldsson et al. (1998).

## 2. Structure and bathymetry

The Grimsey graben is a sub-basin of one of three main pull-apart structures within the Tjornes Fracture Zone. These are the Axarfjordur, Skjalfandadjup and Eyjafjordur Troughs (Fig. 2). The main rift grabens are up to 20 km long, 8 km wide and 400–700 m deep and are bounded by NNW-striking normal faults.

Eyjafjordur and Skjalfandadjup developed as successive spreading centers within the Tjornes Fracture Zone about 4 Ma ago, and Axarfjordur is thought to have been the principal locus of extension for the last 1 Ma (Saemundsson, 1974). Two axial magnetic anomalies are still evident within the Skjalfandadjup and Eyjafjordur Troughs, east and west of Grimsey Island (Jonsson et al., 1991), and records of seismic

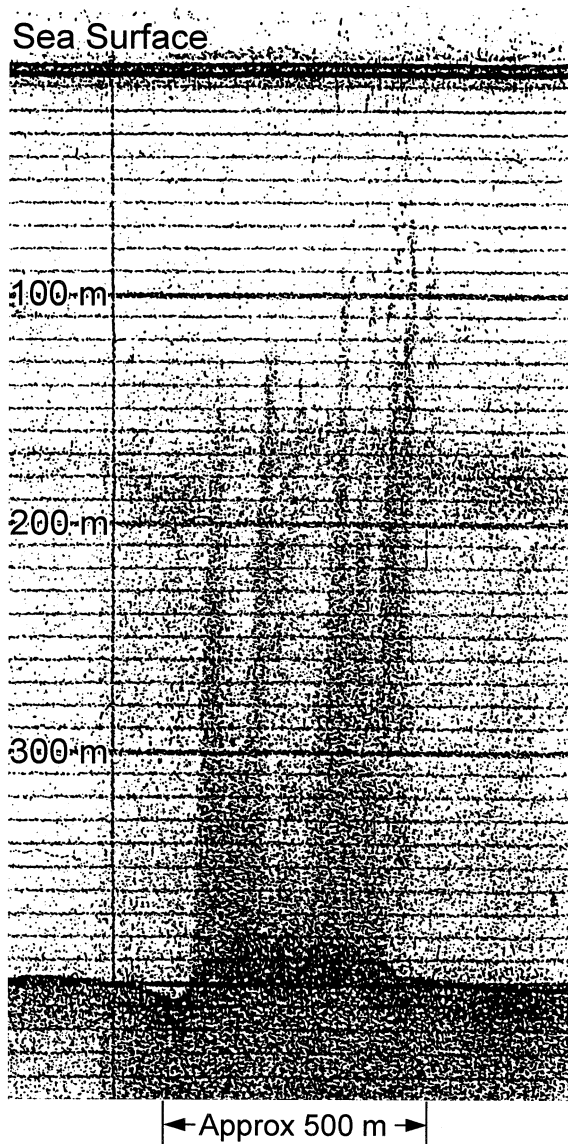


Fig. 5. Steady-state bubble plume in the water column above the main Grimsey vent field (18 kHz south-to-north profile). Acoustic scattering is most intense near the seafloor and the bubbles appear to disperse prior to reaching the sea surface. Although lateral spread of bubble plumes may occur close to the sea surface (e.g. Ernst et al., 2000), the plume profile shown here suggests that this is not happening at Grimsey. The location of the traverse is shown in Fig. 7 and the lateral extent of the plume is shown in Fig. 9.

activity indicate that significant extension may be continuing in both grabens (Thors, 1982; Einarsson, 1991; Rögnvaldsson et al., 1998). Post-glacial submarine volcanism has also been documented in this area (Saemundsson, 1974; McMaster et al., 1977), with the most recent submarine eruptions occurring on the Manareyjar Ridge (1867–68), a short distance north of the Tjornes Peninsula (Thorarinsson, 1965).

Extension within the Tjornes Fracture Zone is accommodated by a series of parallel WNW-striking transform faults, dominated by the Husavik–Flatey Fault in the south and the Grimsey Fault in the north (Fig. 2; Einarsson, 1991; Rögnvaldsson et al., 1998). Right-lateral motion on these faults is considered to be the main cause of subsidence in the area. A zone of intense seismic activity at the north end of the Skjalfandadjup Trough (Fig. 4) is thought to be related to motion on normal faults within the graben, although some earthquakes may record shallow subsurface magmatic activity, as in the Northeast Rift (e.g. Björnsson, 1985). The main seismic swarms in the graben occur immediately south of the Grimsey hydrothermal field.

The subsiding Eyjafjordur and Skjalfandadjup Troughs are separated by a NS-trending volcanic high, which includes the island of Grimsey and the Grimsey shoal. The grabens are filled by glacial sediments and volcanic material dating back to the initiation of rifting in the Tjornes Fracture Zone (Saemundsson, 1974; Einarsson and Albertsson, 1988). The depth to the volcanic basement in the Grimsey graben is not known, but the sediment thickness is probably similar to that in the other grabens in the area. Seismic profiles indicate that as much as 500 m of sediment occurs in Eyjafjordur Trough, and more than 2 km of sediment has been documented in the depression adjacent to the Husavik Fault (Strauch, 1963; Johnson, 1974; Flovenz and Gunnarsson, 1991; Sturkell et al., 1992). Drilling west of the Tjornes Peninsula also encountered up to 500 m of sediment, and the depth to the Tertiary basement within the Axarfjordur depression is at least 400 m (Saemundsson, 1974). A considerable amount of sediment continues to enter the grabens from ice-fed rivers draining the north coast of Iceland (e.g. Jökulsá and Skjalfanda rivers), and thick hyaloclastite deposits associated with recent eruptions are also present in the graben fill.

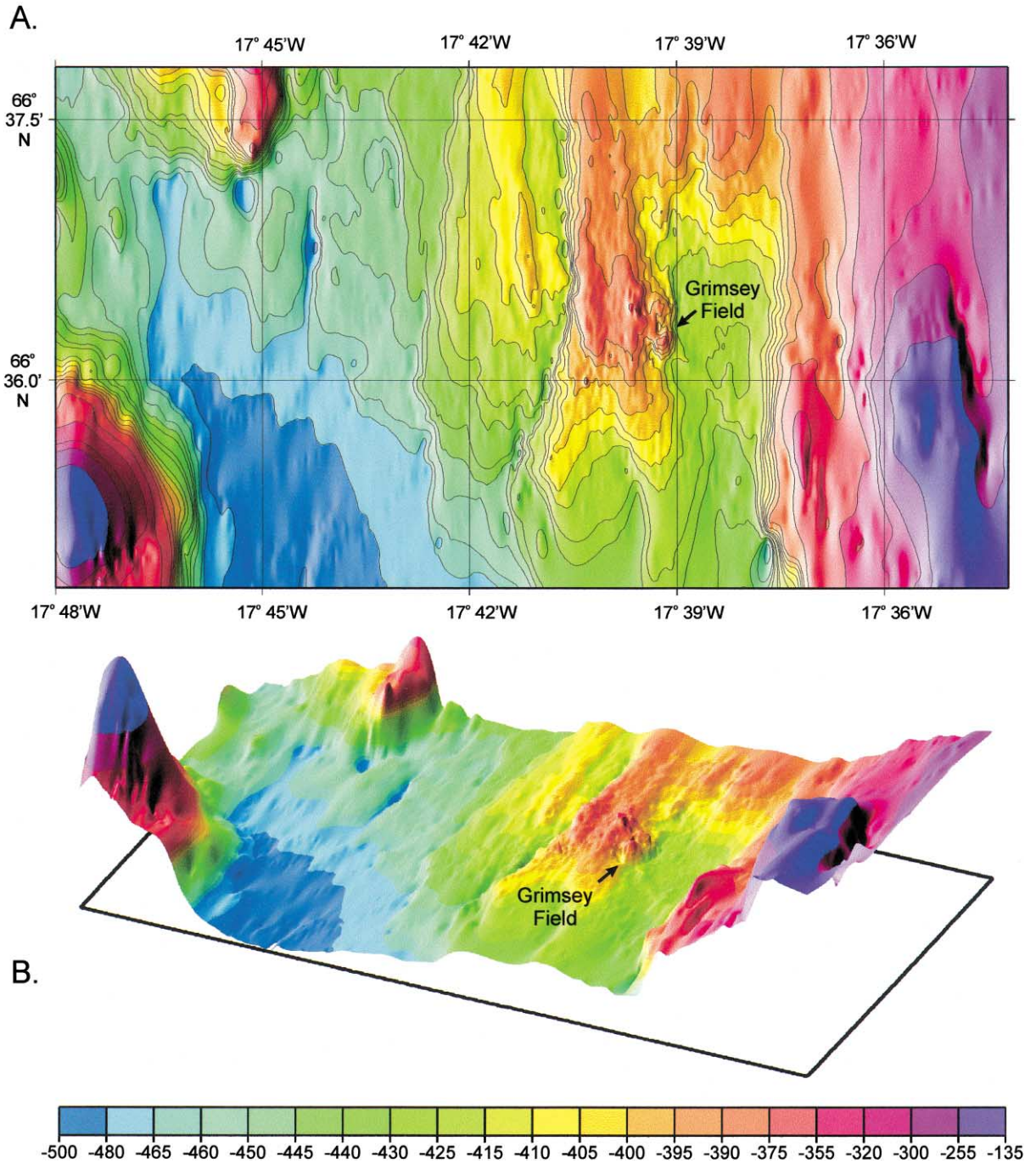


Fig. 6. (A) Color bathymetry of the eastern part of the Grimsey graben compiled from single-channel echo-sounding data. A–B corresponds to the location of a reflection seismic profile shown in Fig. 7. (B) Oblique view looking northwest (2X vertical exaggeration). The main vent field is located on the east side of a prominent structural high on the valley floor. A satellite feature at the edge of this structure corresponds closely to the location of the main anhydrite mounds. Observations from the submersible suggest that it may be composed entirely of massive anhydrite. Contour intervals vary according to the density of data available.

## Poseidon 252 (Profile 24) SW to NE

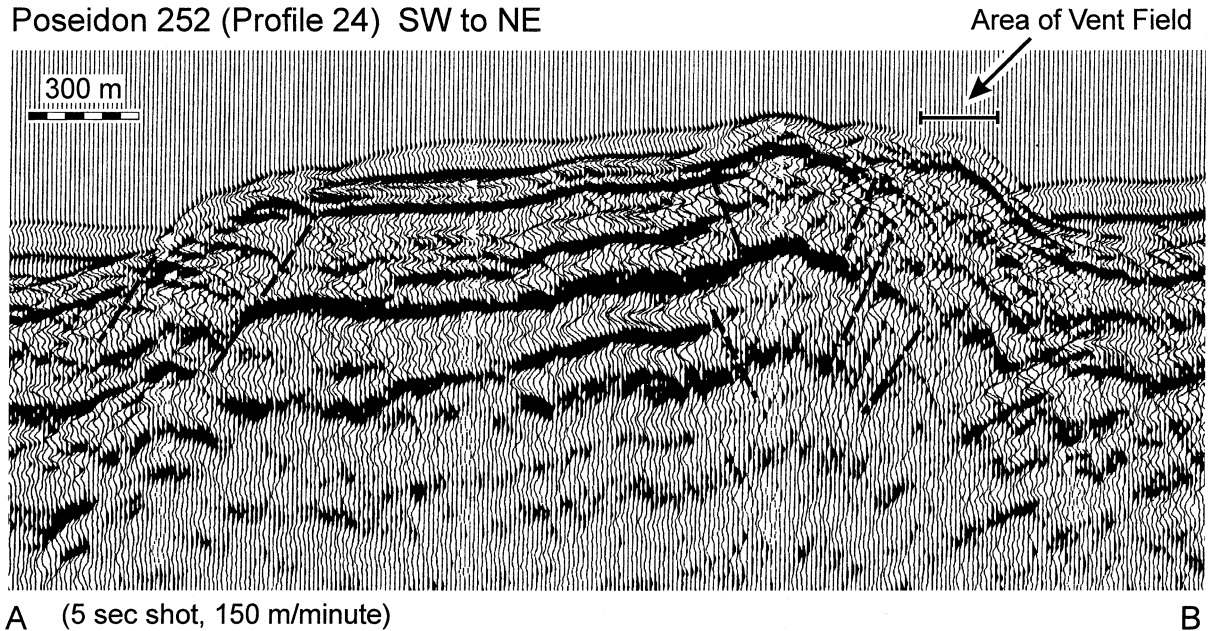


Fig. 7. SW to NE reflection seismic profile across the main structural high of the Grimsey vent field (A–B in Fig. 6). The satellite feature, interpreted to be mainly massive anhydrite, is less transparent to seismic waves than the substrate and has a high scattering effect. Apparent phase reversals in the record beneath the Grimsey field may correspond to subsurface gas accumulations in the sediments (Riedel et al., 1999). Buried normal faults at the margins of the structural high are indicated by the bold lines; smaller faults are inclined toward the center of the high.

### 3. Methods

Active hydrothermal vents in the Grimsey graben were located by the strong acoustic scattering in the water column caused by a large gas-rich plume. Although bubbles were not observed at the sea surface, the plume was readily detected in 18 kHz echo-sounding profiles over the vent field (Fig. 5). Subsequent observations with the submersible confirmed the presence of gas-rich vents at the seafloor. Approximately 140 line-km of profiling was carried out in the area, and the compiled single-channel bathymetric data are shown in Fig. 6. A reflection seismic profile across the map area is shown in Fig. 7.

Preliminary mapping with the submersible *JAGO* in 1997 located the first active hydrothermal vents at depths of between 380 and 400 m. Follow-up mapping in 1999 revealed a large field of anhydrite- and talc-rich mounds and chimneys, with more than 20 discrete vent sites covering an area of at least 1 km<sup>2</sup>. A total of 10 *JAGO* dives were conducted in

the vent field (Fig. 8), and approximately 100 kg of hydrothermal material were recovered from the active vents. An extensive sediment coring program was also carried out in 1999. Gas and water samples were collected from the active vents using 10 l niskin bottles and glass bottles deployed from the submersible. Temperatures of the vent fluids were measured with a digital temperature probe inserted through the hull of the sub. Details of the sampling are given in Stoffers et al. (1997), Botz et al. (1999) and Scholten et al. (2000).

### 4. Grimsey vent field

The main vent field is located at the eastern edge of a prominent, 30–40 m structural high on the eastern side of the Grimsey graben (Fig. 6). The origin of this horst-like feature remains uncertain but may represent differential topography produced by normal faulting and subsidence. North–south trending normal faults adjacent to the structure are evident in the bathymetry



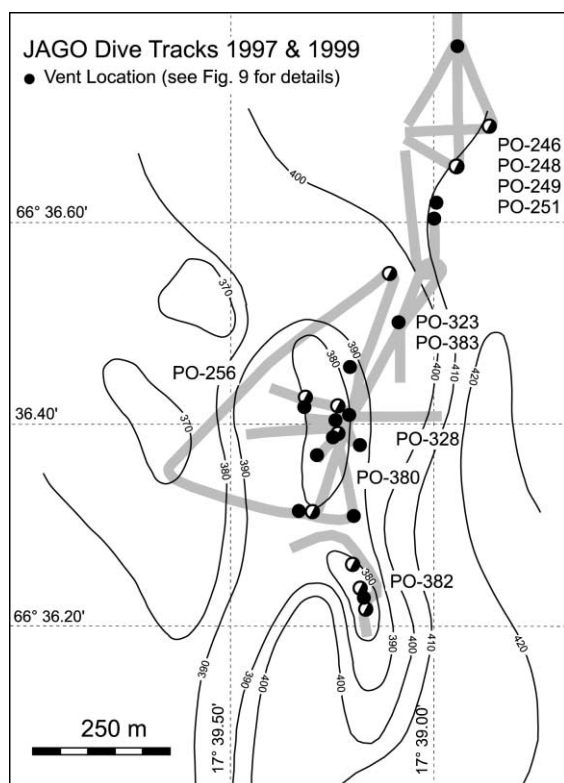


Fig. 8. Plot of dive tracks of the submersible *JAGO* from *R/V Poseidon* cruises during 1997 and 1999. Navigation was by dead reckoning and was facilitated by placement of buoys and markers. More than 5 km of traverses were conducted in the area.

and in the reflection seismic records (Fig. 7). The vent field occurs on a mound-like satellite feature that is clearly visible on the eastern flank of the main structure. Seafloor observations revealed a heavily sedimented bottom, with large parts of the main vent field buried by pelagic and terrigenous volcanic material. However, mapping during *JAGO* dives and follow-up sediment coring suggests that the satellite feature may be constructed entirely of coalesced hydrothermal mounds.

Three main areas of venting were found in the Grimsey field (Fig. 9): (1) a northern field consisting of isolated mounds and solitary anhydrite chimneys, (2) the central field consisting of large coalesced anhydrite mounds, and (3) a smaller southern field of older but still active mounds. An apparent north–south alignment of the vents suggests that their distribution is likely controlled

by a buried structure, similar to the faults bounding the main structural high.

The area of most active venting in the central portion of the field contains 13 large anhydrite mounds. These mounds have coalesced to form an elongate ridge about 300 m long and 200 m wide. Individual mounds in the main part of the field are large-diameter, low-relief structures, up to 10 m across and 3–5 m high, and are capped by numerous 1–3 m tall anhydrite- and talc-rich chimneys (Figs. 10 and 11). Thick crusts of anhydrite occur on top of the mounds and commonly show cracks which may be a result of growth by inflation. Most of the mounds are also littered with chimney fragments and anhydrite debris. The abundance of this talus suggests that the mounds have likely accumulated over time from the ongoing collapse of unstable chimneys. Silt and mud have accumulated in depressions between the mounds, but white patches of anhydrite in the sediment and widespread shimmering water indicate that the entire field is thermally active and that much of the substrate may be composed of massive anhydrite. Outside the main part of the vent field, the bottom is heavily sedimented and has an undulating or hummocky appearance which may reflect the presence of older, buried mounds. Collapse pits in the sediment may indicate where buried anhydrite has dissolved. Locally, fractures or fissures were also observed in the sediment. No vent-specific macrofauna were observed at the seafloor, although a solitary scale worm was recovered on an active chimney.

Another coalesced mound, up to 100 m long, occurs south of the main field, along the same structural trend (site PO-382; Fig. 9). At least one active vent is present on the mound, but overall this part of the field appears to be old. Several samples of reddish-brown mud and ocherous, Fe-rich sediment were recovered from this location, and the presence of oxidized talus suggests that these deposits may be part of an eroded vent complex.

Isolated chimneys and mounds were also found up to 700 m to the north of the central vent field (sites PO-246, 248 and 249; Fig. 9). Solitary chimneys in this area protrude from the sediment and do not appear to have grown on obvious mounds. However, white patches and cracks in the surrounding sediment suggest that this area

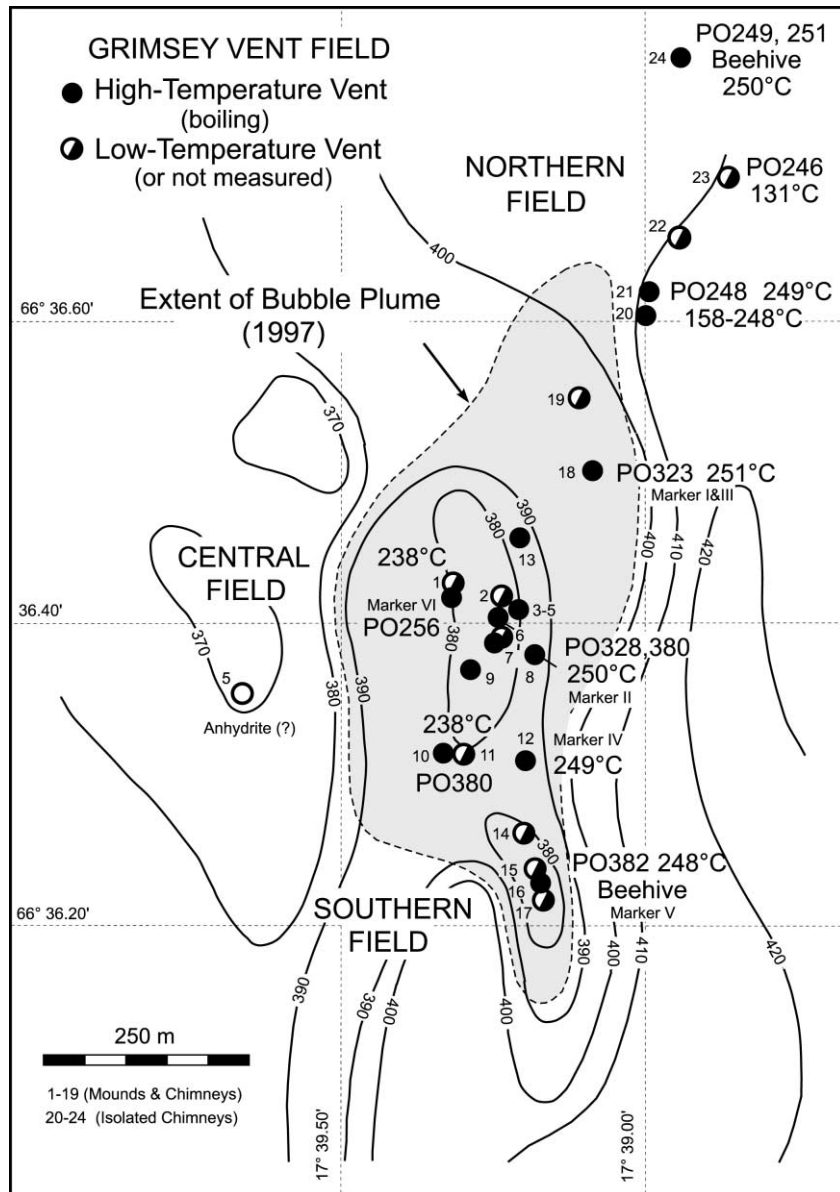


Fig. 9. Location of active vents in the Grimsey vent field. The area of most active venting contains 13 large anhydrite mounds clustered in the central portion of the field. An additional 11 chimneys and mounds are located outside the main area of venting. The shaded area shows the extent of the bubble plume observed in 18 kHz profiles (e.g. Fig. 5). The bathymetry is reconstructed from 23 line kilometers of single-channel profiling at 90-m line spacing. Measured vent temperatures are shown for the main active vents. PO numbers at the different sites refer to specific *JAGO* dives during which temperature measurements and samples were taken.

is also underlain by anhydrite. Dive PO-251, which traversed an area up to 1 km to the north, did not encounter any additional chimneys or mounds.

#### 4.1. Active vents

Most of the high-temperature fluid is discharged through narrow 'candlestick chimneys' protruding

## Anhydrite+Talc Mounds: Grimsey Vent Field

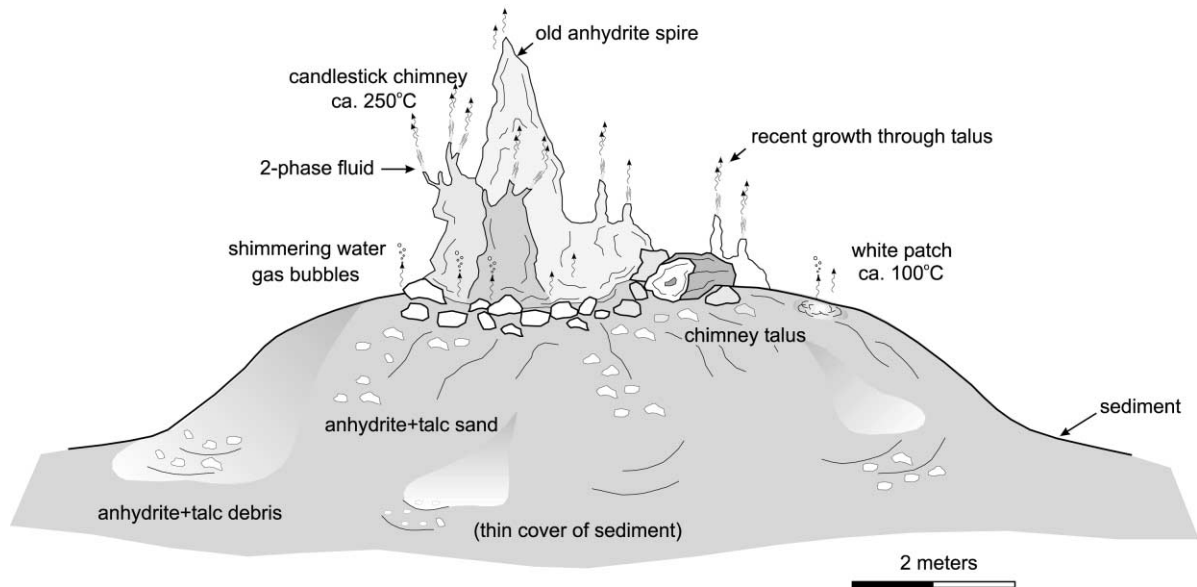
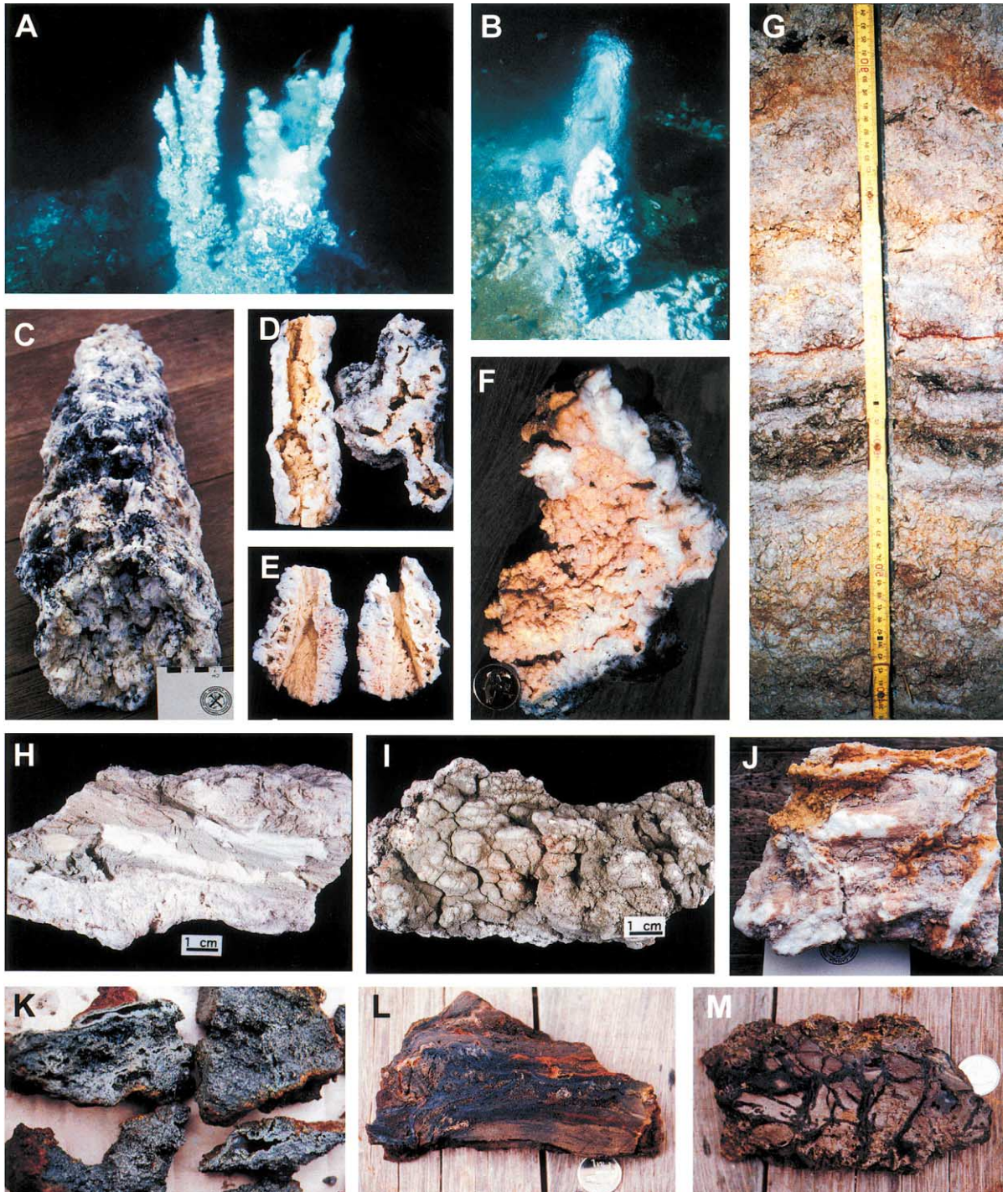


Fig. 10. Sketch of a typical anhydrite mound in the center of the main vent field. The mounds are large-diameter, low-relief structures capped by 1–3 m tall anhydrite–talc chimneys. New chimneys are commonly observed growing through the anhydrite rubble at the base of the collapsed spires.

from large anhydrite spires (Figs. 10 and 11A). The largest chimneys are up to 4-m tall and have as many as 10 outlets. In almost all cases, the measured temperatures of the vents were between 248 and 251°C (see Fig. 9), which is close to the boiling temperature of seawater at 400 m depth. Individual vents have a distinctive flame-like or torch-like appearance caused by H<sub>2</sub>O vapor (i.e. steam) that condenses rapidly within a few centimeters of the opening. The characteristic ‘flashing’ at the vent orifice is similar to that described at other phase-separated vents on the Juan de Fuca Ridge (Massoth et al., 1989; Butterfield et al., 1990; 1994a). Several chimneys that were knocked over produced a vigorous flow of clear, two-phase fluid from large 10–20 cm diameter orifices at the base of the spires. The visible effects of phase separation were observed at all 13 of the high-temperature mounds in the main part of the field as well as at isolated chimneys along the entire 1-km strike length of active venting. The fact that very few of the vents were less than 250°C suggests that the temperature of the entire field is controlled by open-system boiling. Also, because the measured tempera-

tures were close to the boiling temperature of pure seawater, the fluids discharging from the chimneys do not appear to be over-pressured by a high gas content.

Surface temperatures in the sediments on top of the mounds are between 50 and 80°C, with the highest temperatures above white patches of partly exposed anhydrite. In several cases, steady temperatures of between 110 and 150°C were found by inserting the probe to a depth of 10 cm in the sediments, indicating that entire mound may be inflated with hydrothermal fluid. Diffuse venting of clear water was observed from the small excavations in the sediments where the temperature probe was inserted. Although many of the large spires have a thin veil of filamentous bacteria, indicating diffuse flow through the chimney walls, the patchy distribution of bacteria on the surfaces of the mounds suggests that the fluids do not contain enough sulfur to support large bacterial colonies. A smell of H<sub>2</sub>S was apparent when chimney samples were recovered on deck, but the absence of smoke in the venting fluids confirms that the concentrations of metal and sulfur are low.



Gas was observed streaming from small holes in the sediments surrounding the vents, and in places large gas pockets were found trapped in the sediments. The presence of bubble streams well away from the high-temperature chimneys suggests that this gas may have originated at greater depth below the seafloor. The separate discharge of high-temperature fluids and bubbles implies different pathways for the rising gases and fluids, similar to the situation described for phase-separated vents on the Juan de Fuca Ridge (e.g. Butterfield et al., 1990). The bubble plume observed from the surface ship is thought to be produced by gas bubbles that coalesce above the vents and expand as they rise through the water column.

#### 4.2. Hydrothermal precipitates

The largest chimneys are composed almost entirely of anhydrite and talc. They typically have thick outer walls of massive anhydrite and complex internal structures with tortuous fluid channelways. The vent orifices and the inner walls of the chimneys are lined by colloform and botryoidal talc (determined by XRD). Thick masses of talc, up to 1 cm, overgrow the anhydrite and locally clog the chimney orifices. This talc has a pinkish brown to pale yellow or dull green color, which changes to pure white after several days exposure to air (Fig. 11F). Frequent collapse of the chimneys is responsible for the abundant anhydrite and talc sand that covers the surface of the mounds. The instability of the chimneys reflects the poor constructional characteristics of the anhydrite

and the absence of other minerals to cement the structures. Despite the abundant CO<sub>2</sub> in the vapor phase and the high alkalinity of the vent fluids (see below), carbonate minerals are not present in the chimneys.

Trace amounts of gray to black Fe-sulfides occur in the walls of the chimneys, but the presently venting hydrothermal fluids do not contain enough metals or sulfur to precipitate abundant sulfides. Fe-oxide staining was also observed on several of the inactive mounds. However, there is no obvious halo of discoloration in the sediment, as might be expected from the erosion of sulfide-bearing deposits. Rusty pyrite–marcasite crusts (Fig. 11K) were recovered from a partially eroded mound at the southern edge of the main field (site PO-380), but similar sulfides were not observed at the active vents. Silicified Fe-oxides and siliceous sinter-like material enclosing red ochre (possibly weathered pyrite) were also found in the southern part of the field (site PO-382; Fig. 11L–M).

#### 4.3. Results of sediment coring

Seventeen 3- and 5-m gravity cores were taken across the Grimsey vent field (Fig. 12). In the area of active venting, the cores penetrated up to several meters of unconsolidated anhydrite debris and talc-rich sand and stopped in highly indurated and hydrothermally altered mud. A number of the cores were steaming when they were brought to surface, and hot seawater trapped in the sediments was still boiling on the deck of the ship. In these ‘hot cores’, temperatures of up to 102°C were measured with a probe inserted in the sediment at the ends of the core barrels, and almost

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Fig. 11. Bottom photographs and samples of hydrothermal precipitates from the main vent field. (A) Candlestick chimney on top of an anhydrite mound in the central part of the main field. The small flame-like feature at the orifice of each small vent is created by phase separation. The field of view is 3 m across. (B) Small anhydrite chimney protruding from sediment in the northern part of the field. The white patches surrounding the chimney are part of the anhydrite substrate. The field of view is 1 m across. (C) Top of an anhydrite chimney (PO251-1). The interior of the chimney is filled with soft anhydrite. Scale bar is in centimeters. (D) Cross-sections of two small candlestick chimneys from A (PO328-1). The walls of the chimney are 1 cm thick anhydrite and are coated by pale yellow talc. (E) 5 cm chimney tip from a small candlestick chimney (PO323-5). Dendritic growth of anhydrite is characteristic of the leading edge of growth at the narrow vent orifice. (F) Large fragment of a chimney wall (coin is 2.5 cm). The inner wall is lined by colloform masses of pale pink talc. (G) Section of massive anhydrite and talc from gravity core SL347 (1.0–1.5 m). Darker pink layers are dominated by talc sand. (H) Interior of massive anhydrite chimney (PO251-3) showing the intergrowth of anhydrite (white) and dull green talc. (I) Massive colloform talc (gray green) overgrowing massive anhydrite, from the inner wall of PO246B-1. (J) Massive anhydrite block from the base of PO323-4. The pale pink-brown material is talc. Note the late-stage vein of anhydrite (lower right) cutting through the massive anhydrite. (K) Crusts of pyrite and marcasite from a relict mound at the south end of the main Grimsey field (PO380-1). The largest sample is 20 cm across. (L) Silicified Fe-oxide material (sinter) exposed at the edge of an older mound the southernmost part of the vent field (PO382-2). (M) Massive anhydrite (now gypsum) and baked mud from an older mound in the southernmost part of the vent field (PO382-2). Cracks in the anhydrite and mud have been intensely silicified and partially filled by dark amorphous silica.

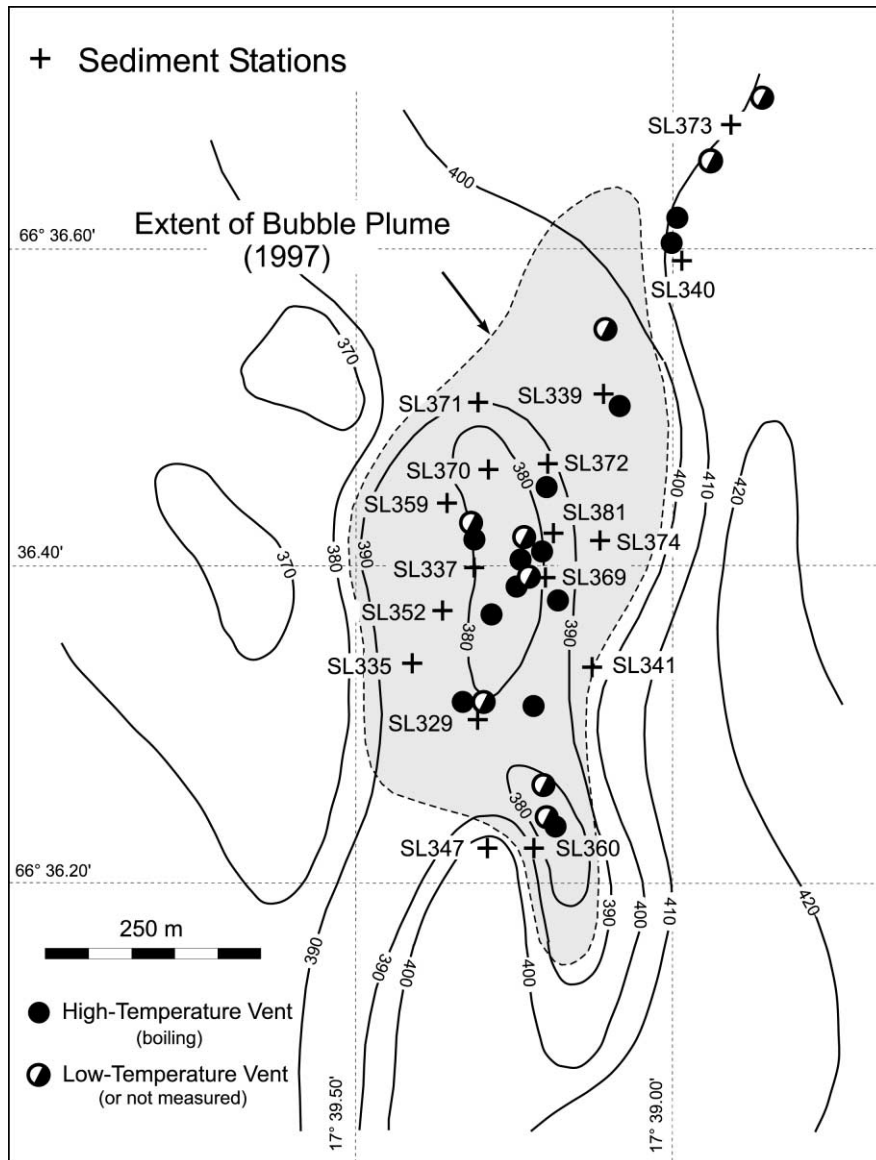


Fig. 12. Locations of 3- and 5-m sediment cores in the Grimsey vent field.

all of the cores had temperatures of 25°C or higher (ambient is 1.5°C). The hottest cores map out an area of extremely high heat flow surrounding the main hydrothermal mounds and presumably delineate the extent of a subseafloor boiling zone (Fig. 13). Typical cores contained 85% altered hemipelagic mud, 10% talc- and anhydrite-rich sandy layers, and 5% hyaloclastite or ash-rich layers. Burrows and other evidence

of biological activity were notably absent in all of these cores.

Seven gravity cores located in the central part of the main field (SL337, 339, 369, 370, 372, 374, and 381) had temperatures in the core catchers between 65 and 102°C, and four of the cores contained boiling fluids. In several cases, large cavities developed within the core barrel due to the expansion of trapped gases,

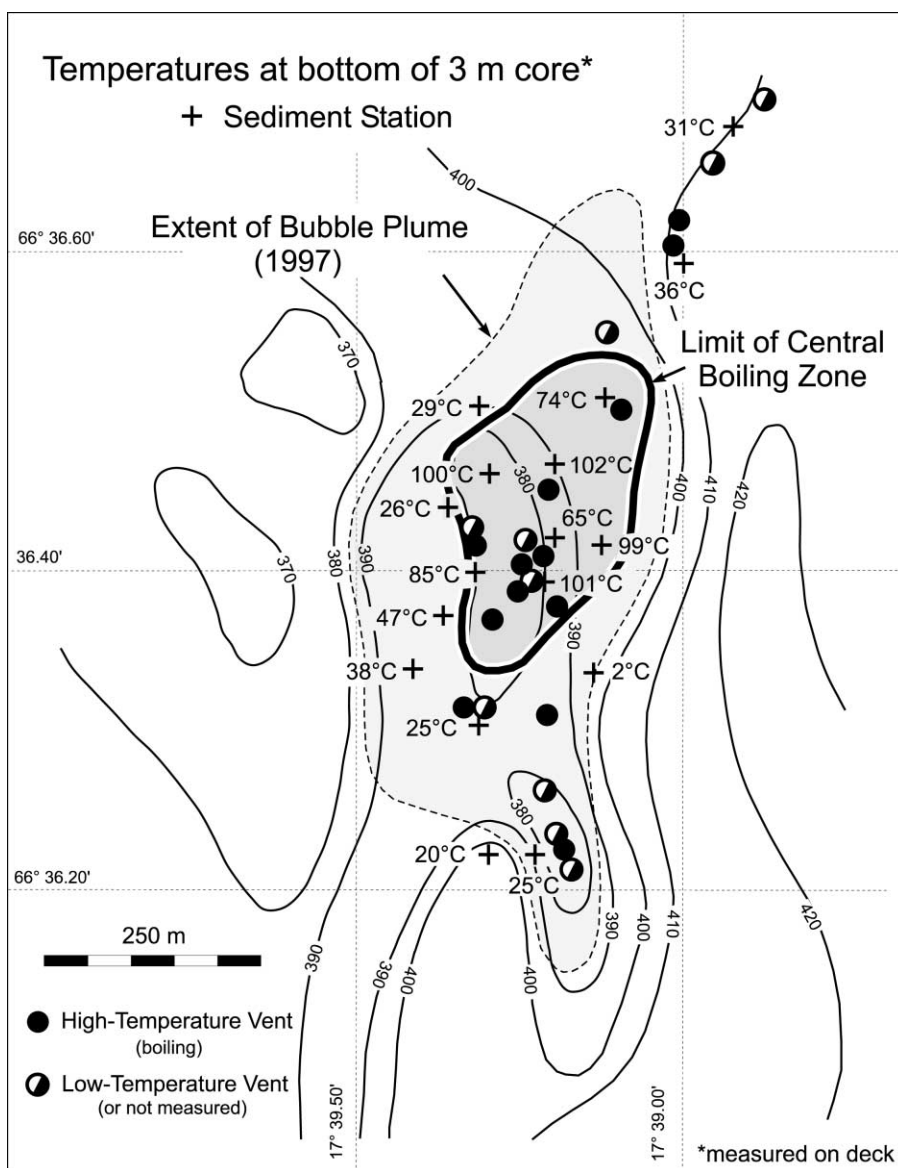


Fig. 13. Temperatures measured in muds at the bottom of the sediment cores. Temperatures at or close to 100°C are assumed to represent boiling fluids in the subsurface and map out the lateral extent of the central boiling zone.

causing some of the core to be lost. Temperatures at the tops of the core barrels were also well above ambient (16, 63 and 65°C). In several cases the upper 1–2 m of sediment may have been lost due to superpenetration of the core barrel (e.g. Fig. 14). However, the high temperatures of the uppermost sediments in the cores are consistent with the high temperatures in surface sediments measured at the seafloor.

The hottest cores almost always contained thick sections (up to 1 m) of anhydrite and talc (Fig. 11G). These layers consist of poorly sorted, talc and anhydrite sand, which is thought to be derived from the collapse of chimneys and the gradual breakdown of the chimney debris. The sand-sized fragments of talc, in particular, have the characteristic botryoidal habit of massive talc found lining the active chimneys.

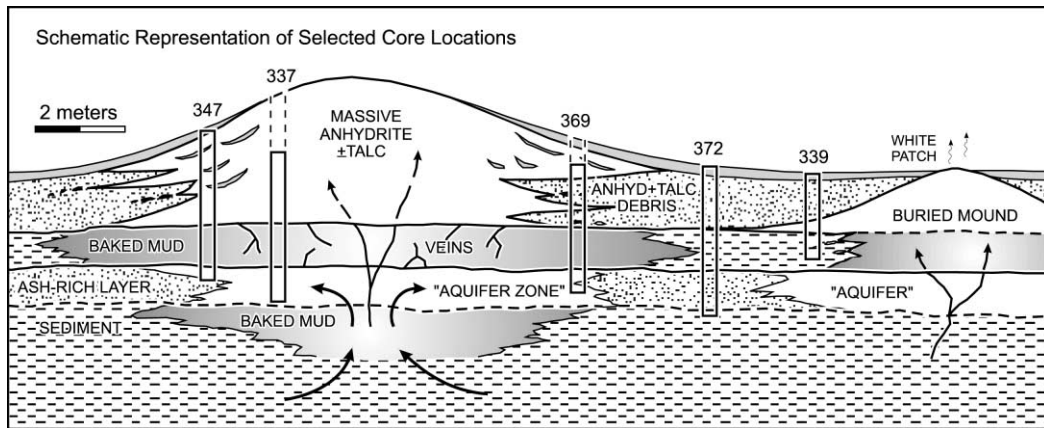


Fig. 14. Schematic representation of selected core locations in the central part of the vent field.

Cores in the depressions between the mounds contain multiple talc- and anhydrite-rich layers, intercalated with baked mud and minor ash. In several cases, the abundance of anhydrite decreases with depth, presumably due to post-burial dissolution. The locally abundant talc at the bottom of the cores could also be explained by dissolution of anhydrite from the sediments. Some cores contained patches of brown, amorphous gel-like material that appears to be altered or neoformed talc. Core SL360, located on an inactive mound at the southern end of the field contained a rusty brown layer that may have been oxidized sulfide material.

A number of the cores bottomed out in coarse, unconsolidated layers consisting of sandy talc and gravel-sized anhydrite clasts in a matrix of blue-gray altered muds. These porous horizons contain abundant free pyrite as fine needles, blades, flakes and dendrites, together with minor amounts of crystalline barite. Similar hyaloclastite or ash-rich beds, up to 50 cm in thickness, were also present in many of the cores, and these layers also contained minor disseminated pyrite.

Most of the cores stopped in hardened layers of baked mud which underlie the massive anhydrite and talc (Fig. 14). The baked muds are notably dehydrated and become hard and friable with increasing depth in the cores. Fracture-controlled alteration of the muds is evident in many cases. The fractures have distinctive light gray to blue-gray, bleached margins and are locally lined by pyrite. Fine pyrite (up to 2 vol%) is also common in open vugs and

disseminated throughout the baked mud. This is particularly evident in cores SL337 and SL369, which intersected zones of extensive blue-gray alteration and veining by pyrite.

Gravity cores located at the outer margins of the main field (SL371, 359, 352, 335, 329, 347, 360, 341) had measured temperatures in the core catcher between 2 and 47°C (Fig. 13). These cores contained 3–4 m of green-brown pelagic mud above hardened, clay-rich layers with fine disseminated pyrite and minor ash. The altered muds at the bottoms of these cores likely represent the limit of high-temperature alteration at the edge of the vent field. In areas of less intense alteration, away from the active mounds, the muds consist of pelagic ooze with only local dehydrated and altered patches. Gravity cores located in the northern part of the field (SL340, 373) recovered mainly greenish brown pelagic sediment, but with temperatures of 36 and 31°C in the core catcher.

#### 4.4. Preliminary results of fluid and gas chemistry

Shipboard measurements of the highest-temperature vent fluids indicate a pH of between 5.9 and 6.8 and high alkalinity (2.4–3.0 meq/l). Mg and SO<sub>4</sub> concentrations in the fluids are 37–44 and 20.6–25.7 mM, respectively, and most likely reflect mixing with seawater in the mounds or during sampling (C.D. Garbe-Schönberg, unpublished). The end-member chlorinity (274 mM), calculated according to Von Damm (1990), is about half of seawater chlorinity and supports the observation of phase separation in



the vents. The concentration of SiO<sub>2</sub> in the hydrothermal end-member is 11 mM, which is similar to that of hydrothermal fluids from other sedimented rifts (e.g. Guaymas Basin) and may reflect extensive reaction between the fluids and sediments below the mounds (e.g. Thornton and Seyfried, 1987; Von Damm, 1990). The abundance of highly reactive basaltic glass in buried hyaloclastite or ash-rich layers also provides a likely source for the high SiO<sub>2</sub> (Fournier, 1985). Although the fluids are saturated with respect to quartz at 250°C, poor nucleation kinetics at this high temperature probably accounts for the absence of silica in the chimneys (Fournier, 1985). The precipitation of talc in the interiors of the highest-temperature chimneys is a consequence of mixing between the SiO<sub>2</sub>-rich vent fluids and Mg-rich seawater. At high temperatures and low degrees of mixing, the small increase in pH caused by advection of seawater through the chimney walls can induce the precipitation of talc (Tivey and McDuff, 1990; Tivey 1995a,b).

Analysis of gas samples that were collected from the vents in 1997 and 1999 indicate that carbon dioxide and methane are the dominant gaseous species (Botz et al., 1999). The high CO<sub>2</sub> concentrations (up to 41 vol%) and  $\delta^{13}\text{C}$  values of  $-2.4$  to  $-3.0$  for the CO<sub>2</sub> gas are indicative of a largely magmatic source, as for other Icelandic geothermal waters (e.g. Poreda et al., 1992), with minor contributions from carbonate decomposition (Botz et al., 1999). The abundant CH<sub>4</sub> in the gas samples (up to 24 vol%) is derived mainly from thermal decomposition of sedimentary organic matter. This is confirmed by  $\delta^{13}\text{C}$  values of  $-26.1$  to  $-29.5$  per mil for the CH<sub>4</sub> and by the presence of higher hydrocarbons, up to butane (Botz et al., 1999). In other sediment-hosted hydrothermal systems, liquid hydrocarbons and bitumens are common products of the thermal decomposition of continentally-derived organic material (e.g. Middle Valley, Guaymas Basin). The absence of similar hydrocarbons in the mounds and chimneys at Grimsey likely reflects the lower organic carbon content of the sediments being shed from the barren volcanic interior of north Iceland.

High concentrations of dissolved CH<sub>4</sub> are present in the water column close to the vents. Concentrations of up to 560,000 nM were found in the vent fluids, and up to 1000 nM was found in the water column 10 m

above the vents. However, only background concentrations were found 100 m above bottom. The steep gradients in the plume are likely caused by mixing with ambient seawater and oxidation of the CH<sub>4</sub> (M. Schmidt, in Scholten et al., 2000).

## 5. Comparison with other sedimented rifts

The Grimsey vent field bears a striking resemblance to the Area of Active Venting (AAV) at Middle Valley on the Juan de Fuca Ridge (Davis et al., 1987; Ames et al., 1993; Goodfellow and Franklin 1993; Turner et al., 1993). This vent field covers an area of 500 × 200 m and consists of low anhydrite mounds and chimneys roughly aligned along a series of buried fault structures. The perimeter of the field is defined by a large area of anomalous high acoustic reflectivity caused by hydrothermal alteration of the underlying sediments (Davis et al., 1992). The hydrothermal fluids ascend through the sediments by diffusional upflow, as indicated by pore water composition (Lydon et al., 1990), and are focussed where the sediments have been hydrothermally indurated and fractured. The vent temperatures are between 184 and 287°C, and the dominant minerals are anhydrite, barite, Mg-silicates including talc, and minor sulfides (mainly pyrrhotite). Individual chimneys contain up to 5 wt% MgO as colloform, banded saponite within and lining the chimney walls (Ames et al., 1993), similar to the talc at Grimsey. Talc-like phases also occur in the sediments in areas of low-temperature (100°C) diffuse venting (Adshead, 1988; Turner et al., 1993; Percival and Ames, 1993), and the hemipelagic muds are characterized by a distinctive gray to blue-green alteration (Goodfellow et al., 1993), similar to that observed in the Grimsey cores. An important difference is the presence of well-developed sulfide stringers and local massive sulfides beneath the seafloor (Turner et al., 1993; Goodfellow and Peter, 1994). Large sulfide deposits were also found at nearby Bent Hill, where massive sulfides occur to a depth of up to 145 m in the sediments (Davis et al., 1992; Zierenberg et al., 1998).

Similar deposits occur in the sediment-covered Escanaba Trough on the Southern Gorda Ridge, where chlorite, smectite and talc occur as alteration of hemipelagic sediment surrounding partially

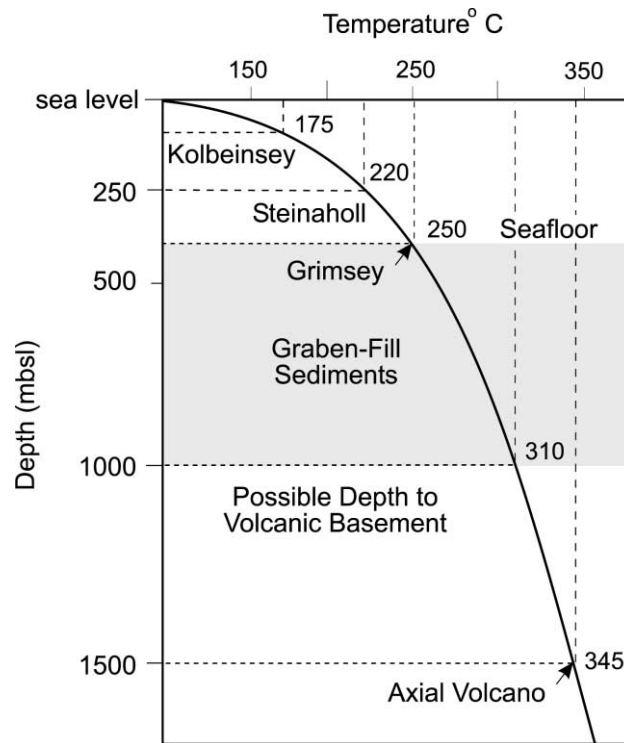


Fig. 15. Temperature-depth relationships on the boiling curve for seawater (modified from Butterfield et al., 1990), showing the boiling temperatures for seawater-dominated hydrothermal fluids at Grimsey, Kolbeinsey, Steinahóll, and Axial Volcano. The depth to basement below the anhydrite mounds at Grimsey (ca. 500 m) is estimated from published measurements of sediment thickness in nearby valleys (see text for discussion). Cooling of hydrothermal fluids that originate at the basalt-sediment contact may be sufficient to cause significant subseafloor deposition of sulfides within the graben fill.

exposed pyrrhotite-rich massive sulfide mounds (Koski et al., 1988, 1994; Zierenberg et al., 1993, 1994; Zierenberg and Shanks, 1994). In the Southern Trough of Guaymas Basin, in the Gulf of California, Mg-silicates are found in active black smoker chimneys forming on anhydrite mounds in the sediments (Lonsdale and Becker, 1985; Koski et al., 1985). Detailed paragenetic studies by Peter and Scott (1988) indicate that the Mg-silicates formed by mixing of SiO<sub>2</sub>-rich vent fluids with Mg-rich seawater at temperatures as high as 250–300°C. Low mounds with crusts of white talc (plus smectite and pyrrhotite) are also found in the Northern Trough at Guaymas (Lonsdale et al., 1980). Although these mounds were inactive at the time of sampling, temperatures of formation of the talc crusts are estimated to have been 280°C, based on oxygen isotope data. In this case, the Mg-rich fluids that produced the talc are

thought to be pore water expelled from the underlying sediment (Lonsdale et al., 1980).

The common association of talc, anhydrite, and pyrrhotite-rich sulfides at Middle Valley, Escanaba and Guaymas is a consequence of the similar vent fluid chemistry; i.e. metal- and sulfur-depleted, reduced hydrothermal fluids with high Mg and SiO<sub>2</sub> concentrations. The characteristically high pH and alkalinity of the fluids and their low  $fS_2$  and  $fO_2$  indicate extensive interaction with sediments (Von Damm et al., 1985; Campbell et al., 1988, 1994; Butterfield et al., 1994b). Entrainment of seawater into the hydrothermal upflow zones is thought to be responsible for the formation of Mg-silicates in the chimneys, and the loss of sulfur and metals by precipitation of sulfides within the sediments accounts for the low metal content of the hydrothermal fluids. A similar fluid history

could account for the observed mineralogy of the Grimsey vents.

## 6. Other boiling hydrothermal systems

Low-salinity, metal-depleted vent fluids, like those at Grimsey, have also been documented in a number of shallow-water boiling hydrothermal systems. Such fluids were first reported in the high-temperature ASHES vent field at Axial Volcano (Massoth et al., 1989), where vapor-phase venting occurs through a 1-m tall anhydrite chimney and a low mound of anhydrite debris (Virgin Mound: Hammond, 1990). Boiling in the ASHES field has had a major impact on the metal-carrying capacity of the hydrothermal fluids and likely has contributed to seafloor deposition of sulfides. The comparison with the Grimsey vents suggests that deposition of sulfides from boiling hydrothermal fluids may also be occurring within the graben.

Similar gas-rich vents were located on the Reykjanes Ridge in 1990 at 63°06'N (Steinahóll vent field: Olafsson et al., 1991; German et al., 1994). Researchers were initially attracted to the area by a seismic swarm that occurred in October–November 1990 (Olafsson et al., 1991). The vents were located by CTD measurements, total dissolved manganese, and acoustic scattering in the water column caused by a bubble plume. Underwater video images of the Steinhóll site showed areas of shimmering water at 250–300 m; however, neither high-temperature venting nor obvious seafloor hydrothermal precipitates were found. Because of the shallow water depth, vent temperatures at Steinhóll are unlikely to be as high as those at Grimsey (e.g. Fig. 15). Dissolved CH<sub>4</sub> concentrations in the bubble plume reached a maximum of 18 nmol/l (German et al., 1994), which is significantly higher than in typical mid-ocean ridge hydrothermal plumes but much lower than the values recorded in the Grimsey field.

Boiling hydrothermal vents have also been found on Kolbeinsey Ridge north of Grimsey. Hydrothermal activity, near Kolbeinsey Island, was first documented in 1974 by Icelandic researchers aboard the *R/V Bjarni Saemundsson* (Olafsson et al., 1989). The vents occur at 90 m depth and are mainly gas jets in small depressions within the volcanic-derived sand. In

1987, a maximum temperature of 89°C was recorded at the vents (Fricke et al., 1989), but direct observations of boiling implied a much higher temperature (up to 180°C: Olafsson et al., 1990). In 1997, *JAGO* visited the same site and measured temperatures as high as 131°C but still about 50°C below the boiling temperature of seawater at 90 m water depth. The low temperatures may reflect difficulty in obtaining accurate measurements or, more likely, a depression of the boiling temperature owing to the high gas contents of the fluids. The absence of any anhydrite chimneys or mounds surrounding the vents is presumably a consequence of the low temperatures (i.e. anhydrite is soluble in seawater at temperatures below 150°C).

## 7. Summary and conclusions

A variety of submarine hydrothermal systems have now been found in diverse geological settings along the offshore extension of the neovolcanic zone of Iceland, including on volcanic ridges such as the Kolbeinsey and Reykjanes ridges and in heavily sedimented rift grabens such as Grimsey. The accumulation of large anhydrite deposits at Grimsey implies that the present high-temperature venting has been long-lived, as any prolonged period of inactivity would have resulted in the dissolution of much of the anhydrite. The deposits in the main part of the field cover an area of more than 100 × 300 m. If we assume continuity to a depth of 10 m below the mounds and a bulk density for the hydrothermal material of about 3 tonnes/m<sup>3</sup>, the deposits at Grimsey could contain as much as 1 million tonnes of massive anhydrite and up to 100,000 tonnes of talc. Significant buried hydrothermal deposits could also be present in the graben, particularly if hydrothermal activity has been ongoing since the initiation of extension in the Tjornes Fracture Zone.

Hydrothermal fluid flow in the upper part of the sedimentary sequence at Grimsey is believed to be channeled through buried aquifers in the sediments below the mounds. Heating of muds above these aquifers and the development of shrinkage cracks in the overlying sediments has provided the pathways for the hot fluids to the seafloor. Similar alteration and fracturing of the sediments at Middle Valley has focussed the discharge above major basement faults, as much

as 500 m below the valley floor, and created the subsurface conduit or stockwork for hydrothermal fluids that are presently venting at the seafloor (Goodfellow and Franklin, 1993; Goodfellow and Zierenberg, 1999). Depending on the depth to the volcanic basement at Grimsey, temperatures at the basalt-sediment contact could be as high as 300°C, based on the temperature-for-depth relationships on the boiling curve for seawater (Fig. 15). This is similar to the temperature estimated for hydrothermal fluids at the contact with the volcanic basement below Middle Valley (Davis and Fisher, 1994). Such fluids could be responsible for significant subseafloor deposition of sulfides in the Grimsey graben.

The hydrothermal field at Grimsey is similar in size to many of the largest thermal areas on land in Iceland, and the measured vent temperatures are close to the reservoir temperatures in nearby producing geothermal fields such as Krafla (e.g. Arnorsson, 1978; Arnorsson and Gunnlaugsson, 1985; Ármannsson et al., 1987). The intense hydrothermal activity may reflect proximity to a magmatic heat source in the Skjalfandadjup Trough or simply deep penetration of the fluids into heated basement rocks. The highly tectonized crust in the Tjornes Fracture Zone may be an important factor in promoting hydrothermal circulation in the Grimsey graben. A number of researchers have attributed productive hydrothermal upflow in similar areas of ridge offsets or transverse tectonic zones to the intense fracturing of the crust and the development of pathways for deep circulation of hydrothermal fluids, even in the absence of magma close to the seafloor (Taylor et al., 1994; Wilcock and Delaney, 1996; German and Parson, 1998). Although Axarfjordur is thought to have been the main site of extension for the last 1 Ma, the discovery of high-temperature hydrothermal activity east of Grimsey suggests that the Skjalfandadjup Trough has remained active and may continue to be an important locus of spreading within the Tjornes Fracture Zone.

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