CHAPTER 5

# SEA-FLOOR MASSIVE SULPHIDES IN ARCTIC WATERS

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Until quite recently the mid-ocean ridges in the Arctic were some of the least explored parts of the global ridge system. However, the interest for these waters has been large, e.g. because of the ultra-slow spreading rates, their proximity to continental margins and large accumulation of sediment in parts of the ridges (hydrocarbon potential), and because of ridge hot-spot interaction and unusually shallow ridge segments in the southern parts.

Systematic mapping and exploration of the ridges to the north of Iceland started in the late 1990s and a large number of active and inactive venting sites have been documented all the way from Iceland into the so-called Eurasia Basin (Figure 1, Pedersen et al., 2010 b). The Arctic ridge system includes six major segments, which from south to north are the Kolbeinsey Ridge, Mohns Ridge, Knipovich Ridge, Molloy Ridge, Lena Trough and Gakkel Ridge.

A significant part of this 4000 km long ridge system is in Norwegian waters where the Centre for Geobiology at the University of Bergen has carried out numerous expeditions.

The southern segment of the Arctic ridge system, the Kolbeinsey Ridge and the southern Mohns Ridge, is strongly impacted by the hotspots under Iceland and Jan Mayen, leading to elevated topography and increased volcanic activity (see Pedersen et al, 2010 b and references therein, Elkins et al., in press, see also the Iceland chapter in this volume). Further north, the magmatic activity and the crustal thickness decrease, and spreading centres and rift valleys become deeper and pronounced. Whereas the ridge is oriented at a right angle to the spreading direction at the southern and northern part of the ridge system (orthogonal spreading), the central segments of the ridge system (i.e. the Mohns and the Knipovich ridges) are characterised by oblique spreading.

## Grimsey Field

The Grimsey Field was discovered in 1997 and is therefore well-studied. It is situated only about 30 km off-shore of the Grimsey Island in a sedimented graben in the Tjörnes Fracture zone (Figure 1 and Figures 13 and 14 in the Iceland chapter).

Active venting occurs over an area of c. 1 km$^2$, with shallow aquifers undergoing boiling. Boiling happens because the fluids reach temperatures up to 250°C at a water depth of only around 400 m (Hannington et al., 2001). Intense gas bubble plumes reach more than 300 m above the seafloor. The fluids come up along a fault system that is connected to a deep normal fault with a reaction zone perhaps 1-2 km beneath the seafloor (Hannington et al., 2001, Kuhn et al., 2003). The field hosts mounds 20 m across and 10 m high above the seafloor, and with 1-3 m high anhydrite and talc chimneys at the top of the mounds (Hannington et al., 2001). It is believed that sulphides precipitate at depth, which is why the fluids venting are clear and depleted in metals. Hydrocarbons in the fluids form during thermogenic breakdown of organic materials in the subsurface (Riedel et al., 2001). More information can be found in the Iceland chapter.

## Kolbeinsey Field

The Kolbeinsey Field is situated just to the south of Kolbeinsey Island (which is about to disappear because of erosion) at a water depth of only 90 m (Figure 13 in the Iceland chapter). The field is related to tectonic lineaments and fissure svarms in the subsurface (Botz et al., 1999). Sediment swarms at the site varies from less than

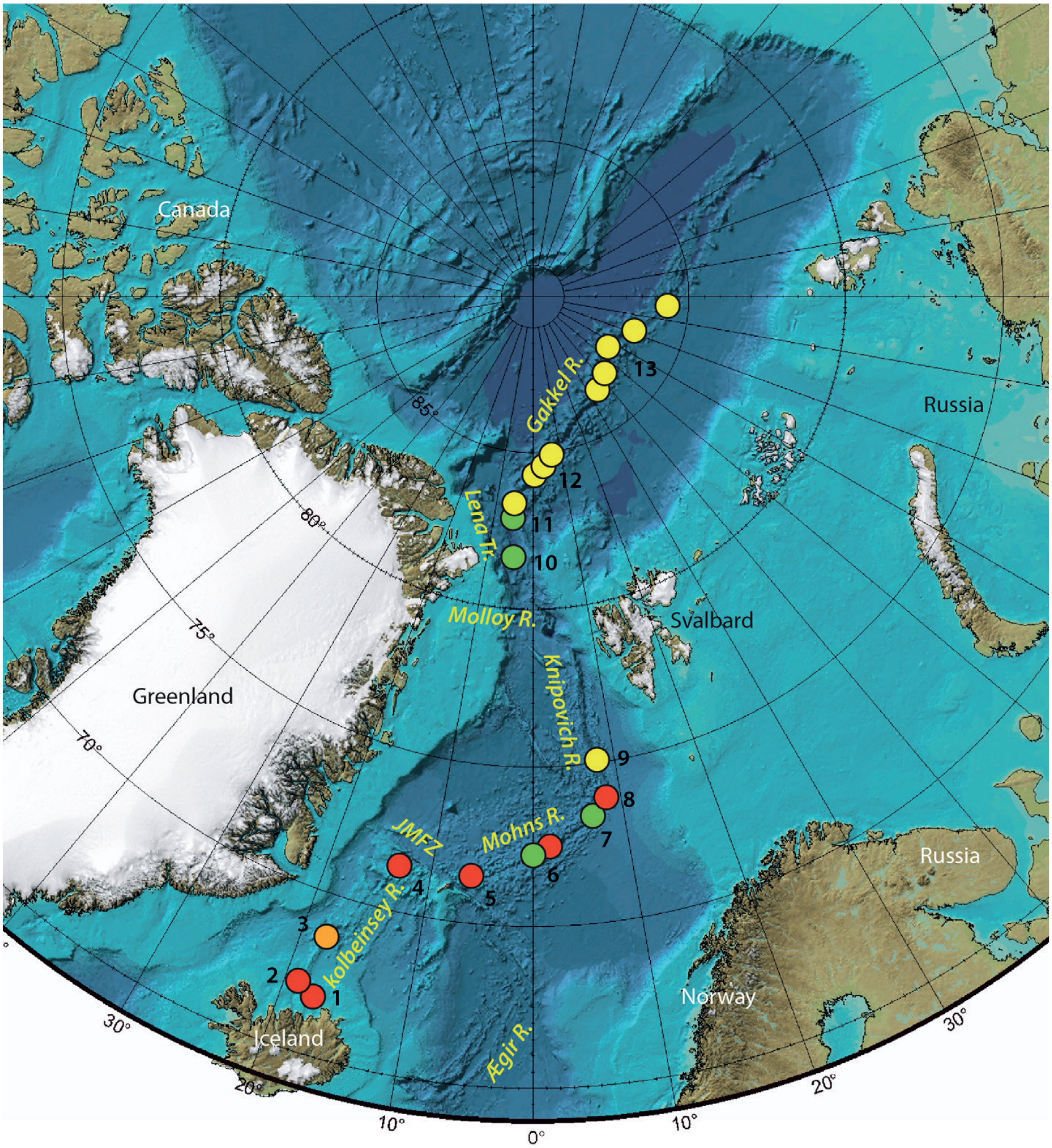


Figure 1. Overview of the active (red) and extinct (orange) vent fields, sulphide deposits (green) and hydrothermal plumes (yellow) found along the Mid-Atlantic Ridge north of Iceland: 1) Grimsey, 2) Kolbeinsey, 3) Squid Forest, 4) Seven Sisters 5) Soria Moria, Troll Wall, Perle & Bruse, 6) Copper Hill, Aegirs Kilde, 7) Mohns Treasure, 8) Loki's Castle, 9) hydrothermal plume, 10) sulphide deposit, 11) sulphide deposit and hot waters, 12) and 13) hydrothermal plumes (modified from Pedersen et al., 2010 b).

100 m to 3-400 m. The hydrothermal fluids have a maximum measured temperature of 130°C, which is about 40°C below the boiling point at that depth. However, vigorous boiling is observed, suggesting that a high gas content has lowered the boiling temperature. A strong magmatic gas component is evident, both from this field and the Grimsey field (Botz et al., 1999). No significant hydrothermal deposits occur around the vents, only smectite, amorphous silica and iron-hydroxides which cement the volcanic breccias. More on this field can be found in the Iceland chapter.

## Squid Forest

Squid Forest is an extinct field at the Kolbeinsey Ridge at 68°N. It was discovered in 1999 during a cruise with R/V Håkon Mosby carrying the ROV "Aglantha" (Pedersen et al., 2010 b). The field is located at 900 m water depth at the plateau of a flat-topped semi-circular volcano and consists of two sites (op.cit.). The first is in a depression on a small volcanic ridge and comprises about 30 chimney structures. These are typically 2-4 m tall, 30-50 cm wide and are situated at the top of mounds in clusters. The other site is in a sediment-covered depression close to the edge of the volcano. This is a smaller site, composed of two clusters of 8-10 up to 4 m tall chimneys, and a mound with smaller chimneys on top. Based on analyses of a sampled chimney of pyrrhotite, sphalerite, barite and amorphous silica (Nygaard et al., 2003), fluid temperatures are estimated to have been 250-300° C. (Nygaard, 2004).

## Seven Sisters (Syv Søstre) Field

The field is located 170 km west of Jan Mayen at the northernmost segment of the Kolbeinsey Ridge. The central part of this segment is anomalously shallow with large, young volcanic constructions reaching up to 30 m below sea level. The Seven Sisters field is linked to a row of semicircular, flat-topped volcanoes. Active high-temperature venting is taking place at a depth of around 150 m and has given rise to unusual hydrothermal deposits that form large mounds. The vent field was discovered by a team from the University of Bergen (UiB) in 2013 and was revisited and sampled in 2014. Detailed reports on this vent field are in preparation.

## Troll Wall (Trollveggen) Field

This vent field is located at the southernmost segment of the Mohns Ridge. Like the northernmost segment of the Kolbeinsey Ridge, this part of the ridge is shallow and more magmatic productive than the ridge system further to the north. Two vent fields, Troll Wall and Soria Moria, were discovered in this area in 2005 (Pedersen et al., 2005), and a third field, Perle & Bruse, was located in the same area in 2013. This shallow and very hydrothermally active part of the ridge is termed the Jan Mayen vent field area, and the vent fields in this area are collectively referred to as the Jan Mayen vent fields.

The Troll Wall field occurs along a normal fault defining the eastern wall of the rift valley at a water depth of c. 550 m (Figure 1, Pedersen et al., 2010 b, Pedersen et al. in prep). In the field there are at least 10 major sites of venting, each comprising several 5-10 m high chimneys. The chimneys emit white smoker vent fluids with temperatures up to 270°C (op. cit., Baumberger et al. in prep). As regards base metals, the chimneys and hydrothermal deposits are Zndominated with sphalerite as the main sulphide mineral, and with less pyrite and chalcopyrite (Pedersen et al 2010b, Cruz, 2016). A $CO_2$-rich gas phase is released from the vents and bubble plumes reach high above the seafloor (Steinsland et al., in prep.). Diffuse flow through talus deposits supports mats of sulphur-oxidizing bacteria. Some hundred metres west of the high-temperature vent sites diffuse, low-temperature venting occurs along fractures and faults in the rift valley floor. Here numerous mounds of yellow-brown iron hydroxide deposits have formed (Johannessen et al., in review). The Jan Mayen fields do not support a high biomass of vent-endemic fauna. No mussel beds or alvinocarid shrimps characteristic for vent sites further south on the Mid Atlantic Ridge (MAR) are present (Schander et al., 2010).

## Soria Moria Field

The Soria Moria Vent Field is also situated at the Mohns Ridge and only approximately 5 km to the south of the Troll Wall Field (Figure 1). It is found on top of a volcanic ridge at a water depth of c. 700 m (Pedersen et al., 2010 a, Pedersen et al., in prep). There are at least two venting areas

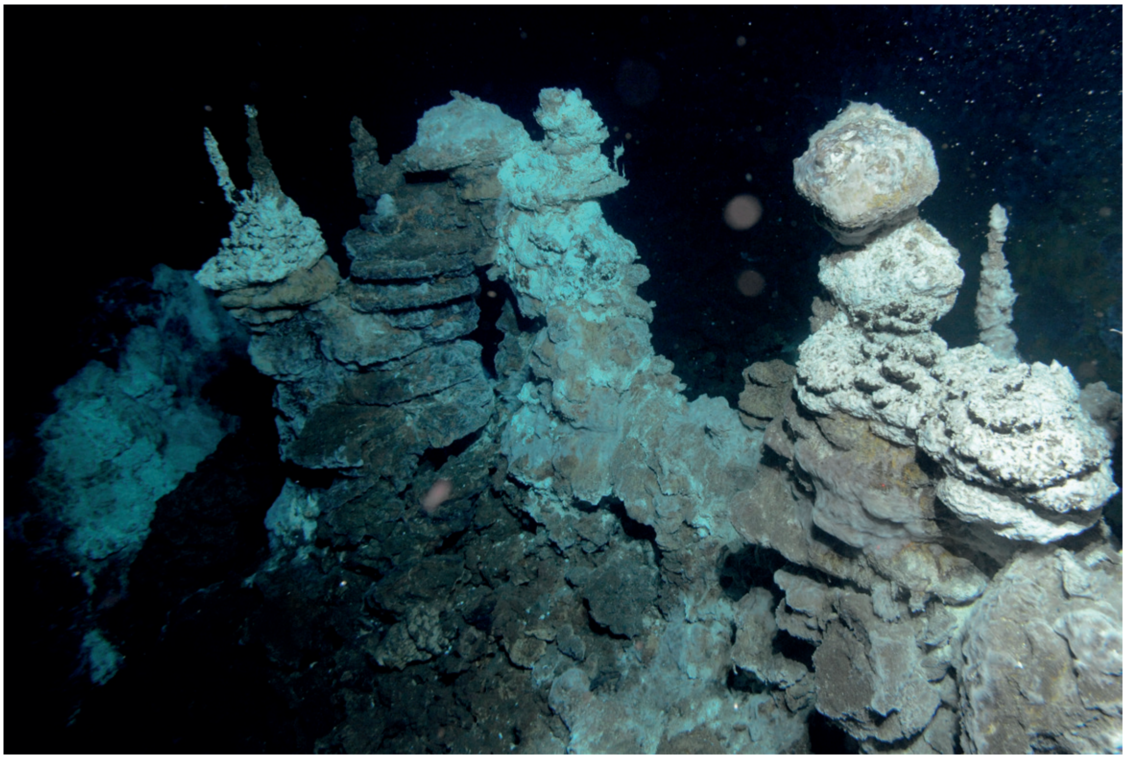

Figure 2. Sulphide-rich, multiflanged chimneys in the Soria Moria Vent Field.

100-200 m or more across, which are underlain by lava flows. As at the Troll Wall Field, the fluids at Soria Moria reach temperatures of 270°C and are enriched in $CO_2$ (up to 91.7 mmol/kg, Pedersen et al., 2010, Baumberger et al., in prep). The field contains 8-9 m tall sulphide chimneys with spalerite as the main sulphide phase, as well as irregularly shaped areas of edifices 15-20 m across and up to 10 m high, which emit clear fluids (Figure 2). The edifices are composed of barite, silica and minor pyrite, sphalerite and galena. As at the Troll Wall vent field, the base metal composition of the hydrothermal deposits is Zn-dominated: they contain significant concentrations of Ag and Au.

## Perle & Bruse

The Perle & Bruse field is located around two kilometres east of the Troll Wall field at the flank of a large central volcano that is undergoing rifting. Both active and extinct vent sites are present in this area and large areas with hydrothermal deposits have been mapped using an AUV carrying a synthetic aperture sonar system (SAS) (Alden et al., 2015). The active venting occurs along rift-parallel faults, and is primarily located at two hydrothermal mounds that are separated by 300 m. Vent fluid temperatures and compositions are comparable to that of the nearby Troll Wall and Soria Moria fields. Perle & Bruse also emits a $CO_2$-rich gas phase that forms two distinct gas flares above the vent field. The field was discovered by UiB in 2013, and it was revisited and sampled in 2014 and 2015.

## Copper Hill

Samples of sulphide mineralized breccias were dredged at the Mohns Ridge at 72.32°N in 2000 (Pedersen et al., 2010 b). The fault zone is situated at the NW side of the rift valley at around 900 m water depth and is probably related to an oceanic core complex. Some of the matrix-supported breccias are heavily sulphide mineralized, dominated by chalcopyrite, which have been deposited during tectonic activity (Nygaard, 2004). Based on the mineralogy of both clasts and sulphides, it is suggested that alteration and mineralization took place in the epidote zone of the hydrothermal zone (temperature 330-370° C) before the breccias gradually were exhumed during faulting (Nygaard, 2004).

## Aegirs Kilde (Vent)

Aegirs Kilde was discovered in 2015 at the Central Mohns Ridge during an UiB-lead deep sea expedition with R/V G.O. Sars and a new Norwegian ROV-system named Aegir 6000. The vent field is located at around 2500 m water depth at the crest of a large axial volcanic ridge. The vent field will be revisited and sampled during an expedition in 2016.

## Mohn's Treasure

Massive sulphides were dredged at 73.5° N at the eastern part of the Mohns Ridge in 2002 (Pedersen et al., 2010b). More than 100 kg of hydrothermal material was brought up from 2600 m depth, mainly composed of pyrite, and as porous chimney fragments with fluid channels. No seawater anomalies were recorded, thus the material most likely comes from an extinct field.

Some 16 km to the southeast a sulphide layer was recovered in gravity cores around 1.5 m subsurface (op.cit.). The layer is located on the other side of the axial valley ridge, meaning that the sulphide must come from a different source.

## Loki's Castle (Lokeslottet) Field

The Loki's Castle Vent Field was discovered in 2008 and was the first black smoker vent field visited at an ultraslow spreading ridge and in Arctic waters (Pedersen et al., 2010 a). The field is located where the Mohns Ridge turns about 80° to a more northerly trend and becomes the Knipovich Ridge (Figure 1). The water depth is about 2400 m and the field is situated near the summit of a large axial volcanic ridge. Venting occurs at the top of two hydrothermal mounds that are around 20-30 metres high and approximaltely 200 m across. Venting is marked by a plume that rises 3-400 m above seafloor and is characterised by anomalies in Eh, $CH_4$ and $H_2$ (Pedersen et al., 2010 b, Baumberger et al. in press). Low-temperature venting occurs at the flank of the mound and this give rise to a distict field of barite chimneys (Eickmann et al. 2014). Although the vent field is underlain by volcanic rocks, the influence of sediments from the nearby Bear Island sedimentary fan is observed in the fluid chemistry (e.g. very high methane and ammonia values). The Loki's Castle field hosts a unique Arctic vent fauna (Pedersen et al. 2010a).

## Hydrothermal plumes at the Knipovich Ridge

Pronounced anomalies in Mn, $CH_4$ and adenosine triphosphate (ATP), showing hydrothermal activity, were discovered at the southernmost part of the Knipovich Ridge in 2000 (Connelly et al., 2007, Figure 1). The source of the anomalies are probably situated to the north of the volcanic ridge, where serpentinites and other ultramafic rocks outcrop at the seafloor (op.cit.).

## Sulphides in the Lena Trough

Massive sulphides were recovered from the Lena Trough at 81° N in 1999 (Snow et al., 2001, Figure 1). The dredge recovered 30 kg of sulphides, alteration products and hydrothermal sediments. Oxidized porous material resembling chimney pieces was also recovered. There were also fragments of ultramafic rocks (serpentinite and harzburgite), indicating an ultramafic host rock. Because the field was found without any other indications before dredging, it was named "Lucky B" (resembling the finding of the Lucky Strike Field further south on the Atlantic Ridge).

Approximately 200 km further north, at nearly 83° N, another dredge recovered massive sulphides in 2002 (Edmonds et al., 2003, Figure 1). Here the Lena Trough makes a sharp eastward bend, and transitions into the Gakkel Ridge. The sulphides represent chimney fragments. Furthermore, a camera tow above the site showed shimmering water, indicating some hydrothermal activity (op.cit.).

## Hydrotermal activity at the Gakkel Ridge

A number of hydrothermal plumes has been detected along the 1100 km long Gakkel Ridge segment of the Arctic Ridge (Figure 1, Pedersen et al., 2010 b). No sulphides have been recovered or observed. Of the nine potential vent sites, a plume at 85° E was the most active found so far (Edmonds et al. 2003, op.cit.) with a plume 1400 m thick and centered 1000 m above the seafloor. Sampling revealed high concentrations of $CH_4$ (up to 250 nM) and $H_2$ (up to 100 nM, (Upchurch et al., 2007). Bacterial mats were observed at the seafloor, supported by slightly warm and reduced fluid seeps through cracks in the fresh volcanics (Shank et al., 2007).

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