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Submarine pingoes: Indicators of shallow gas hydrates in a pockmark at Nyegga, Norwegian Sea

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Abstract

Complex pockmarks up to 300 m wide and 12 m deep are located in the Nyegga area in the Norwegian Sea. Bathymetric data and direct visual documentation and sampling with ROVs (remotely operated vehicles) have shown that these pockmarks contain abundant methane-derived authigenic carbonate rocks. Furthermore, geochemical results and the finding of seep-associated organisms, including tubeworms and bacteria shows that the pockmarks are still active fluid flow locations [Hovland, M., Svensen, H., Forsberg, C.F., Johansen, H., Fichler, C., Fosså, J.H., Jonsson, R., Rueslåtten, H., 2005. Complex pockmarks with carbonate-ridges off mid-Norway: Products of sediment degassing. Marine Geology, 218, 191–206.]. Here we report the discovery of localized pingo-like sediment mounds up to 1 m high and 4 m wide. They occur inside one of the Nyegga complex pockmarks, 'G11.' All of the seven structures we investigated have four characteristics in common. (1) They have a positive topography (rounded mounds and cones). (2) They are partly covered in bacterial mats (indicating ongoing fluid flow). (3) They are partly covered in a carpet of small, living tubeworms (polychaetes, which utilize methane). (4) They have distinct corrosion pits on their surfaces, indicating fluidization and point-source corrosion of the covering sediments (probably caused by localized sub-surface hydrate dissociation). We interpret the features as true submarine pingoes, formed by the local accumulation of hydrate (ice) below the sediment surface. It is inferred that the pingoes are formed as documented hydrocarbon gases, methane, ethane, propane, and butane migrate upwards through distinctive sub-surface channels or conduits inside the pockmark. We suggest that these submarine hydrate-pingoes manifest the exact locations where fluid flow through the seafloor is currently active, and that they can therefore be used as small-scale indicators of active seepage.

Keywords: hydrate pingo; complex pockmark; Nyegga; gas hydrates; fluid flow; sediment stability; shallow gas; methane flow; porewater flow

1. Introduction

It has long been known that gas hydrates hosted in oceanic low-permeable sediments have the ability to deform the sediment surface (Soloviev and Ginsburg, 1994; Ginsburg and Soloviev, 1998; Clennell et al., 1999; Hovland et al., 2001). Submarine structures suspected to have originated from the formation and dissociation of sediment-hosted gas hydrates have previously been described as 'hydrate mounds' (Aharon et al., 1992; MacDonald et al., 1994; Ginsburg and Soloviev, 1994; Sager et al., 2003; Chapman et al., 2004), 'giant gas mounds' (Kvenvolden, 1988; McConnell and Kendall, 2002), disruption craters (Prior et al., 1989; Lammers et al., 1995), sediment slides (Schmuck

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and Paull, 1993; Sultan et al., 2003) and large collapse features (Dillon et al., 1998).

Normal water-ice related pingoes have been described from offshore permafrost regions (Shearer, 1971; Bondarev et al., 2002). However, to our knowledge, submarine hydrate 'pingo-like structures' have only been found in Barklay Canyon, on the northern Cascadia Margin, Pacific Ocean (Chapman et al., 2004). But whereas the features we describe herein are totally covered and hidden by sediments (like the ice in terrestrial pingoes), the Barklay Canyon features represent large bodies of partly exposed massive gas hydrates covered by a very thin sediment dusting. The objectives of this paper are to characterise a new discovery of submarine hydrate pingoes from the mid-Norwegian margin, suggest a viable formation mode, and briefly discuss the implications for seep detection.

We discovered small (up to 1 m high) suspected submarine hydrate pingoes during a detailed visual ROV survey into complex pockmark "G11" at Nyegga (64°40′00″ N, 05°17′30″ E) an area also called 'the NE flank' of the Storegga slide offshore mid-Norway (Hovland et al., 2005).

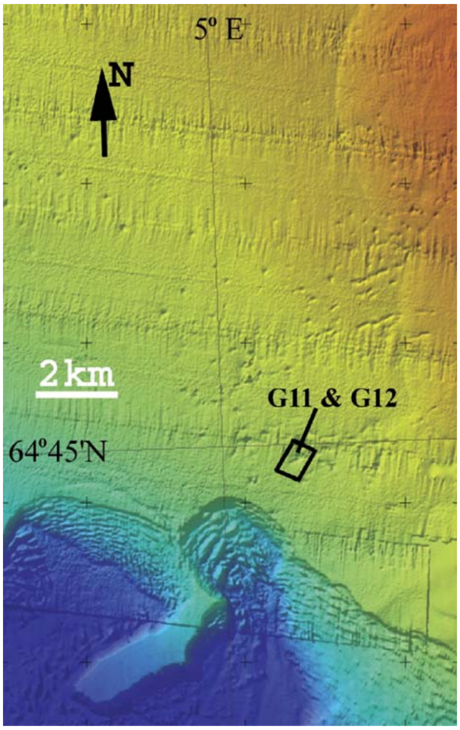

Fig. 1. General location of study area G11 (within small rectangle, see Fig. 2) is shown on this digital terrain model over the Nyegga area. Note that parts of the north-eastern failure front of the Storegga Slide occurs only 2 km south of the study area.

2. Geological setting

The seabed of the Nyegga region has a general slope angle of only 1° and represents the 'shoulder' of the continental slope leading down to abyssal depths of about 3000 m in the Norwegian Sea Basin, to the west. The region we studied (Fig. 1) lies at the border between two large sedimentary basins: the Møre Basin to the south, and the Vøring Basin to the north (Bünz et al., 2003; Hovland et al., 2005). A prominent BSR occurs in the Nyegga region and spreads to the north, west, and south of our study area (Mienert et al., 1998; Gravdal et al., 2003; Bouriak et al., 2000; Hovland et al., 2005). However, the presence of gas hydrates in this area has never been verified by sampling. More details of the general geological setting relative to the complex pockmarks of Nyegga can be found in Hovland et al. (2005). Our study area (Fig. 2) lies only 2 km north of the northern failure front (slide scar) of the Storegga Slide (Bugge, 1983; Bryn et al., 2003).

The pockmarks of the Nyegga area are morphologically more complex than 'normal' seabed pockmarks (Hovland and Judd, 1988), and occur as near-circular, up to 12 m deep and 300 m wide depressions. Their most distinctive feature is the occurrence of chaotic heaps of large carbonate rocks and slabs, which protrude from the central part of the depressions up to the mean surrounding seafloor level or, even slightly higher. A total of four complex pockmarks, named: A, C, G8, and G11 were investigated in 2003 (Hovland et al., 2005). The pockmarks are located at water depths between 600 and 750 m, and contain a variety of carbonate morphologies dominated by low $\delta^{13}C$ aragonite. Shallow push-cores from G11 showed the presence of occluded and adsorbed light hydrocarbon gases (Hovland et al., 2005).

On 2D-seismic records, the pockmarks are seen to occur immediately above vertical 'chimneys' or pipes (also called 'wipeout' zones, and 'blow-out pipes'), which extend down to and in some cases beyond the BSR, about 200 m sub seafloor (Mienert et al., 1998; Bünz et al., 2005). They are inferred to represent an endmember of a megapolygonal fault system.

3. Methods

We discovered small (up to 1 m high) mounds during a detailed visual ROV survey into complex pockmark 'G11' at Nyegga (64°40′00″ N, 05°17′30″ E) offshore mid-Norway (Hovland et al., 2005).

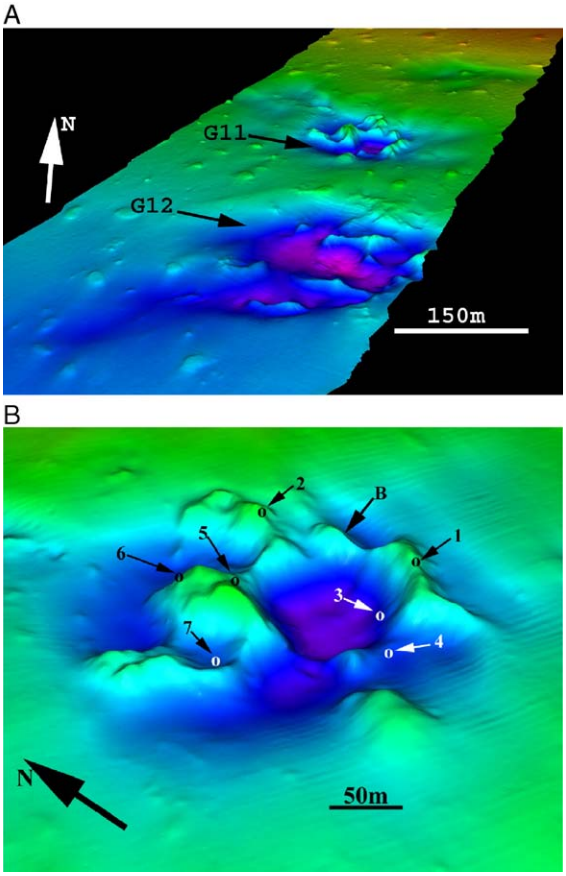

Fig. 2. (A) Oblique perspective view of the study area, seen from south (based on multibeam echosounder). Two complex pockmarks are shown, G11 and G12. G11 measures about 220 m in diameter and is approx. 12 m deeper than the surrounding general seafloor. The general water depth just north of G11 is 725 m. Just north of G12 the general water depth is 727 m. (B) Similar, but closer view of complex pockmark G11, where the hydrate pingoes were discovered. The ridges within the pockmark consist of irregular carbonate blocks (Hovland et al., 2005). The pingoes, visually documented in 2004 during an ROV grid survey are shown as small, numbered circles (1–7). 'B' indicates location of sediment sample acquired in 2003, at a bacterial mat. Note that the pingoes and bacterial mat occur adjacent to and on the carbonate ridges.

Both visual inspection and general ROV-based geophysical mapping and coring were performed in the Nyegga area, in 2003 (Hovland et al., 2005). The pockmark G11 was, furthermore, targeted for a detailed ROV survey in 2004. The G11 complex pockmark where the suspected pingoes were found, was first surveyed with ROV-based geophysical systems (multi-beam echosounder, 1.5 kHz high-resolution seismics and 100 kHz side scan sonar) in 2003, using the survey vessel '*Normand Tonjer*' and ROV 'Hirov 5' (Hovland et al., 2005). In addition to sub bottom profiling (Hovland et al., 2005), a series of three 1-m long sediment samples were acquired inside this pockmark. They were acquired at locations where seepage was suspected to take place, including one location with bacterial mat. Two carbonate samples were also acquired during the 2003 survey from within G11 (Hovland et al., 2005). Complex pockmark G11 was re-surveyed in 2004 with the survey vessel '*Edda Fonn*' and ROV 'Hirov 6.' The objective was to map out the distribution of sediments and carbonate material. It was during this detailed inspection that the suspected pingoes were discovered. However, limited survey vessel time prevented sampling of the pingoes during this campaign. Thus, there exists no physical evidence of gas hydrates occurring immediately below surface at the suspected hydrate pingo locations.

4. Results

4.1. Geomorphology

Complex pockmark G11 is the deepest and most spectacular of the Nyegga pockmarks surveyed in 2003. During the visual 'Hirov 6' grid survey, of the pockmark, a total of seven local sediment mounds, suspected to represent pingoes, were discovered. They were named 'Ice1' to 'Ice7,' and their locations inside G11 are shown in Fig. 2B. G11 has two large irregular ridges, with a central sediment basin between them. Additional small interior basins and piles add to its chaotic topography (Fig. 2). The largest individual carbonate block seen inside any of the four pockmarks measures about $4 \times 3 \times 2$ m, i.e., a volume of about 24 m^3, and occurs at location 'Ice2,' inside G11 (Fig. 2B).

4.2. The hydrate pingoes

We have selected five of the seven suspected hydrate pingoes for detailed description here. They are 'Ice1,' 'Ice2,' 'Ice4,' 'Ice5,' and 'Ice6' (Figs. 3–6). All seven features have three main characteristics in common, i.e., that they (1) occur as local positive topographic unlithified sediment structures, (2) their surface is partly or totally covered with small tubeworms, (3) they have irregular patches of bacterial mats on their surface, and (4) they have corrosion pits and sometimes fluidised sediments on their surface.

4.2.1. Location 'Ice1'

This was the first location noted for its anomalous appearance (Fig. 3). Because of its distinct circular

Fig. 3. Video-grabbed image of pingo at location "Ice1" (see '1' in Fig. 2B). The pingo measures about 1 m across, and has rims that protrude about 25 cm out of the seafloor. These rims are partly coated in thin bacterial mats, indicating active seepage. The pingo has a central sag, indicating sub-surface dissolution of hydrates. Note that it is located on top of a dome-shaped portion of the seabed.

positive topography and the associated bacterial mats and dense tubeworm populations, we decided that 'frost heave' and partly 'melting' sub-surface ice was occurring. After a closer inspection, we decided that the feature probably represented a submarine pingo, and continued the visual grid survey. Several more, similar features with similar characteristics were then discovered. Because we have only performed a grid survey, without visually covering the whole internal area of the complex pockmark, G11, it is expected that there may exist many more such features in the pockmark.

The suspected pingo at Ice1 is distinctly circular with elevated rims. It measures about 0.5 m in diameter and had a circular or oval raised rim protruding about 0.25 m above the surrounding domed seafloor. Whereas the sediment surface surrounding the feature has a dense population of tubeworms, probably pogonophorans, the inside of the raised structure is more-or-less 'barren' (devoid of tubeworms) except for a patchy bacterial mat overgrowth.

4.2.2. Location 'Ice2'

At location Ice 2, the most prominent seabed features are two large angular blocks of carbonate rock, one of which is the 24 m^3 rock mentioned previously (Fig. 4). These two blocks are divided by a vertical crevasse of about 1 m width. The sediment surface inside this crevasse contains at least two distinct small suspected pingoes, one of which is shown in Fig. 4B. This suspected pingo is about 0.3 m high, and 0.4 m across, in both directions at its base. There is a slight circular depression (about 0.2 m deep) to the left of the suspected pingo and an even and undisturbed seabed to the right of it. To the left of the suspected pingo there is evidence of corrosion and fluidised sediments. The suspected pingo is partly covered by small bacterial mats and a growth of tubeworms. These two aspects discern it from the undisturbed seabed to the right, which has neither tubeworms nor bacterial mats. Another smaller suspected pingo at location Ice 2 is situated about 2 m further to the right in the crevasse. It is small, and symmetrical, measuring only 0.25 m in height and

A

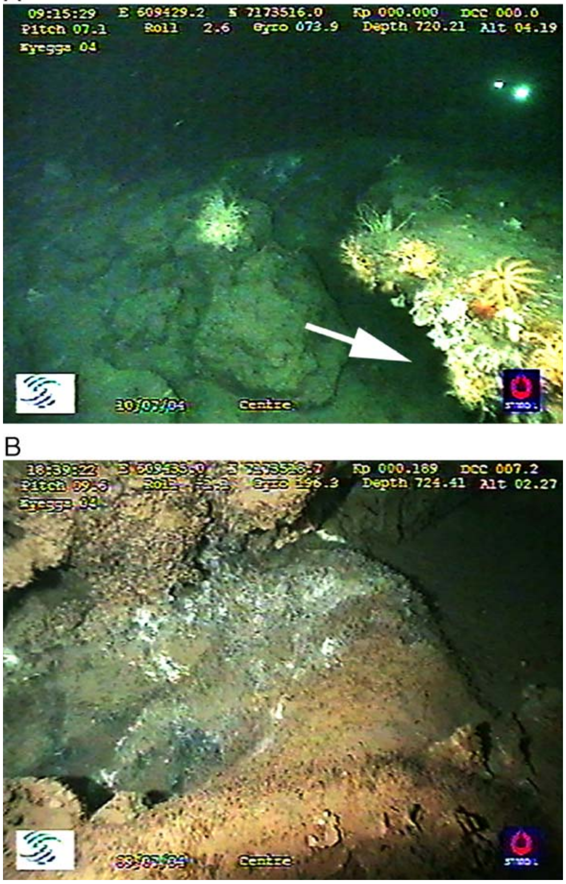

Fig. 4. (A) Video-grabbed image of pingo-location "Ice2" (see '2' in Fig. 2B). There are two small pingoes here, located inside a crevasse between two large carbonate blocks seen in the image (arrow). Note the abundant sessile organisms growing partly on the underside of the largest block. Also note lights from another ROV sitting about 15 m from the viewing ROV. (B) The largest of the two pingoes found at location Ice2. Note that the pingo is partly coated in thin, white and grey bacterial mat, and that it is partly covered by a carpet of small tubeworms, looking like a grass-carpet. Also note the close proximity to the large carbonate block, indicating that the fluids passing through the pingo are channelled from below the carbonate block.

Fig. 5. Video-grabbed image of pingo-location “Ice4” (see ‘4’ in Fig. 2B). This pingo is about 1 m high and has a near-perfect parabolic geometric shape. In contrast to the other pingoes described so far, this one has very little bacterial mat cover (but plenty of tubeworm cover). The arrow points at a small corrosion pit, ‘Cp,’ which seems to be typical for hydrate pingoes. Note the small stream of sediments that occurs below this pit (below the point of the arrow). Parts of the sampling gear on the ROV are visible on the left.

about 0.3 m across at its base, which is nearly circular. It also has a cover of tubeworms on its summit and sides.

4.2.3. Location ‘Ice4’

The pingo located at Ice 4 is more or less perfectly symmetrical and is conical (‘haystack’) shaped. It sits on a generally flat seabed, and rises to a height of about 1 m above the adjacent seafloor (Fig. 5). At the base it is circular, with a diameter of about 1.5 m. Also this pingo is partly covered in tubeworms and bacterial mats. There is a small hole in its side, which is interpreted as a corrosion pit, because there is evidence of fluidised sediments (mass wasting) originating from the hole (Fig. 5).

4.2.4. Location ‘Ice6’

The largest pingo structure was found at location Ice6. It resembles an irregular ‘whale back,’ with steeply inclined slopes up to a gently curved ridge (Fig. 6A and B). It measures about to 4.0 × 2.0 × 1.0 m, and is irregular in plan. Most of its surface is covered in tubeworms and bacterial mats. It bears distinct evidence of pitting and corrosion.

4.2.5. Location ‘Ice5’

The ROV was landed onto the back of this pingo adjacent to a patch of seemingly disturbed or disrupted slight seabed depression measuring about 0.4 m across. Upon landing onto the pingo, sediment-laden water emitted from numerous holes in this disturbed patch. The transfer of ROV weight onto the seafloor evidently triggered this flow of what we interpret as water containing suspension sedimentary particles which were stored immediately underneath the surface, in porous sediments.

4.3. Fauna

The 2004 survey also documents the existence of a pockmark-specific micro- and megafauna, which includes bacterial mats (probably *Beggiatoa* sp.), fields

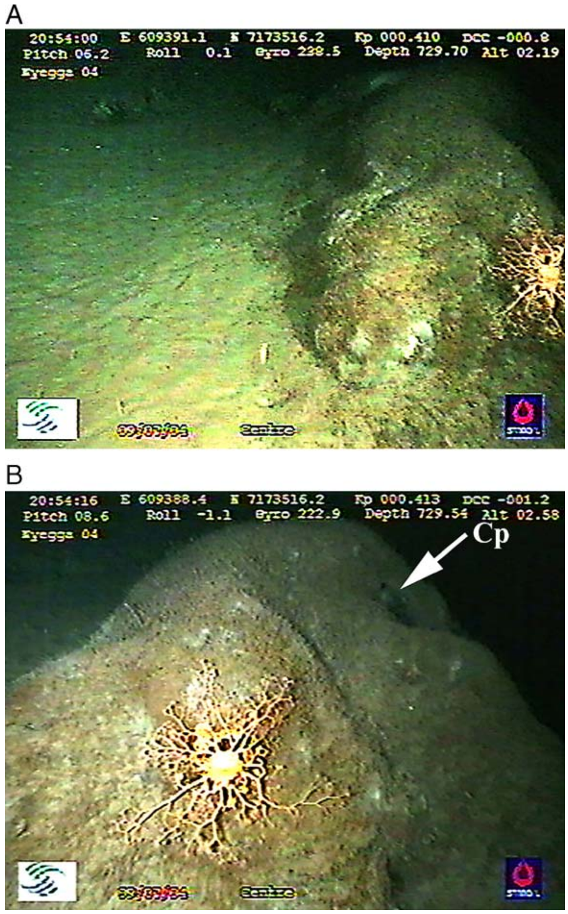

Fig. 6. (A) This is the location with the largest pingo, location ‘Ice6’ (‘6’ in Fig. 2B). In the next image (B) the ROV moves to the right of this pingo. Notice the undisturbed sandy seafloor to the left of the pingo, and also the abrupt way it has risen out of the seafloor. Here it is seen rising about 80 cm over the undisturbed sandy seafloor. Note also the large organism, a basket star to the far right, sitting on the pingo. (B) This view illustrates the size of the pingo. The arrow points at a large corrosion pit, ‘Cp,’ in its side. Note the 1 m diameter basket star.

of small tube-worms (polychaetes) and large (15 cm) pycnogonids (sea-spiders, suspected to be of the species *Colossendeis probiscae*) (Fig. 7A) (Hovland et al., 2005). The bacterial mats were located in the deepest, soft sediment-covered portions of the G11-pockmark, and were observed amongst other places at one of the geochemical sample locations (Fig. 7). In addition to the typical discoloration of the seafloor, slimy filaments were seen 'waving' in the currents set up by the ROV during sampling in 2003. Large (up to 1 m diameter) ophiurids (basket stars, Fig. 6) occur both on suspected pingoes (Fig. 6A and B) and on many of the carbonate blocks (Fig. 4).

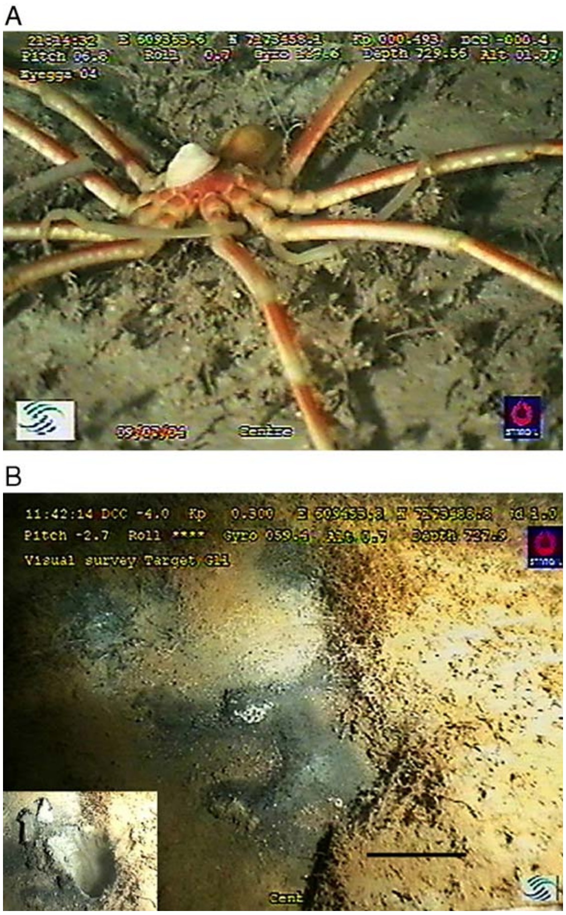

Fig. 7. (A) This image of a pycnogonid carrying a large, white foraminifer on its back, is from location 'Ice7' ('7' in Fig. 2B). Numerous giant pycnogonids (probably of the species *Collossendeis probiscae*) are found inside complex pockmark G11 (Hovland et al., 2005). Near the small pingo shown in Fig. 4B, three such pycnogonids were seen simultaneously sitting on the vertical wall of the large carbonate block. In this close-up image, notice the abundance of tubeworms and other organisms living on the pingo surface. For scale, the size of the white foraminifer is about 12 mm. (B) A video-grabbed image from our investigations in 2003, before we realized the existence of pingoes in G11. The location of this grey and white bacterial mat is shown in Fig. 2B, marked 'B.' Here, an ROV sediment sample was acquired for geochemical analysis. The sediments contain relatively high concentrations of hydrocarbons (methane to pentane), indicative of active micro-seepage. Also at this location, a giant pycnogonid appeared during the sampling operation. The inset, lower left shows the hole remaining in the clay after sampling. For scale, a black 10 cm bar is shown, lower right.

5. Discussion

5.1. Terrestrial vs. submarine pingoes

A terrestrial pingo is a distinct geomorphologic structure found in regions of permafrost: it is described as a "…relatively large conical mound of soil-covered ice (commonly 30–50 m high and up to 400 m in diameter), raised in part by hydrostatic pressure of water within or below the permafrost of Arctic regions…" (Bates and Jackson, 1987, p. 504). They are formed in low-permeable soils, as a result of groundwater migration towards the water-vapour partial low-pressure that exists at a freezing front (Miller, 1980; Konrad and Duquennoi, 1993). Here, ice will accumulate as more and more water migrates to the freezing-front, thus causing local ice accretion. Typical terrestrial pingoes are circular, dome-shaped, or cone-shaped structures. They are also characterised by having plant growth and occasional craters (corrosion pits) on their surface. During warm periods, when the sub-surface ice core melts, either a mound of wet soil or an oval small lake remains on the surface. Pingoes are also suspected to occur on other planets with freeze–thaw conditions, such as Mars.

It is believed that submarine hydrate pingoes have been found in several places with seepage of hydrocarbons in deep water, such as in the Gulf of Mexico. However, they have never been recognised as such and have therefore acquired other names such as "hydrate mounds" and "giant gas mounds," etc. The only hydrate-associated pingo-like structure to be mentioned in the geological literature, to our knowledge, are the aforementioned pingo-like masses of hydrates found at 860 m water depth in Barklay Canyon off Pacific Canada (Chapman et al., 2004).

5.2. A qualitative model for hydrate pingo formation

Given the evidence described (see also Hovland et al., 2005), the suspected hydrate pingoes are thought to have formed in a manner, which is outlined below. The prerequisites for pingo formation are: (1) a

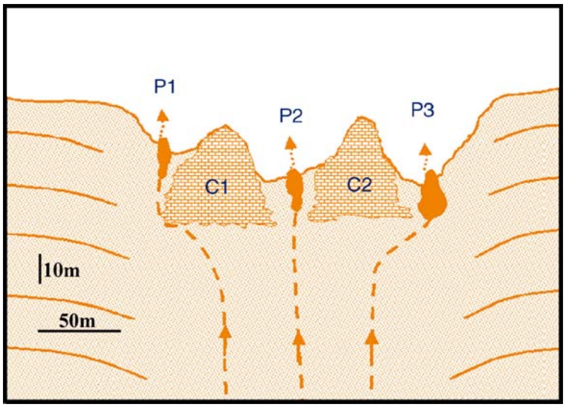

Fig. 8. A conceptual sketch, outlining the suspected fluid pathways and the general physical situation inside complex pockmark G11. Because the pingoes and bacterial mats were consistently found adjacent to carbonate ridges and inside crevasses, between large carbonate blocks, it is suggested that the upwardly migrating fluids are channelled around these. The fluids must migrate through distinct conduits, which remain active for long periods, such that pingoes can form and grow. 'C1' and 'C2' denote such carbonate masses. The dark bodies in the figure, marked P1, P2, and P3, are pingoes.

relatively high-flux, focused hydrocarbon gas flow through the seafloor, (2) cool bottom water temperatures, and (3) water depths beyond about 400 m (thus ensuring supercooling of the fine-grained environment where the gas hydrates would form (Clennell et al., 1999)).

Based on the G11 pockmark evidence, it is suggested that the flux of hydrocarbons through the floor of the pockmark is heterogeneously distributed and that the flux may vary over time. We surmise that pingoes will only form where the gas flux is highest and probably where seawater can easily enter through the adjacent seafloor sediments to exchange and replenish seawater consumed by the gas hydrate formation below ground (Fig. 8).

For the hydrates to accumulate sub-surface and expand upwards, the gas flux needs to be maintained over a prolonged period. Because gas hydrates have previously been believed to 'cement' sediments, this may seem counter-intuitive, but it is known that hydrates are relatively permeable (Austvik et al., 2000). For the fluid flow to occur at the same location over a prolonged period, we think it is necessary that the flow is governed by conditions in the deeper-lying pockmark plumbing system. This is because near-surface processes such as bacterial mat formation, hydrate formation, and authigenic carbonate formation are processes that tend to clog up the fluid conduits (Hovland, 2002). Thus, the high local flux rate is persistent and more gas hydrate forms at the same location, thus forming a gas hydrate column inside the near-surface sediments with volume expansion upwards (in the direction of least mechanical resistance).

It may seem counter-intuitive that hydrate formation, which is normally a process causing volume reduction (Ginsburg and Soloviev, 1998) should lead to expansion, as we predict: "This makes hydrate generation basically different from freezing of water, which is known to entail an increase of volume." (Ginsburg and Soloviev, 1998, p. 192). However, whereas we describe an 'open-flow system' at the Nyegga G11 complex pockmark, with gas recharge from below and water recharges from adjacent sediments and from seawater, Ginsburg and Soloviev (1998) describe a 'closed-system,' without any addition of gas or water. In the open system, there is apparently no limit to the amount of water and gas that can accumulate as hydrate 'ice' inside the pingoes. The mechanisms associated with gas and water advection and percolation through marine sediments in the context of hydrate formation, are discussed in Clennell et al. (2000). Since hydrate formation consumes free water, we predict that 'new' porewater is drawn in from the adjacent sediments, which in many cases also causes seawater to flow into the pingo (Fig. 9).

But, gas hydrates are not in chemical equilibrium with normal seawater because of low hydrocarbon concentrations in the ambient seawater. The seawater will achieve contact with the hydrates some centi- or

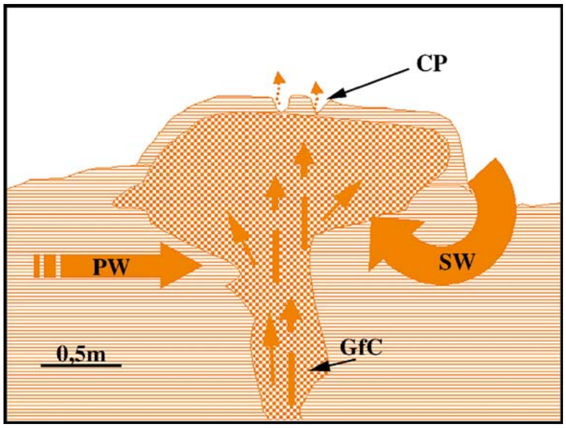

Fig. 9. A close-up sketch of a pingo at Nyegga. It is shown in a 'matured' stage, and has developed corrosion pits (CP) on its upper surface sediment cover (where seawater has attacked). Note the two arrows within the sediment, one indicates suspected flow of porewater (PW) and the other suspected flow of seawater (SW). GfC = gas flow conduit. Note how all arrows converge on the sub-surface hydrate body.

decimetres below the pingo sediment surface resulting in points of dissolution interfaces. This causes corrosion pit formation and perhaps local sediment fluidization of the covering sediment. This will again result in a release of methane and hydrate-bound water. As documented in G11, bacteria may utilize the emitting gas-charged and anoxic water, most likely after a 'steady-state' flow has been achieved.

5.3. Implications

There are several implications of dynamically forming and disintegrating gas hydrate pingoes on the seafloor. The two most important ones are believed to be:

A) For biology/environment, i.e., the possibility for enhanced local primary (microbial) productivity.
B) For engineering and anthropogenic seabed usage, i.e., seabed topography change over time.

For many years it has been recognized that sub-surface gas hydrates cause seabed surface deformations. In our discovery of pingoes inside complex pockmark G11 at Nyegga, we have documented that the "seabed tundra" really exists. However, we still do not know exactly which processes may link pingoes with the large carbonate ridges located inside G11. Because of their intimate relationship, we surmise that there must exist a close link, and that the pockmark topography, the carbonate material, and the mechanically dynamic pingoes all relate to the main causative process of focused fluid flow (Hovland et al., 2005). The engineering implications for constructions on the seafloor in hydrate-infested regions have been summarized and discussed by Hovland and Gudmestad (2001).

On a larger scale, it has been speculated that there may be a close link between gas hydrates and slope instability (Mienert et al., 1998; Hovland et al., 2001). However, our new results from G11 suggest that the processes involved are complex. We suggest that before such links can be understood properly, we have to find out more about focused fluid flow as documented both on the Canadian margin (Wood et al., 2002) and at the Norwegian margin (Bouriak et al., 2000; Hovland et al., 2005). Are the complex pockmarks and pingoes, for example, to be regarded as excess-pressure release "valves," which actually prevent large slope failures — or are they instrumental in such failures?

Besides the obvious hazards and challenges to seabed construction and engineering (Hovland and Gudmestad, 2001), the hydrate/pingo dynamics and fluid flow processes are evidently of great significance to local marine life. Bacteria and tubeworms evidently grow on them, and a host of other macro-species seem to rely on their products, which probably include: low Cl-water, mineral-rich water, of which dissolved light hydrocarbons are part, and possibly also CO_2 and H_2. Thus, the pingoes manifest not only mechanically active seabed patches, but also biologically significant seabed locations.

6. Conclusions

The discovery of up to 1 m high sediment mounds, here called 'hydrate pingoes,' on the mid-Norwegian margin adds to the diversity of seabed seep-related features. We have previously documented anomalous ridges of methane-derived authigenic carbonates, together with a distinct fauna. We interpret the mounds as submarine pingoes, formed as a result of gas hydrate sub-surface build-up at specific focused fluid flow locations. The process is dynamic in the sense that the pingoes grow and collapse over time due to probable cycles of freezing and thawing of hydrates in the shallow sub-surface. Although there seems to be a close relationship to the adjacent carbonate ridges, it is still unknown which processes link the two phenomena (carbonate production and pingo formation).

We suggest that the pingoes manifest a close interplay between seawater, dissolved gases migrating up from depth, gas hydrate formation and release of melt-water (dissociation fluids). This is also in agreement with geochemical results obtained from shallow cores showing the presence of abundant hydrocarbon gases in the sediments. Our findings imply that pingoes can be used as seep localizers, and probably also manifest the whereabouts of shallow gas hydrates. The pingoes emphasise the dynamic nature of pockmarks, and provide information that should be taken into account for engineering purposes. However, much more fieldwork is needed at locations such as G11 before the true mechanisms of complex pockmarks and pingoes are understood.

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