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The Geomorphology and Nature of Seabed Seepage Processes

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1. Introduction

The seafloor is mostly flat and smooth, reflecting sedimentation, the dominating seabed formation mode. In this communication, I shall focus on how vertical fluid flow, also called “seepage” may alter and imprint the seafloor geomorphology. Seafloor seeps occur globally, wherever a fluid (gas or liquid) resides in the sub-strata below the seafloor and finds a way up. The fluids may come up from depths of several kilometres below surface or from shallower depths. Because they have lower specific gravity than their surroundings, they tend to move through the pore-spaces of sediments or fissure-networks of solid rocks, and upwards towards the surface. At locations where they break through the seafloor, depressions and sometimes mounds may form (Fig. 1).

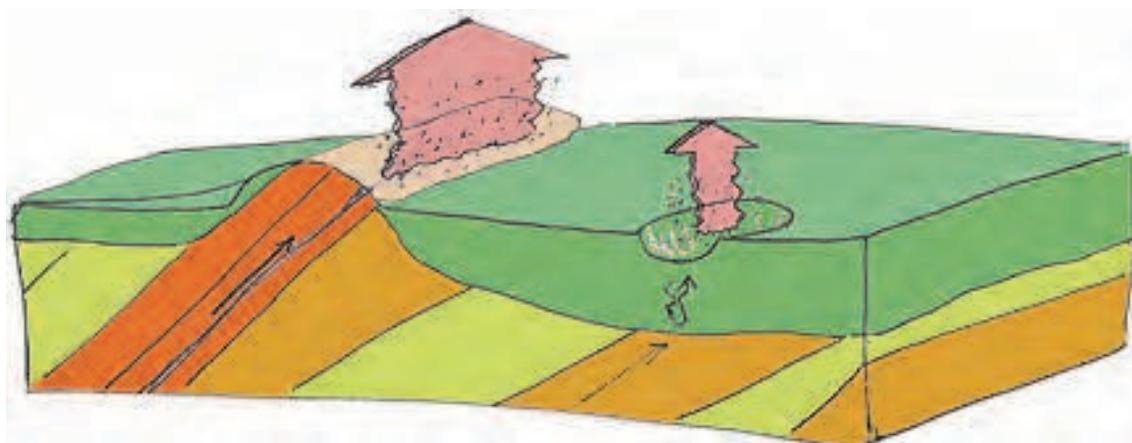


Fig. 1. Seepage of fluids (liquids and gas) though the seafloor may occur through positive seafloor relief (left arrow) or it may induce negative relief features in the seafloor (right arrow).

2. The “Second Surface” with seep and vent manifestations

The seafloor is the “Second Surface” of our Planet, indicating that it is hidden in many ways. Totally, it covers an area which is about 3 times larger than the land-surface. Paradoxically, there exists more visual documentation of the total surfaces of both Moon and Mars, than of the immensely more important combined Land- and Second Surfaces of Earth. From sediment sampling, fishing (trawling), scientific dredging (dredge sampling), and drilling,

in all oceans, over time, it is currently known that the Second Surface mostly consists of mud (clay), sand, rock, and in some areas metals and salts. But, because it is flooded by water, it is both pressurized, and buoyed at the same time, and behaves accordingly. On average, the Second Surface has a much thinner crust (up to 15km thick) than the on-shore continental crust (up to 200 km thick) and is, therefore, more likely to be exposed to high heat-flow from the Earth's interior. Thus, along tectonic plate boundaries (mid-ocean spreading zones, transform faults, and subduction zones) the high heat-flow induces venting of warm and hot fluids in so-called 'hydrothermal vent systems', which will only be treated briefly in this chapter.

Generally, the ocean floor is covered in thick sediments that deposit by gravitation, with particles that sink through the water column and accumulate in thick layers on the Second Surface. The fluids, including petroleum gas and liquids (hydrocarbons) trapped underneath such sediments are lighter than the solids and, therefore, move upwards to surface at discrete locations due to buoyancy. This process is also called "migration" and where the flow penetrates the Second Surface from below it is called "fluid flow" (e.g. Judd and Hovland, 2007). The discrete locations where the fluids occur at the surface are called 'cold seep' locations (seep 'manifestations'). Depending on the geological setting, the distance between each cold seep location on the seafloor varies considerably, from kilometres, to only several metres. However, cold seeps are important for life within, on, and above the Second Surface because they represent transport pathways for dissolved chemical constituents including nutrients and can, therefore, sustain unique oasis-type ecosystems at the seafloor (e.g. Hovland, 1984; Hovland and Judd, 1988). Fluids expelled through seeps contain re-mineralized nutrients (silica, phosphate, ammonia, and alkalinity) and hydrogen sulphide, as well as dissolved and free methane from microbial degradation of sedimentary organic matter. Because methane gas molecules (CH_4) have the highest relative hydrogen content (4 hydrogen atoms to 1 carbon atom) of any organic compound, they represent a valuable energy source to certain primary producers: archaea and bacteria, i.e., the methanotrophs and the methane oxidizers. Apart from near cold seep locations, seawater has generally very low concentrations of methane and other light hydrocarbons, such as ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}). Perhaps the single most important reaction associated with cold seeps, is the anoxic oxidation of methane (AOM) by archaea and sulphate reducing bacteria (SRB), with secondary reactions involving the precipitation of carbonate (CaCO_3), in the form of inorganic aragonite and calcite (Hovland et al., 1985). Reeburg (2007) pointed out the complexity of the biogeochemistry of oceanic methane circulation and stated: "A geochemical budget is a flux balance that provides a useful means of partitioning and estimating the magnitudes of sources and sinks. Budgets are very useful in exposing our ignorance, but they have no predictive power." Even though there is still a high uncertainty about the impact of methane seepage from the seafloor, this is certainly one of the emerging areas for scientific studies.

In contrast to the petroleum-related natural seeps, the fluids that seep up from volcanic activity in the deep-ocean are often a mixture of carbon dioxide (CO_2), methane (CH_4), and hydrogen (H_2). Organisms that feed on nutrients brought up in such deep-water seeps can build large structures on the seafloor made out of carbonate rock (CaCO_3). These structures are called "reefs" and mounds. Figure 2 provides a remarkable illustration of some ancient seep-related carbonate mounds that grew on a now uplifted seafloor located in the Sahara

desert, of all places. These fossil carbonate formations occur in the eastern Anti-Atlas mountains, southern Morocco (Belka, 1998).

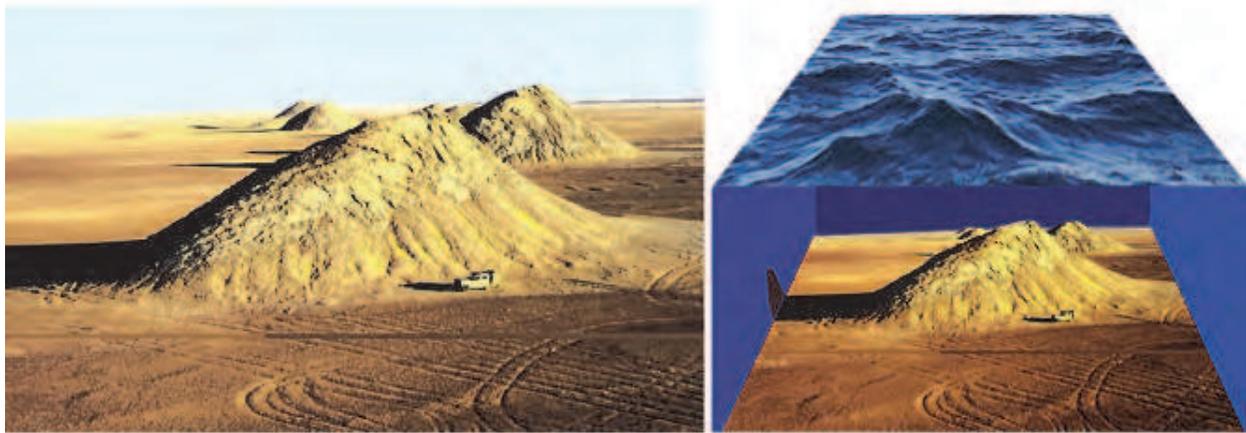


Fig. 2. Left: Some ancient, spectacular fossil coral reefs as found in the Sahara desert today, after they have been buried by sand for many millions of years (Wendt et al., 1997). Right: A rendering of how they might have looked like, when alive, some 380 million years ago.

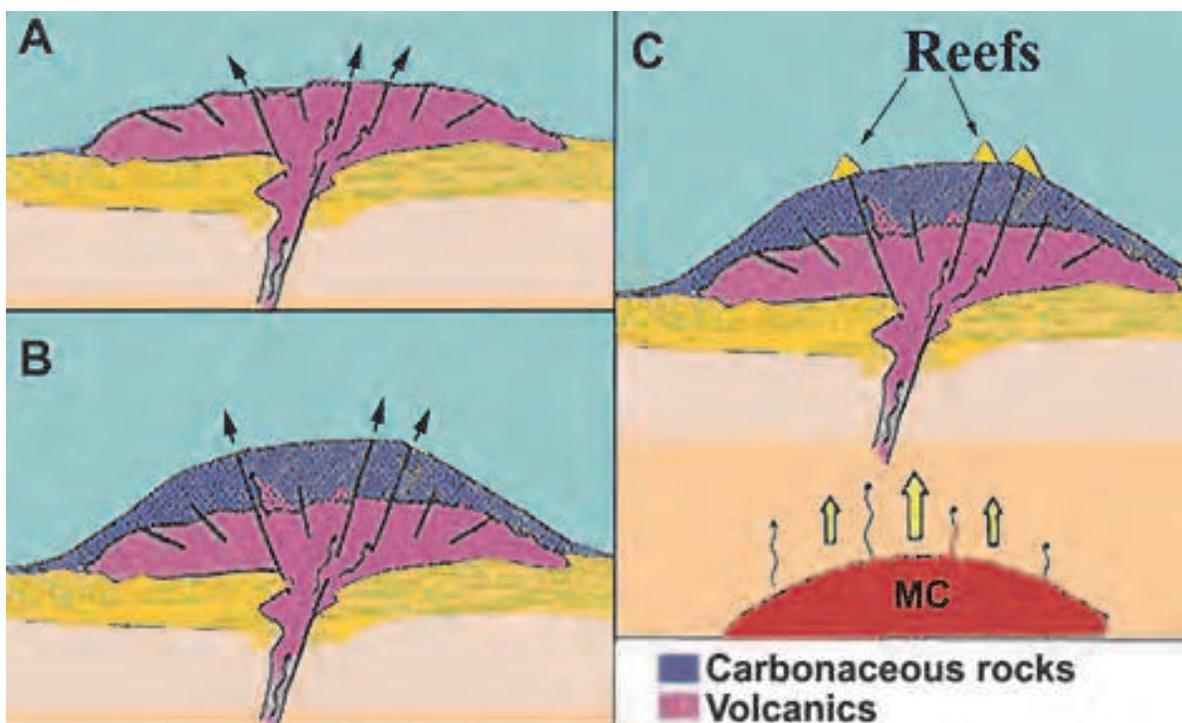


Fig. 3. Conceptual cartoon (based on Belka, 1998) indicating in chronological order (A, B, C) how volcanic outflow onto the seafloor may have stimulated the growth of the carbonate mounds (yellow cones, denoted “Reefs”) of Sahara. “MC” = magma chamber.

They are of Early Devonian age and are possible to see only because they occur in a desert landscape, without vegetation. In all, there are 54 such structures within the Hamar Laghdad area of Sahara (Hovland, 2008). The fossils within these ancient Saharan mounds include trilobites and crinoids. There are also corals, brachiopods, ostracods, gastropods,

and pelecypods. Even though there are markings from worms and sponges, there are no signs of algae. This indicates that the structures have been growing at depths greater than 100 m (Belka, 1998). A special character of these mounds, are the numerous “neptunian dikes”, fracture systems, which have been filled with other sediments and minerals. It is suspected that these dikes represent spring conduits (seeps) during the formation of the mounds, and that the seeping fluids were of a hydrothermal nature (Fig. 3), which must have stimulated the organic growth in the first place.

3. Seeps in the North Sea

Within the central and northern North Sea, there are three, fairly well-studied methane seep locations: the Tommeliten seep area (56°29.90' N, 2°59.80'E) (Hovland and Sommerville, 1985; Hovland and Judd, 1988; Niemann et al., 2005; Wegener et al., 2008; Schneider von Deimling, 2010), the Scanner pockmark seeps (58°28.5' N, 0°96.7'E) (Hovland and Sommerville, 1985; Hovland and Thomsen, 1989; Dando and Hovland, 1992), and the Gullfaks seeps (61°10.1' N, 2°15.8'E) (Hovland, 2007; Wegener et al., 2008). Although each of them are located in different geological settings, they have one main aspect in common: - they occur as continuous macro-methane seeps (Fig. 4). Except for the Scanner seeps, the

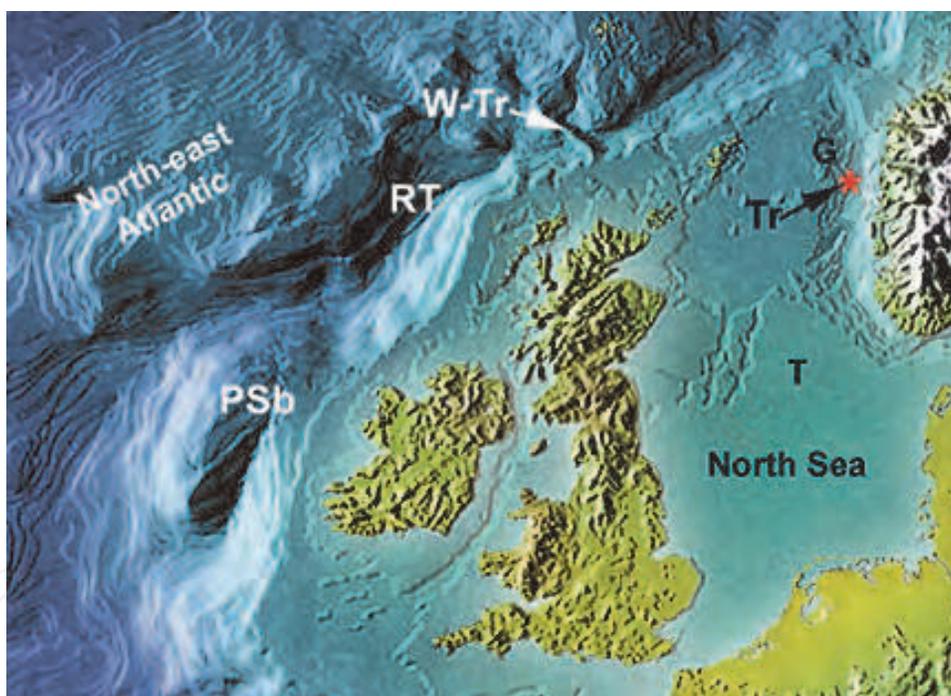


Fig. 4. The general bathymetry of the North East Atlantic Ocean including the North Sea. Seep locations in the North Sea are shown on the map as: T=Tommeliten, G=Gullfaks, and Tr=Troll. The Scanner seeps are located just north of T. The other features indicated, PSb=Porcupine Seabight, RT=Rockall Trough, and W-TR=Wyville-Thomson Ridge (based on Hovland, 2008). Because the mean sea-level during the Last Glacial Maximum (LGM) was about 120 m lower than at Present (Jelgersma, 1979) and because the three mentioned seep locations occur at three different water depths, the seafloor sediments at these locations geologically span the transition zones from *terrestrial* (Tommeliten, at ~75 m water depth, wd), through *intertidal* (Gullfaks, 130 m wd) to *submerged marine* (Scanner, 160 m wd) , and Troll, ~300 m wd zones.

two others have, over the last 20 years, been studied by multidisciplinary (including microbial) scientific surveys, with some interesting and also generalizable results.

3.1 Seeps at Tommeliten

A research cruise was mobilized by Statoil, in 1983, to perform a first-hand assessment of the seep features at Tommeliten. The vessel 'Skandi Ocean' was equipped with towed side scan sonar, combined with sub-bottom (high-resolution) profiler, an ROV (remotely operated vehicle) capable of acquiring gas samples, and a gravity coring system (Hovland and Judd, 1988; Judd and Hovland, 2007). The seafloor at Tommeliten has a mean depth of 75 m, and is generally flat and even. It consists of a ca. 5 cm layer of fine to medium quartzite sand, overlying stiff clay and marl layers. As documented by the several km² area surveyed with the towed system, a much smaller, 0.25 km², area was surveyed visually, with the ROV (Fig. 5). Here, a total of 22 actively bubbling seeps were observed. However, the whole seep area which is about 100 m in diameter is estimated to contain 120 individual bubbling seeps. The total methane output from this seepage field, was estimated to be 24 m³ of methane per day, at 75 m water depth (Hovland and Sommerville, 1985; Hovland et al., 1993). These were all concentrated within an area of about 0.06 km² (Wegener et al., 2008).

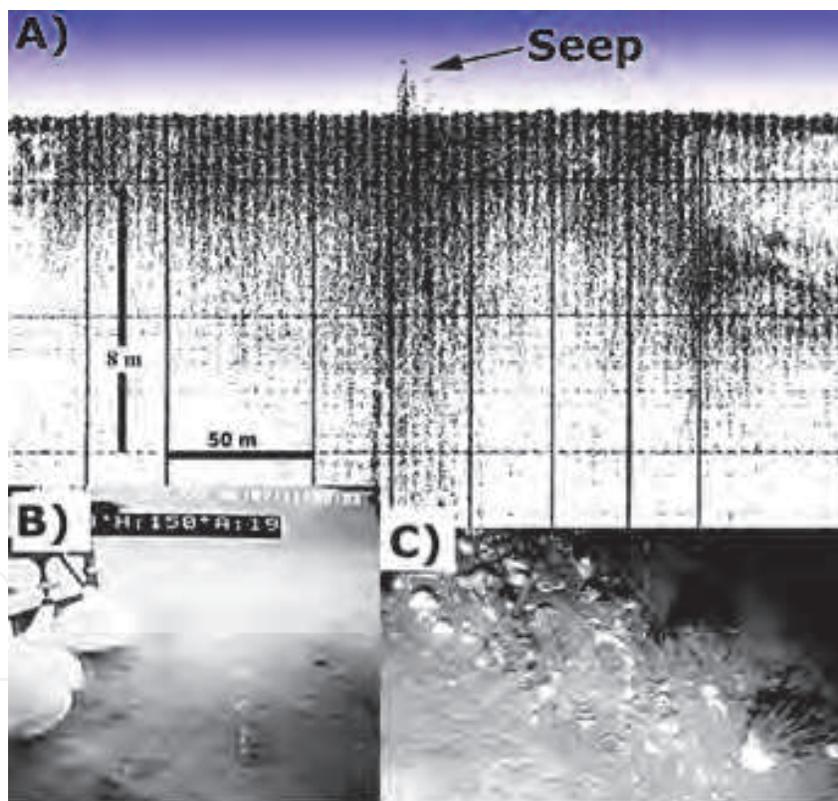


Fig. 5. A) One of the many bubbling seeps at Tommeliten, as recorded with the high-resolution sub-bottom profiler (SBP, 5 kHz). Note the gas-charged sub-surface sediments, which provide a strong backscatter (dark) acoustic signature. B) A bubbling seep at Tommeliten, seen in ambient light conditions, June, 1983. The size of the white funnels are about 20 cm high (Hovland and Judd, 1988). C) A small 'bioherm' located inside an 'eyed pockmark' near the seep depicted on A and B. The sea-anemone on the lower right is about 10 cm high (from Hovland and Thomsen, 1989).

The ebullition at Tommeliten is easily detectable with acoustic systems. However, these mid-water hydroacoustic “flares” (named thus because they are highly visible on echosounder recordings) are not only caused by various sized bubbles, but possibly also by water density contrasts caused by high concentrations of dissolved methane in the water. Thus, Niemann et al. (2005), reported up to 2 orders of magnitude higher concentrations (500 nM) of methane within the acoustic plumes (flares), compared to the background methane concentration (5 nM). Other possibilities for the formation of large, acoustic flares will be discussed later in this chapter. In general, a consequence of the hydrogen sulphide transported with escaping gas and interstitial water to the seafloor surface from deeper strata is the formation of sulphur oxidizing bacteria, notably the filamentous *Beggiatoa*, *Thiothrix*, and *Thioploca* spp (Dando and Hovland, 1992). They normally occur over patches of the seafloor where the sub-surface sediments are charged with reduced gases. They also occur close to gas outlets and on the underside of rocks (often carbonates) brushed by venting gas bubbles (Brooks et al., 1979; Hovland and Thomsen, 1997). These bacteria utilize chemical energy from sulphide oxidation to fix carbon dioxide into organic matter (Nelson et al., 1995). The grazing of macrofauna on bacterial mats has also been observed (Stein, 1984; Hovland, 2007).

3.2 The Scanner seeps

The actively seeping Scanner pockmark in the Witch Grounds, near the Forties field in the UK sector of the North Sea was found during a drillsite survey (Hovland and Sommerville, 1985). Subsequent mapping of the area revealed that the 900 m long, 450 m wide, and 22 m deep pockmark has several other large active pockmarks in its neighbourhood. The seeps were first noticed as acoustic flares on hull-mounted echosounder and towed side scan sonar data. During an ROV-based survey conducted by Statoil, in 1985, they were acoustically detected with the vessel ‘Lador’ and visually localized with the ROV ‘Solo’. However, compared to the acoustic flares, the bubble streams issuing from the Scanner pockmark were disappointingly small and feeble (Fig. 6). Only three bubble streams were found inside the pockmark and one of them, located adjacent to a protruding MDAC (methane-derived authigenic carbonate) block was sampled (Fig. 6). The maximum gas production (by bubble streams) was estimated to be 1 m³ per day from the entire pockmark (Hovland and Sommerville, 1985).

During one ROV survey line across the active Scanner pockmark, in 1985, the ROV ran at a constant depth of about 130 m across the pockmark (Fig. 7). During this run, the ROV-mounted side scan sonar recorded some diffuse ‘noise’ on both sides of the vehicle. It looked like small parcels of water with contrasting density or acoustic reflectivity (caused by change in impedance). The survey vessel ‘Lador’, followed the ‘Solo’ and had the hull-mounted 38 kHz echosounder running. The ‘Lador’ echosounder recording shows the ROV beneath the vessel as a horizontal intermittent line. But a strong impressively large acoustic flare was centred over the pockmark (Fig. 7). During the horizontal survey transect through the water above the pockmark, no bubbles were seen on the ROV-acquired video from the water column in front of the ROV. Later, Wegener et al. (2008) observed a relatively large acoustic flare over the Scanner pockmark, which reached to about 80 m below the sea surface. The Scanner pockmark consists of a dense series or cluster of unit pockmarks (Hovland et al., 2010; Judd and Hovland, 2007), which becomes evident when the ROV moves from the outside over the outer rim of the pockmark. The landscape is undulating as

the ROV descends down the gentle slope to the pockmark bottom, which lies 22 m below the surrounding seafloor. Because the seafloor consists of soft clay (mud), the ROV operation calls for careful navigation. Too much use of ROV-thruster energy renders the seawater murky and reduces visibility to less than 50 cm.

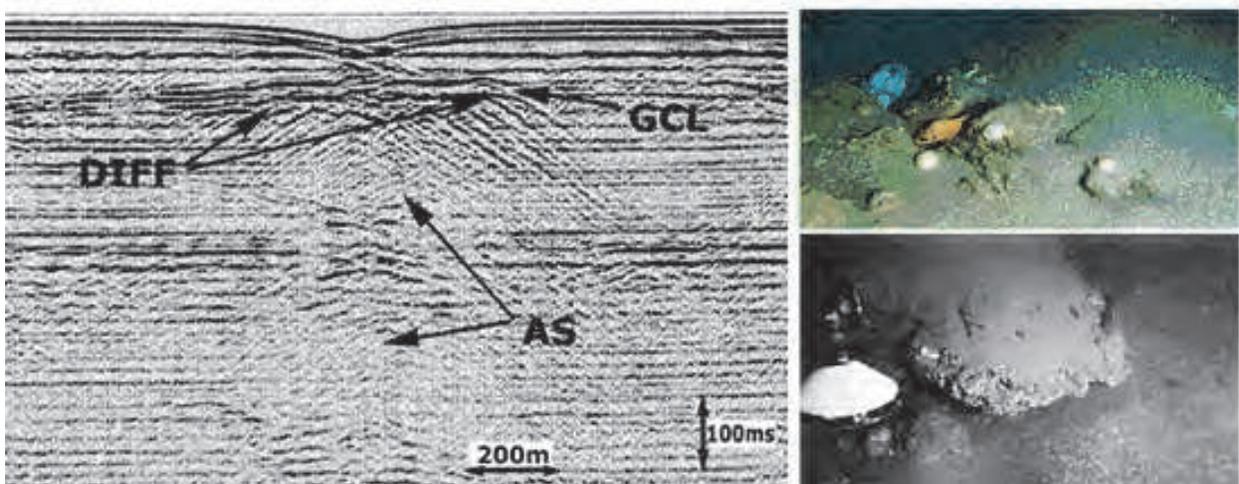


Fig. 6. The Scanner seep location is within a 22 m deep pockmark crater in the Witch Grounds of the North Sea, not far from the Forties field. The left image is a reflection seismic record showing reservoired gas (GCL) residing immediately below the pockmark depression. "Diff" = acoustic diffractions, "AS" = acoustic shadow zones. To the right are two images of the seafloor environment at the bottom of the pockmark. The lower one shows a white funnel (20 cm high), mounted on the ROV for gas sampling. Furthermore, there is a large MDAC rock adjacent to the bubbling gas stream being sampled (not visible). In the upper right photo, the red fish is about 20 cm long

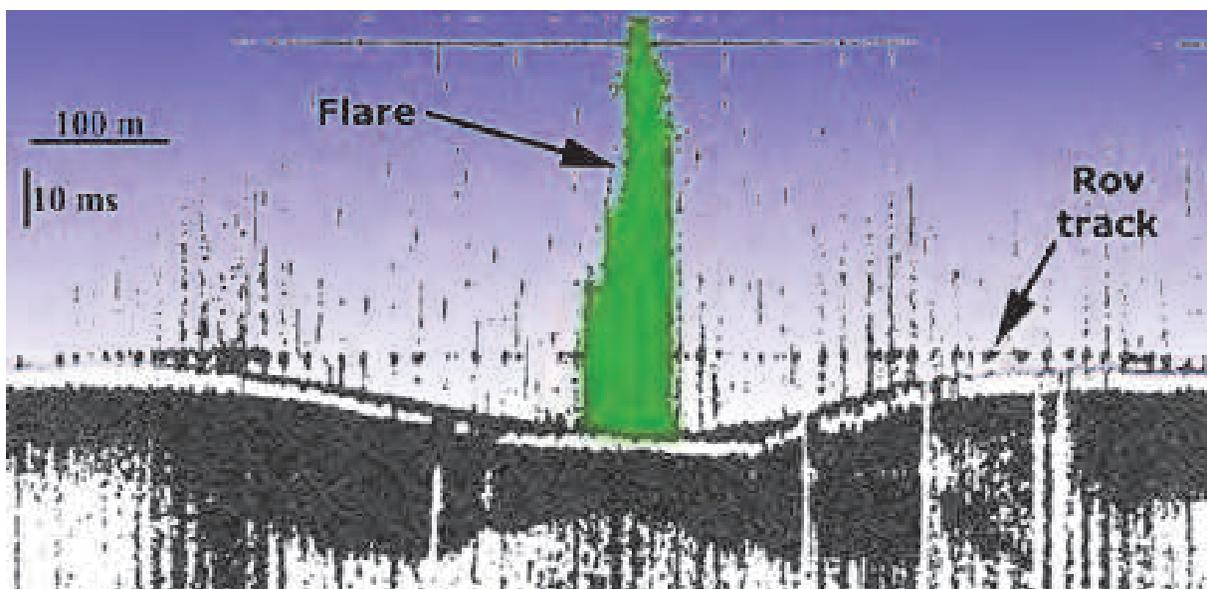


Fig. 7. A unique single beam echosounder record acquired over the Scanner pockmark by the vessel 'Lador' as the ROV 'Solo' surveyed the pockmark at a constant depth (~130 m) (see text for further details).

To explain the apparent mismatch between the feeble gas seepage observed and sampled inside the pockmark compared to the large hydroacoustic flare, it is suggested the flare is not only caused by rising bubbles, but may also be caused by high concentrations of methane and/or, perhaps, hydrogen (H₂). There is also another possibility: - that gas bubble clouds rising through the water column create a weak sound, i.e., noise that could be picked up as flares or weak reflections by echosounder and side scan sonar transducers. Either of these suggestions may be likely, but only careful acoustic and chemical studies will be able to determine how valid they are.

3.3 Pockmarks at Troll

The large Troll gas field is located at 310 m water depth inside the broad (>100 km wide) 'Norwegian Trough', which runs parallel with the southern and south-western coast of Norway (Fig. 4). There are numerous pockmarks in this area, which are up to 100 m in diameter and 8 m deep (Tjelta et al., 2007; Judd and Hovland, 2007). Despite the high density of up to 20 pockmark craters per km², at Troll, there are no known macro-seeps, detectable as hydroacoustic flares in the water column (Fig. 8). This probably means that most of the gas released in the area, is done episodically through the pockmarks. However, the periodicity of such release is still unknown (days, months, or years?).

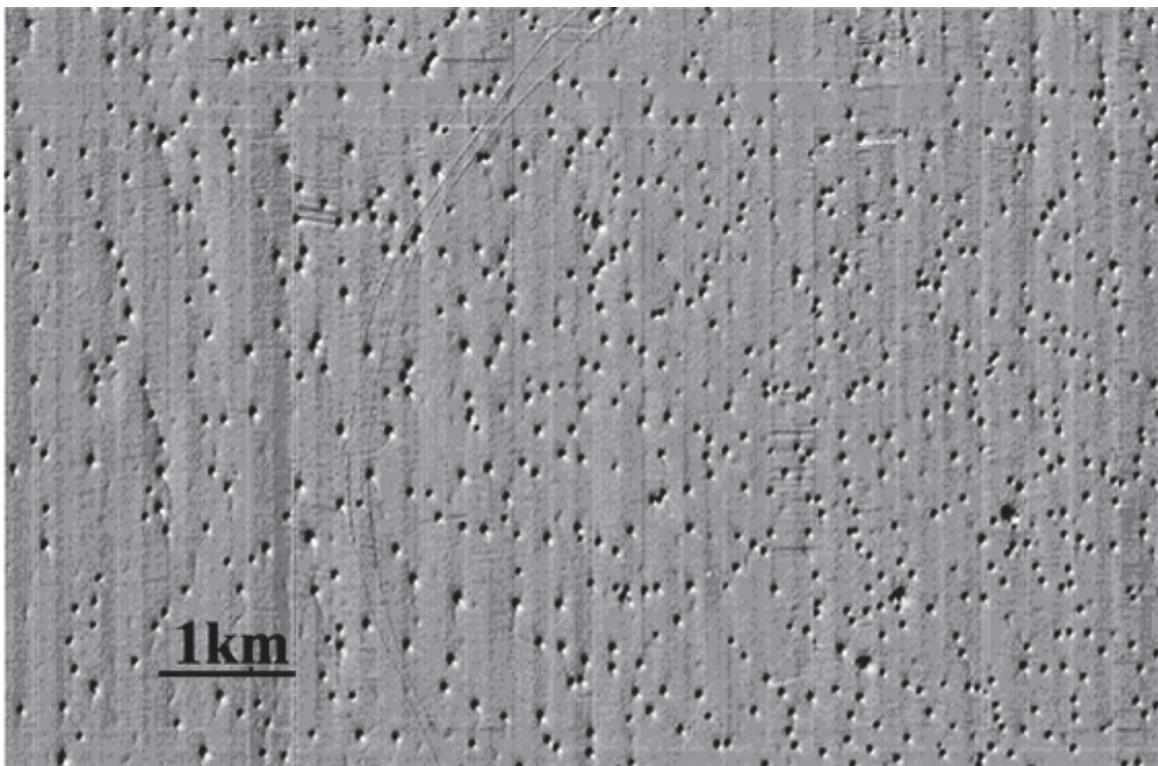


Fig. 8. Pockmarks mapped with hull-mounted multi-beam echo-sounder (MBE) near the Troll field, Northern North Sea. The resulting digital terrain model (DTM) is here presented as a shaded relief image with artificial lighting from the NW (north is up).

Statoil investigated some of the largest pockmarks over parts of the Troll field to find out more about the rate of natural sub-seafloor hydraulic activity (Forsberg et al., 2007) (Fig. 9). It is inferred that the eight 'satellite' pockmarks surrounding the parent-pockmark occur as a

consequence of self-sealing of the parent, by the formation of MDAC across its bottom (see Fig. 9) (Hovland, 2002).

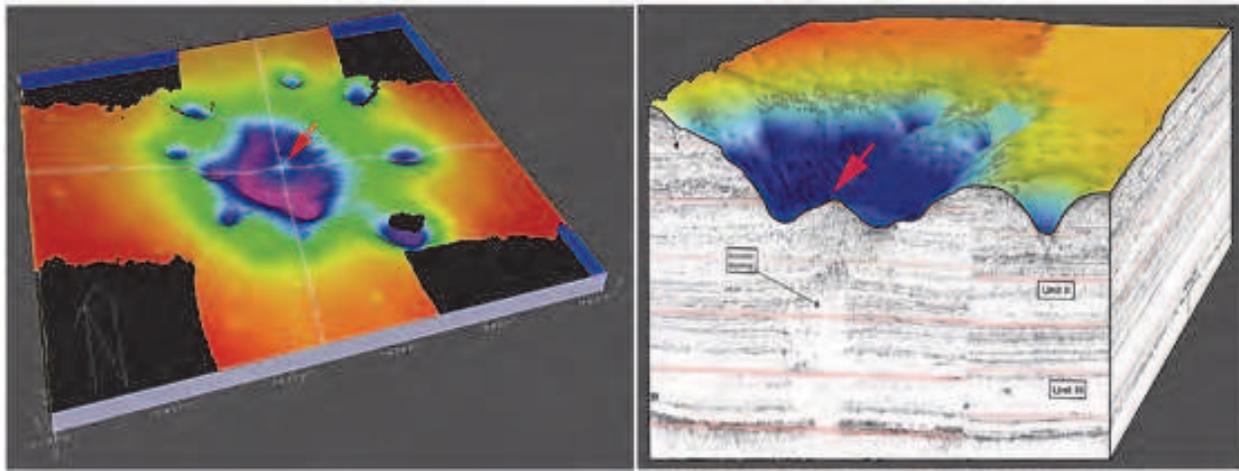


Fig. 9. The left image is a perspective view of a portion of the seafloor at the Troll field mapped at high resolution with ROV. It shows one central (old) 'parent pockmark' in the middle and eight of the other smaller 'satellite pockmarks' surrounding it. Right: Another view of the same features with enhanced vertical scale combined with high resolution SBP-data across the pockmarks. This drawing is made as a composite image based on real sub bottom profiler and bathymetric data from the actual location. The sides of this diagram are about 800 m, by 600 m, by 30 m. The red arrow points at the features seen in Fig. 10.

ROV-mounted sub bottom profiling (SBP) was also performed across this parent-pockmark. A vertical zone of disturbance and anomalous reflections beneath the centre of the pockmark were detected (Hovland et al., 2010). This zone is probably caused partly by the occurrence of MDAC and also a presence of small amounts of free gas, suspected to represent a cylindrical 'chimney' below the pockmark. On visual inspection with an ROV they came across some large colonies of soft coral (*Paragorgia* sp.) inside the largest pockmark inspected (Tjelta et al., 2007). To our knowledge, this is the first time large corals have been documented in the Norwegian Trough. The find came as a surprise as conditions are regarded to be far from perfect for such filter-feeding organisms. The two large *Paragorgia arborea* (one white and one red) individuals are perched inside the 8 m deep pockmark, which has a 1 m high conical methane-derived carbonate rock protruding up from its centre (Fig. 10). The corals are firmly based on this 'natural concrete' substratum. Clusters of up to 30 *Acesta excavata* bivalves are also affixed to the same structure. Because these animals live at a depth of up to 6 m below the general seafloor it is likely that they must tolerate frequent periods of heavy silting and sedimentation. These organisms undoubtedly occur here as a result of seepage-induced nutrient enrichment inside the pockmarks (Hovland et al., 1985).

Strings of small pockmarks were already identified on side scan sonar records in the middle of the Norwegian Trough during the early seafloor mapping activities conducted there (van Weering et al., 1973; Hovland, 1981, 1982; Hovland and Judd, 1988; Judd and Hovland, 2007). However, from the high-resolution mapping with ROV-mounted MBEs and side scan sonars conducted in 2005 (Fig. 11), the 'habitat' of unit-pockmarks in the near-Troll area has been documented. The most remarkable occurrences are those associated with clusters of

normal-pockmarks, where one large pockmark occurs in association with several ‘parasite’ or satellite-pockmarks, as shown in Fig. 9 (Forsberg et al., 2007; Webb et al., 2009).

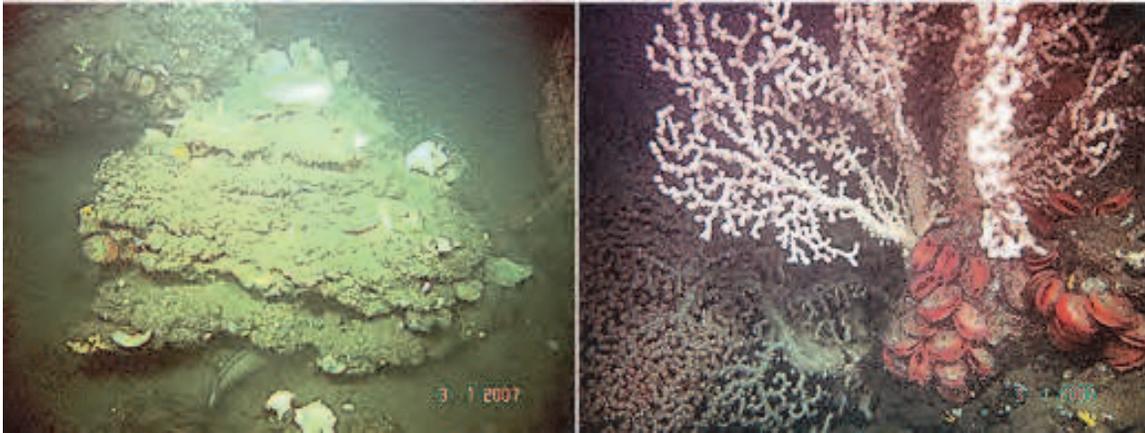


Fig. 10. Left: Large carbonate rock, a methane derived authigenic carbonate (MDAC). It serves as foundation for the *Paragorgians* and *Acesta* organisms seen in the right image. Notice the dense cluster of about 10 cm long *Acesta excavata* bivalves attached to the stems of the large gum corals and to the underlying MDAC-rock (From Hovland et al., 2010).

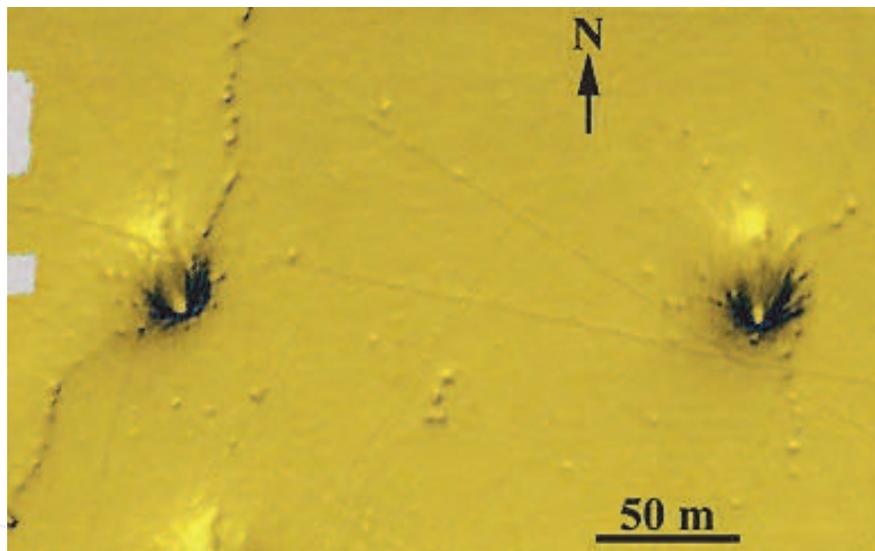


Fig. 11. High-resolution MBE data from the Troll-area (ROV-mounted MBE). This shaded relief DTM is presented in a light tan colour to enhance topography. Strings of pockmarks and trawl-marks are seen in this shaded relief image. The small (<5 m diameter) pockmarks making the strings are called “Unit pockmarks”, and were defined by Hovland et al. (1984).

3.4 What are pockmarks?

In the foregoing, there has been a lot of mention about pockmarks, the mysterious craters in the seafloor. The strange fact is that they are about as mysterious today as they were when Lew King and Brian MacLean, back in the late 1960’s discovered them (King and MacLean, 1970). The main reason for them not being understood yet, is that there are no such features on the terrestrial surface of our planet, only on the water covered Second Surface, which we have great difficulties in both imaging and understanding. Figures 8 and 12, however, give a

good idea of how common they are on the seafloor in some areas, especially where there are hydrocarbons (gas and oil). One thing is certain, however, they have something to do with the hydraulics of the soft seafloor, which is both pressurized, and buoyed at the same time. One other important aspect is also that gases have something to do with their formation, as recently concluded by Cathles et al. (2010) and Hovland et al. (2010):

- “The local seafloor is either characterized as ‘hydraulically active’ or ‘hydraulically passive’, dependent on the occurrence of pockmarks and other fluid flow features (active) or the absence of such features (passive).
- The type of surface fluid flow manifestations determines the type and vigour of activity, i.e, cyclic/periodic, high, or low hydraulic activity.
- Whereas Unit-pockmarks most likely represent cyclic pore-water seepage, normal-pockmarks represent periodic or intermittent gas bursts (eruptions) with intervening periods of slow, diffusive, and cyclic pore-water seepage.
- The driving force behind seafloor hydraulic activity is reservoired, buried gas pockets.

In practical terms, this means that when sampling for seeping fluids, we recommend ‘seep-hunters’ to target the Unit-pockmarks. The higher investment needed to ensure detection and mapping of the small Unit-pockmarks, may be balanced by a higher success rate in sampling dissolved gases in the seeping pore-waters resulting from the active pumping by the trapped under-ground gas.” (Hovland et al., 2010)

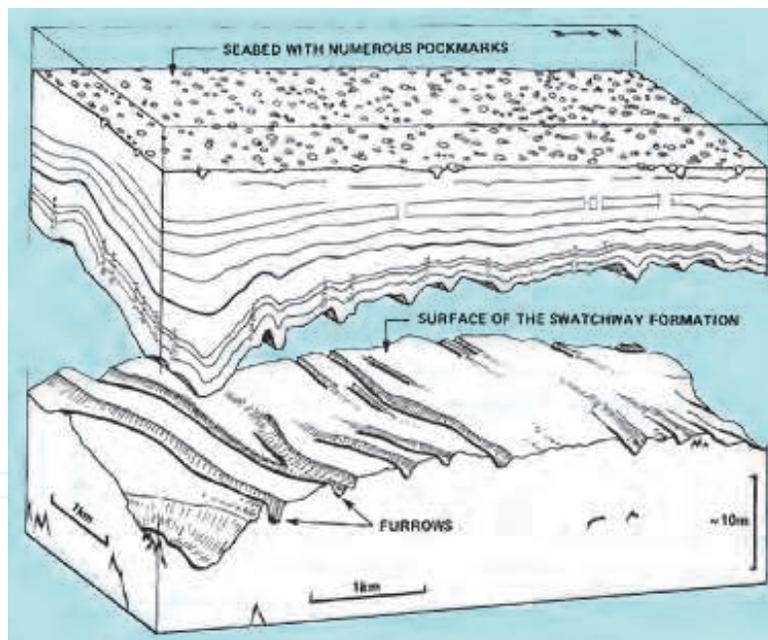


Fig. 12. Pockmarks in the Forties area, central North Sea (Based on Hovland and Judd, 1988).

4. Seeps off Mid-Norway

Part of the north-eastern Atlantic Ocean located to the west of Mid- and Northern-Norway is called the “Norwegian Sea”. It stretches from the North Sea, north of the 62nd parallel to the islands of Spitzbergen. Over large areas, the seafloor off Mid-Norway and also parts of the Barents Sea, is still heavily iceberg plough-marked (Fig. 13). Thus, the geomorphology is very different from the seafloor over the majority of the North Sea and there is hardly any

soft, layered sediments that have been laid down over the iceberg-scoured clay-rich sediments since the last glacial maximum (LGM) period about 20 thousand years ago (Judd and Hovland, 2007; Hovland, 2008). However, despite the dominating seabed topography being the kilometre long, up to 50 m wide and over 5 m deep linear troughs, there are more recent bedforms occurring, such as pockmarks, linear ridges and deep-water coral reefs (DWCRs), which have been partly or fully induced by fluid flow (seepage).

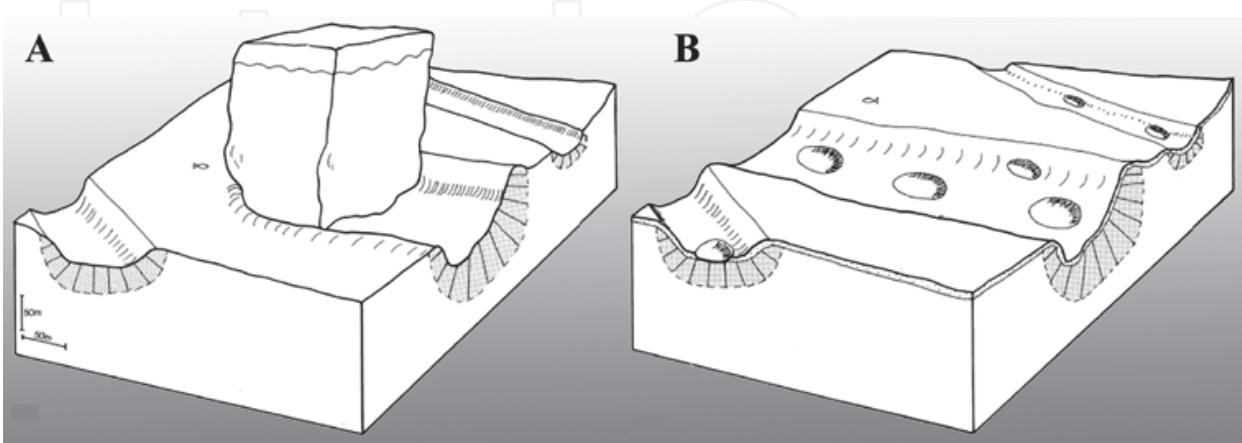


Fig. 13. A sketch showing how iceberg plough-marks were formed by grounded icebergs moving across the seafloor (A), during the melt-off period, after the LGM. Note that more recent pockmarks may form especially inside the ploughed troughs, as often seen on the present seafloor off Mid-Norway and in the Barents Sea (B) (adapted from Hovland and Judd, 1988).

4.1 Deforming gas-charged clay at Onyx?

Even though linear trends produced by drifting icebergs are very common offshore Mid-Norway, another, strange seafloor topography was found over the Onyx field, in concession block 6407/4, off Mid-Norway (Hovland, 2008). The more-or-less parallel ridges, there, resemble inverted iceberg plough-marks. These are, however, fundamentally different, as they are rounded upwards (Fig. 14 and 15). Furthermore, there are numerous seeps (detected as hydroacoustic flares) issuing from these ridges. The seafloor was only briefly investigated and no visual evidence of seepage was found on the seafloor. Only the occurrence of colonies of deep-water corals and an apparent bacterial mat (Fig. 16) were found to support the acoustic flare interpretations (Hovland, 1990a; 2008).

According to the suggested formation model, gas permeates into the soft, relatively stiff clay from below (shown as small dots in Fig. 14, 1-3). The gas is expected to occur within the clay as finely disseminated minute bubbles, so that the bulk density of the gas-laden clay is less than that of the surrounding, gas-free clay. As more and more gas flows up from weakness zones in the underground, the upper surface layer (perhaps 20 m thick) starts to deform because of the bulk density (buoyancy) contrasts. As the deformation reaches a critical point, the clay becomes permeable and gas flows out to the water column, causing the observed hydro-acoustic flares. Gas will now follow these established conduits and the deformation ceases (Hovland, 1990a). A similar model was also used to explain the formation of linear, diapiric mud formations in the Adriatic Sea (Hovland and Curzi, 1989).

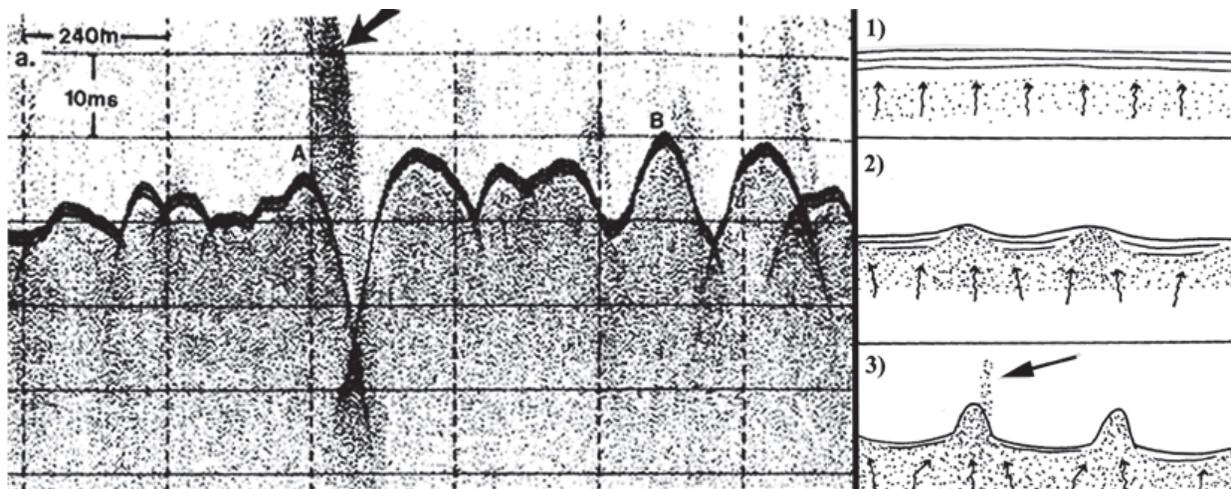


Fig. 14. Seepage and evidence of deforming clay at the Onyx field, off Mid-Norway (Based on Hovland 1990a and 2008). The sketches to the right, numbered 1 - 3 indicates a novel development model suggested by Hovland (1990a). See text for further description.

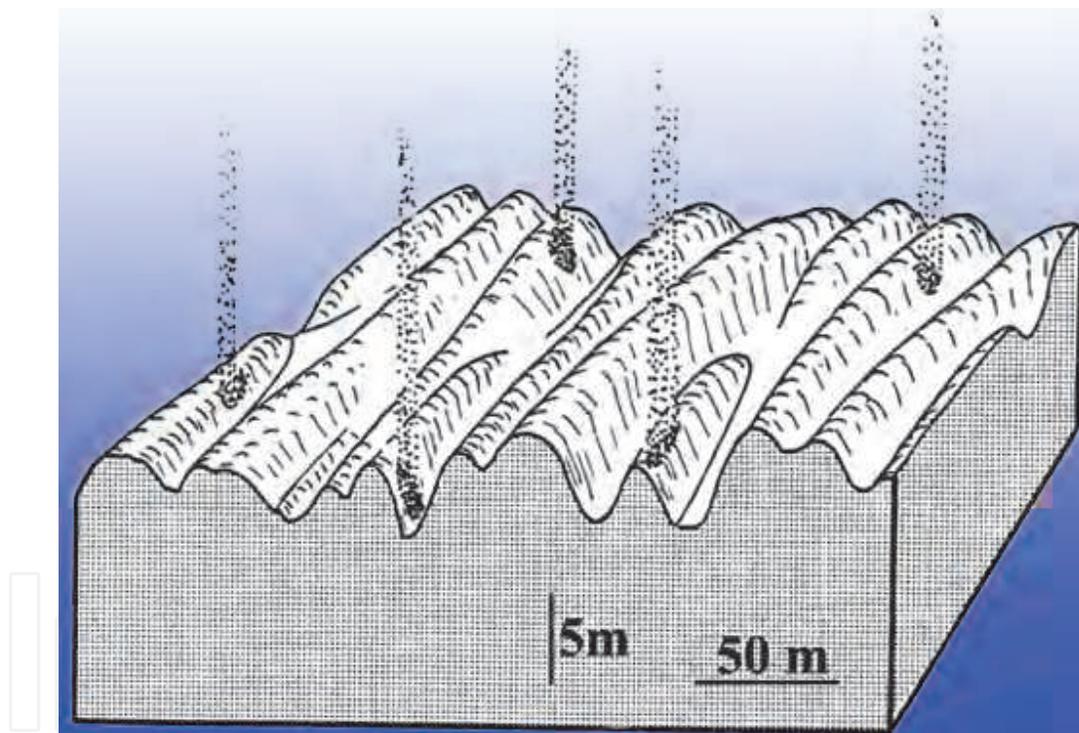


Fig. 15. A sketch showing how gas is suspected to flow out along linear ridges on the seafloor at the Onyx field off Mid-Norway. See text for further description and discussion (based on Hovland, 2008).

Figure 16 shows a coral accumulation at Onyx, near one of the seep locations. The field of view is about 1.5 m across at the base. Note the minute bacterial mat arrowed, which indicates the occurrence of reduced fluids in the sub-stratum. The organisms seen here are *Paragorgia arborea* (pink large coral, about 1 m high), some sponges, and a small colony of the white stony coral, *Lophelia pertusa*, in the foreground. This latter species is the main reef-building organism off Mid-Norway (Based on Hovland, 2008).

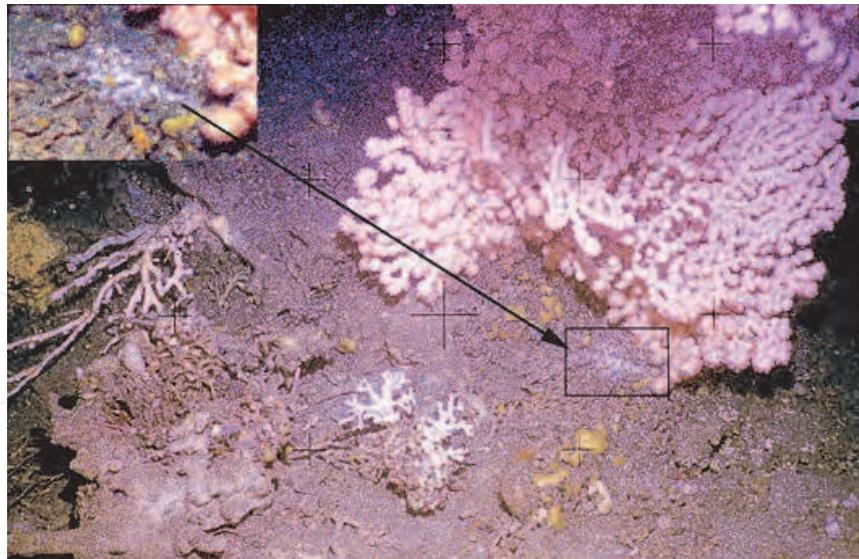


Fig. 16. A spectacular image of the seafloor, which was acquired in 1991 by use of ROV at the Onyx field (Block 6407/4, Hovland, 2008), near the seeps shown in the previous two figures. The arrowed insert image has been enlarged to show a white bacterial mat (see text for further explanation).

4.2 The deep-water coral reef (DWCR) enigma

One of the main and controversial questions still remaining to be answered with respect to the impressive deep-water coral reefs (DWCRs), found in the thousands off Mid-Norway (Hovland et al., 1995a; Mortensen et al., 1995; Hovland and Thomsen, 1997; Hovland and Risk, 2003; Hovland, 2008) is why they occur in deep and cold water, even north of the Polar Circle. This is despite there hardly being any photosynthesis occurring in the surface waters during the winter months. A 'hydraulic theory' suggesting that they rely on locally produced nutrients coming from the extra energy percolating upwards as light hydrocarbons (especially methane, ethane, and propane), was put forward by Hovland (1990b), and has been reiterated several times since then, as more supportive data occurs. However, this theory is hard to prove, and the "consensus" view among the world's leading marine biologists on this matter is still that deep-water coral reefs represent natural biologic entities that are not dependent upon such (exotic) local nutrients: "Colonial scleractinians need hard substrate for settlement. This substrate can be a shell or a pebble, and as soon as one colony is present it provides new hard substrate for subsequent colonisation." (Buhl-Mortensen et al., 2010). So, the question remains as to why only less than 0.1 per mille (‰) of the total area in the depth zones where they occur is covered by cold-water coral reefs? Why, for example, are there no more of them in the Norwegian and New Zealand fjords, where the distribution of intermediate and deep water masses is right, and where there is ample suitable hard substrate (rock bottom) with high current speeds?

However, the search for further support to the Hydraulic theory continues, and some recent microbial studies seem to point the way forward. Thus, Yakimov et al. (2006), for example, recently found metabolically active microbial communities associated with deep-water corals in the Mediterranean. Also recent research of the microbial food chain surrounding the coral reefs off Mid-Norway, have provided some interesting new findings. The contrast

between coral-associated and free-living bacteria may suggest that few free-living bacteria are directly ingested by the coral and that instead, corals feed on non-bacterial plankton. Small (100 – 200 μm) zooplankton has been suggested to be important in the diet of corals (Sorokin and Sorokin, 2009). In addition, the tissue-associated bacterial communities potentially provide a direct translocation of nutrients through metabolism of particulate and dissolved organic matter in the seawater. One *Lophelia pertusa* associated bacterium was studied in more detail and named “Candidatus Mycoplasma coralicola” (Neulinger et al., 2008). It was found to be abundant in *L. pertusa* from both sides of the Atlantic Ocean and is considered an organotrophic commensalist. Given the importance of chemosynthesis in deep-water ecosystem development and functioning, cold-water coral reef communities may be linked to a diversity of chemoautotrophic microorganisms that synthesise organic compounds from inorganic compounds by extracting energy from reduced substances and by the fixation of dissolved CO_2 . Just a tiny fraction of microorganisms associated with deep-water coral reefs have yet been identified, and even less assigned to a function. Although no nutritional symbiosis based on chemosynthesis (Tavormina et al., 2008) have to our knowledge been documented on deep-water coral reefs, primary producers affiliated with chemoautotrophs (utilizing H_2S , NO_2^-) and methanotrophs (utilizing CH_4) have been found associated with the reef animals and their ambient environment (Penn et al., 2006). Thus, also light hydrocarbons can probably stimulate the growth and the high biodiversity found on the *Lophelia*-reefs associated with some Norwegian hydrocarbon fields (Hovland, 2008). Only further detailed studies of the reefs will be able to answer these important questions (Jensen et al., 2008).

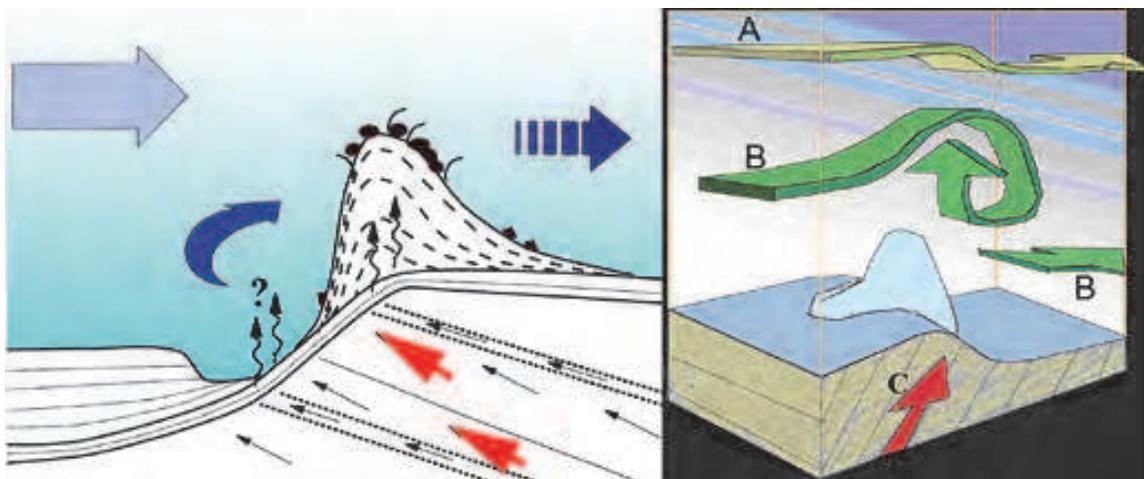


Fig. 17. The DWCR Hydraulic theory is illustrated in these two sketches. The concept is based on the idea that nutrients are brought up to the seafloor surface through seepage (red arrows). The arrow A represents the general prevailing current, B is the turbulent near-bottom current, and C, fluid flow (seepage) from below (Based on Hovland, 2008).

Despite the fact that no nutritional symbiosis involving chemosynthesis have been documented on deep-water coral reefs, other than ‘unassigned’ primary producers affiliated with chemoautotrophs and methanotrophs utilizing H_2S , NO_2^- , CH_4 , and possibly iodide (Penn et al., 2006; Yakimov et al., 2006; Jensen et al., 2008), it was recently concluded that hydrocarbons probably stimulate the growth, the high biodiversity, and biodiversity, including the rare purple octocoral found on the pockmark-*Lophelia* reef, MRR (Morvin Reference Reef), at Morvin (see Hovland, 2008, and Fig. 19). Further support to the

Hydraulic theory comes from microbial studies conducted on the large sub-surface hydrocarbon plume emitted during the Deepwater Horizon blowout in the Gulf of Mexico, in 2010 (Redmond and Valentine, 2011). They found that three types of microbial communities bloomed as a result of the hydrocarbons in the water: *Oceanospirillales*, *Colwellia*, and *Cycloclasticus*. The two first of these community types, which apparently utilize ethane and propane in the water, are also found in the near-bottom water surrounding DWCRs at Morvin off Mid-Norway (Jensen et al., 2008; 2010).



Fig. 18. A typical Norwegian *Lophelia*-DWCR consists of a large mound of live and dead *Lophelia pertusa* skeletons, other colonizing organisms, are sponges and other coral species. A live *Lophelia*-colony is seen here (the white coral in the foreground, Hovland, 2008). Fish, like the seithe (*Pollack*) and red fish (*Sebastes*) seen here, are normally associated with the reefs. The seithe is about 1 m long and the red fish about 30 cm.

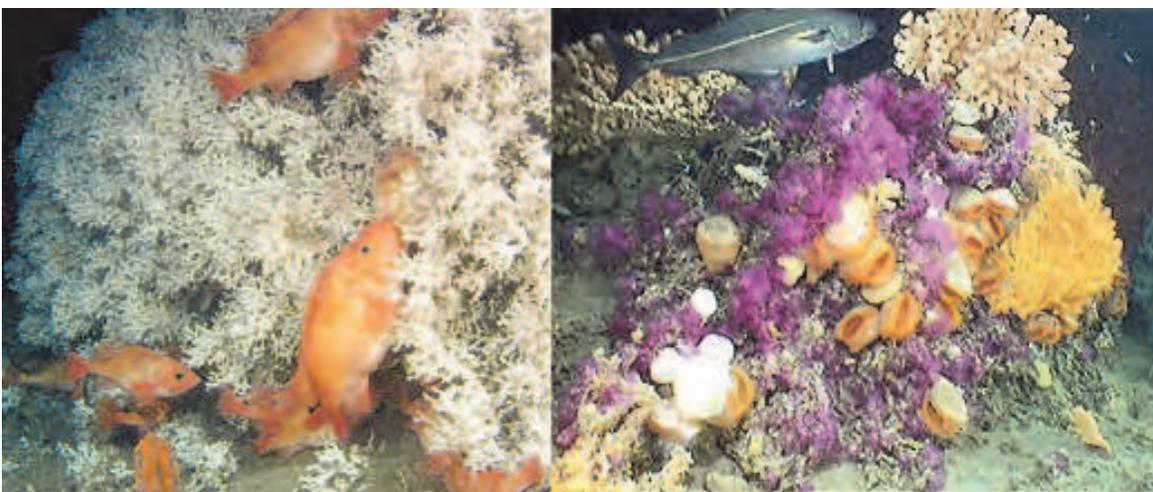


Fig. 19. Left image, the *Sebastes* red-fish probably preparing for spawning at a *Lophelia*-reef at the Morvin field off Mid-Norway (the nearest red fish is about 35 cm long). Right, the beautiful violet coral *Anthothela grandiflora* covering a dead *Lophelia*-colony at the Morvin Reference Reef. The seithe swimming by is about 1 m long (see also Hovland, 2008).

4.3 The Fauna reef and Unit-pockmarks

A relatively large, composite (ca. 500 m long, 100 m wide, and 25 m high) DWCR, was recently discovered in association with numerous Unit-pockmarks (Hovland et al., 2010). This “Fauna reef” was named after one of the vessels used during the investigations, the “Edda Fauna”. The area is located at 07° 53′ E and 63° 54′ N, near the well-known Sula Reef Complex (Freiwald et al., 2002; Hovland, 2008), off Mid-Norway (Fig. 20).

A total of 233 Unit-pockmarks and the large Fauna reef occur within the detailed surveyed rectangular area measuring 920 m by 245 m, mapped with ROV-mounted MBE (0.2m by 0.2 m gridding). Whereas 79% of the Unit-pockmarks were evenly scattered up-stream of the prevailing current at the Fauna reef (shown in Fig. 20), the rest of them were scattered up-stream of a much smaller DWCR. This latter one (ca. 50 m long, 30 m wide, 7 m high) was, however, located on the outer rim of a large Normal-pockmark crater of 180 m diameter and 16 m depth.

Previous seafloor investigations in this region have revealed DWCRs closely associated with Normal-pockmarks of up to 200 m width and 12 m depth. Such pockmark-related reefs occur at the nearby Haltenpipe Reef Cluster (HRC, Hovland and Risk, 2003; Hovland and Thomsen, 1997) and at the Kristin and Morvin hydrocarbon fields (Hovland, 2008). At all these other locations, Unit-pockmarks also occur adjacent to the reefs, and are densest up-stream with respect to the prevailing current direction (Fig. 20). Generally, the concentration of light hydrocarbons (methane – pentane) within the sediments of Unit-pockmarks is found to be higher than in the background, surrounding sediments (Hovland et al., 2010). It was concluded that Unit-pockmarks probably provide the necessary seep-related nutrients to stimulate year-round healthy coral growth and reef development, even in the dark winter season. A possible test to this theory would be to attempt detection of stable carbon-isotope variations in DWCR skeletons, as a function of season.

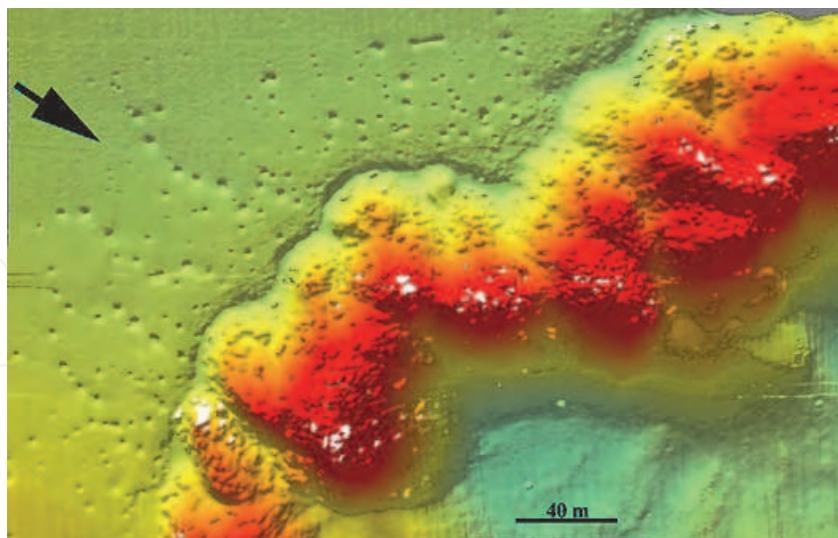


Fig. 20. The enigmatic ‘Fauna Reef’ off Mid-Norway. The black arrow indicates the prevailing current direction. The reef is about 25 m high (indicated here in red and yellow colours) and consists mainly of living *Lophelia pertusa* colonies. Notice the high density of Unit-pockmarks occurring in an up-stream direction relative to the reef (Based on Hovland et al., 2010). Note, the white patches are gaps in data (gaps in the DTM grid), as it is very difficult to cover the whole area of this reef-associated complex topography with ROV-MBE.

5. Other seep-related seafloor features, worldwide

In this last section, I will touch upon some other important seep-related seafloor geomorphology features that have been documented around the world over the last 30 years or so. Although the geomorphology associated with seafloor gas hydrates is very important, there is only space to cover a small portion of this issue. Three other aspects of seep/vent-associated seafloor geomorphology have also evaded detailing in this chapter. These are: 1) mud volcanism, which is perhaps even more common on the Second Surface than on land (e.g. Milkov, 2002). 2) The strange asphalt volcanoes, which tend to be associated somehow with the formation of salt domes (Hovland et al., 2005). 3) The vast subject on hydrothermal venting along tectonically active zones. Some of the pertinent information has, however, been treated by Judd and Hovland (2007).

5.1 Sandwave pattern modified by seepage

Sandwaves represent common geomorphology features on the seafloor where there is abundant sand in combination with high current velocities. Such conditions occur in the Southern North Sea and along the eastern coast of UK. During mapping campaigns offshore Belgium and the Netherlands in parts of the southern North Sea, Statoil mapped large fields of sandwaves. The waves were up to 12 m high and nearly 40 metres long. The detailed mapping was performed in association with pipeline route surveys for the laying of trunk pipelines from Norway to Belgium and France in the mid 1990's. Hull-mounted MBEs were used in combination with towed SBPs. By careful inspection of the results, it was disclosed that pockmarks had formed even in this high-energy and high-relief seafloor 'landscape' (Fig. 21). This part of the sandwave field is located where there are strong indications on the SBP-data of gas-charged sediments and peat deposits underneath the seafloor (Judd and Hovland, 2007). Slight hydroacoustic flares were also found on the original SBP-recordings, showing active ebullition through the seafloor at one of the pockmark locations.

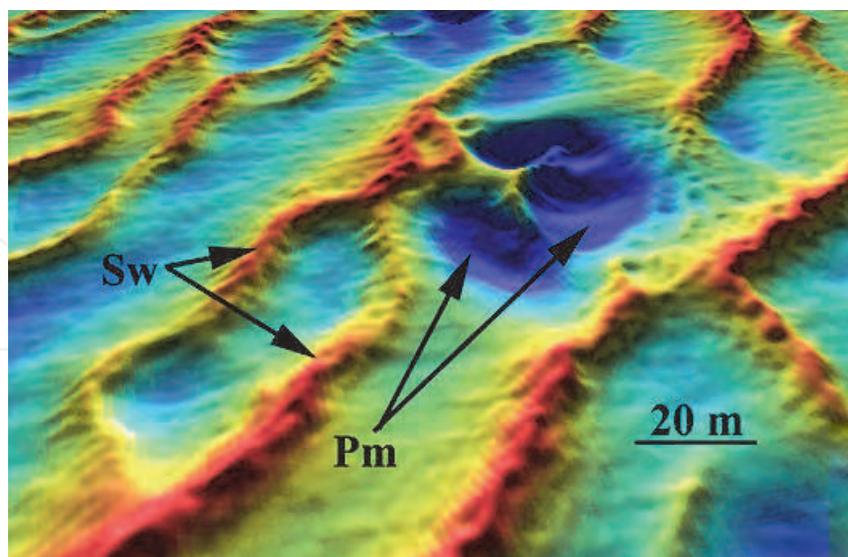


Fig. 21. A digital terrain model of a sandwave-field in the Southern North Sea. The regular sandwave pattern has clearly been disturbed by pockmark development (see text for further details). Sw=Sandwave, Pm=Pockmark. The highest sandwave crest is about 12 m above the 'normal' seafloor (greenish hue) and the deepest pockmark is about 2 m below that same depth (Based on Judd and Hovland, 2007).

The disturbance of the sandwave pattern occurs as a consequence of the 'competing' force of vertical fluid flow. This flow makes sand-grains more easily moved by the horizontal tidal currents, such that they are swept away and pile up where there is no vertical fluid flow. Thus, the sand piles up at the nearest location where this is possible, and large, sometimes pyramidal "freak sandwaves" result, thus breaching the otherwise rhythmic and regular sandwave pattern (Judd and Hovland, 2007).

5.2 Deep-sea carbonate mounds

Large, mounded structures occurring in relatively deep-water, often located inside depressions on the seafloor were first found off the SW coast of Ireland, in the Porcupine Basin (Fig. 22, Fig. 1). They were detected on 2D-seismic records and were later published by Hovland et al. (1994b). It was speculated that these structure, and similar ones, occurring on the other side of the planet, off NW Australia actually represented carbonate knolls, that had formed due to seepage, as suggested by Hovland (1990b).

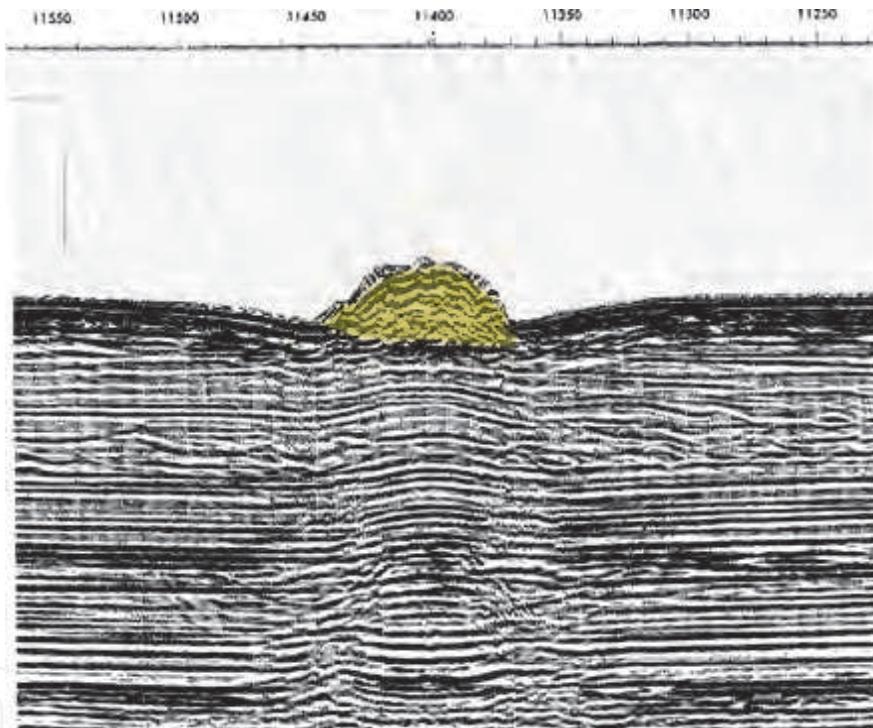


Fig. 22. A 2D reflection seismic image of a live, giant carbonate mound (yellow) off SW-Ireland (Hovland et al., 1994b). The height of the carbonate mound is about 100 m and its length at base is about 1 km. The water depth is about 800 m (see also Hovland, 2008).

The very same year as the paper came out, in 1994, at least three academic research vessels conducted further seafloor mapping offshore west and southwest Ireland. It was documented that the mounds were built up as carbonate structures, capped with living deep-water corals. However, it seems that the reason why they build up where they do, may be more complex than previously suspected, even despite drilling campaigns where one of the now dead mounds was sampled by drilling (Ferdelman et al., 2006; Hovland, 2008). Therefore, much more scientific multidisciplinary work is needed to be done before we know why and how they build up (Foucher et al., 2009).

5.3 Gas hydrates in deep-sea sediments

Gas hydrates are crystalline, ice-like compounds composed of water and gas molecules, where the small gas molecules are trapped within a cage-like framework of hydrogen-bonded water molecules (Hovland, 2005). These structures (chemically called 'clathrates') are formed under very specific temperature and pressure conditions in an environment with adequate water and gas. The right conditions can be found on land, in polar regions, where surface temperatures are very low, and within water or seabed sediments at depths exceeding about 300 m and where the temperature is adequately low (generally $< 10^{\circ}\text{C}$). The four conditions that need to be fulfilled before gas hydrates, a substance resembling ice, form are: i) The presence of abundant water (H_2O); ii) free gas molecules, small enough to fit into the water cages, i.e., methane, ethane, propane, n-butane, and/or carbon dioxide (CO_2) and hydrogen sulphide (H_2S); iii) adequately high pressure, and iv) adequately low temperature. The most common hydrate occurring in the oceanic sediments, are methane hydrates, where one cubic metre of pure methane hydrate can contain up to 169 Sm^3 (Standard cubic metres) of methane. Thus, oceanic hydrates may represent a vast energy resource currently being studied by several energy-hungry countries, including Japan, Germany, Korea, USA, Canada, and India.

Lake Baikal, in Siberia, Russia, is volumetrically the largest lake on Earth, containing about 20% of the surface fresh water volume. It was formed by rifting of the crust, and is still tectonically active, with several types of seepage phenomena, including petroleum seeps, gas seeps, and warm, hydrothermal vents (Fig. 23). After 4 years of intensive mapping of the lake, with multi-beam echosounding, coring, biological sampling, and, not least, repeated deployment of two manned Russian MIR submersibles, a series of spectacular discoveries have been made (Leifer et al., 2011):

- Several bitumen mounds, the largest being about 50 m high and still actively seeping oil,
- numerous locations of mud volcano-like mounds with gas hydrates and active gas seepage (Fig. 23), and
- new seep-related micro- and macro-animal species.



Fig. 23. Sampling gas hydrates, Lake Baikal, 2010. The image on the right is a screen shot of the on-board echosounder (EM400), showing the gas seepage from under-ground gas hydrates on a slight ridge on the lake floor (depth: 403 m below the central seep plume)

The new species discovered by sampling and visual inspection include nematodes, sponges, oligochaetes, molluscs, crustaceans, and giant flatworms. At least 10 animals are new species for science, among them two novel nematode species. Diverse microbial communities have been discovered both inside and outside bitumen structures. They consist of methanotrophic bacteria, fungi of the genus *Phytium*, eubacteria, and archaea. In the sediments near zones of naturally seeping oil, single colourless sulphur bacteria of the genus *Thioploca* were observed (Leifer et al., 2011).

The gas hydrates in Lake Baikal contain both methane and carbonate dioxide (Figs. 23 and 24) (see also De Batist et al., 2009, for more information about Lake Baikal hydrates and the associated geomorphology).

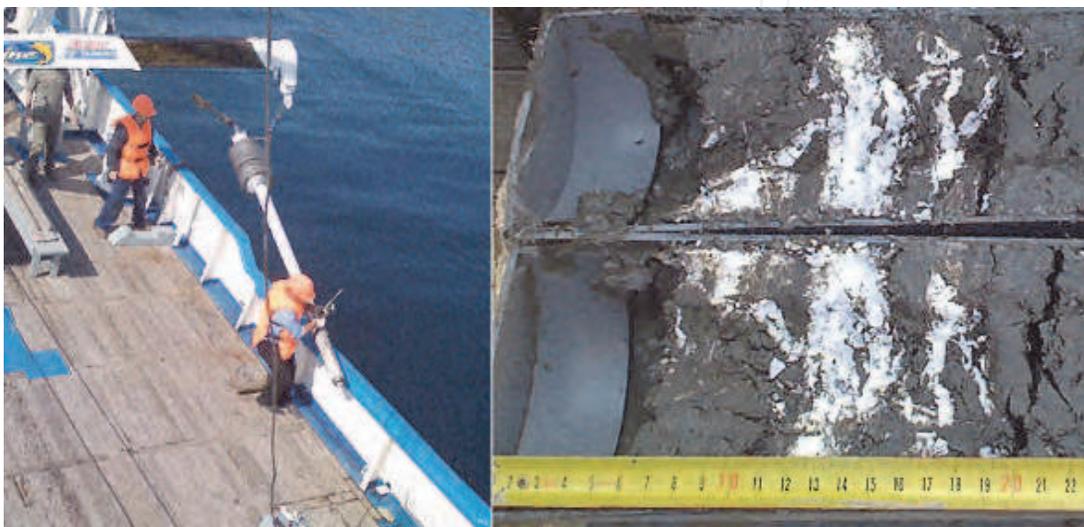


Fig. 24. The sampling of gas hydrates in Lake Baikal, 2010, was achieved by the use of a 800 kg heavy gravity corer, seen on the left being hoisted on board after having penetrated the seafloor, at 403 m water depth. After the clay-rich sediment core was split in two the result is seen on the right. There are veins and layers of pure gas hydrates inside the soft sediments.

Gas hydrates may dissociate (“melt”) rapidly, when disturbed by heating on the seafloor or depressurization by lifting. When sediment-hosted hydrates dissociate they return free gas and water to the environment, which may result in a total change of the physical sediment conditions and even of the seabed topography. Consequently, at water depths and sediment depths within the gas hydrate stability zone (GHSZ), any planned interaction with the seabed has to consider the possible existence and potential formation of gas hydrates (Hovland and Gudmestad, 2001).

If there are high-porosity sediments present, such as buried sands and gravels in regions with hydrocarbon flux, within the GHSZ, these sediment layers are likely to develop into massive gas hydrate reservoirs, as demonstrated by the Mallik gas hydrate research well in the MacKenzie Delta, Canada (see for example, Judd and Hovland, 2007 and also Clennell et al., 1999). Also, with increasing hydrocarbon flux and increasing tectonic activity, the amount of gas hydrates within the near-surface sediments increases. In addition, the seafloor topography is affected, and the presence of gas hydrates may even lead to large slope failures and seafloor collapse events.

On the continental slope off Mid-Norway, at Nyegga (the north-eastern boundary of the Storegga slide scarp), there are some large, complex pockmarks with carbonate ridges inside them, Fig. 25 (Hovland et al., 2006). The water depth ranges between 600 and 800 m and the upper sediments consist of soft, sandy and silty clay. The complex pockmarks and other fluid flow features are associated with a bottom simulating reflector (BSR), and several manifestations of gas migration at depth, including vertical conduits (pipes) seen on 2D- and 3D-reflection seismic records (Ivanov et al., 2007; Plaza-Faverola et al., 2010). There are also some distinct organic-rich sediment mounds, ‘hydrate pingoes’, up to 1 m high and 4 m wide (Hovland and Svensen, 2006; Hovland, 2008). Work by Ivanov et al. (2007), proved that the pockmarks contain nodules or layers of gas hydrate occurring 1 to 1.5 m below surface. This discovery has provided confirmation of their status as active methane seeps or vents (Fig. 25, right image). Unit-pockmarks were also found on the seafloor outside the complex pockmarks (Hovland et al., 2010).

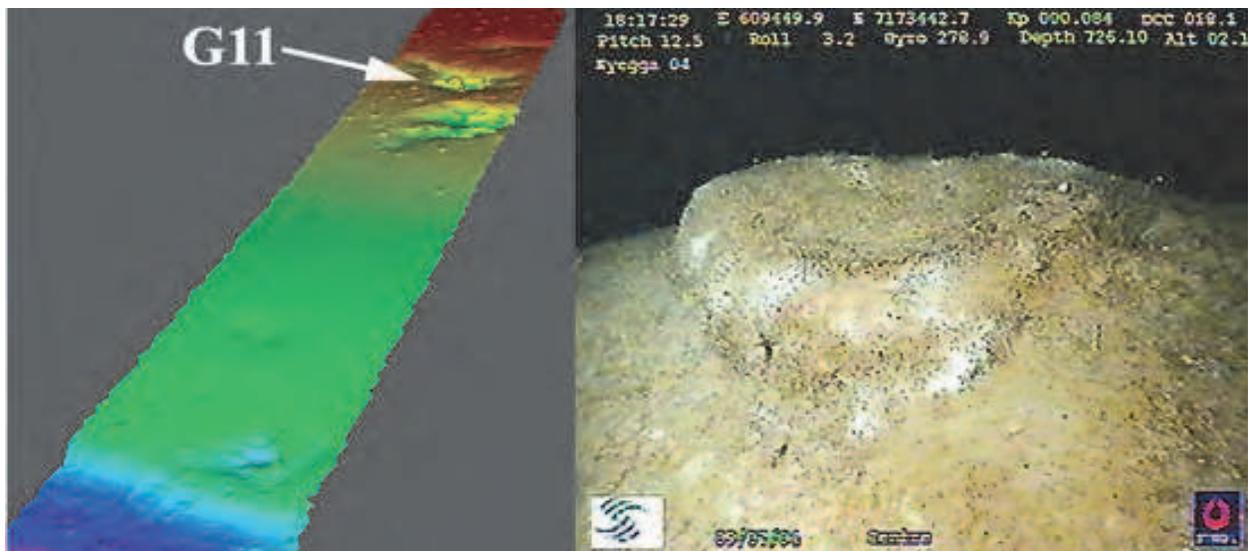


Fig. 25. At Nyegga, off Mid-Norway, there are numerous geomorphology features on the seafloor suggesting the presence of seeping gas and formation of gas hydrates under ground. In the left image, which covers a ca 6 km long and 2 km wide portion of the continental slope, there are at least three “complex pockmarks”, one of which is arrowed here as “G11”. Inside this pockmark there are several gas hydrate cored “pingoes”, one of which is seen in the right image, its size is about 1.2 m wide (From Hovland and Svensen, 2006).

6. Conclusions

Seepage and venting of fluids through the seafloor occurs at all depths in the ocean and the processes act on the Second Surface in various ways causing local alterations in topographical expression. The most common seepage induced features found on the seafloor, are pockmark craters, which have been documented in all of the seas and oceans of our planet and also in some of the lakes. Seepage of ‘exotic’ (allocthonous) fluids through the seafloor not only affects the seafloor geomorphology, but also the organic (primary) production within the seafloor surface and the above water column. Hydroacoustic flares testify that the fluids spread high into the water column, and probably also affects life in the

ocean to a much greater extent than previously suspected. The cross-disciplinary study of the effects of seepage and venting on the ocean and lake sediment surface and water columns can be regarded as a rapidly emerging new scientific theme.

7. References

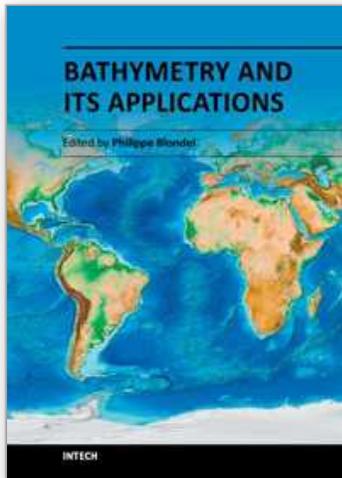
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Edited by Dr. Philippe Blondel

ISBN 978-953-307-959-2

Hard cover, 148 pages

Publisher InTech

Published online 25, January, 2012

Published in print edition January, 2012

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How to reference

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Martin Hovland (2012). The Geomorphology and Nature of Seabed Seepage Processes, Bathymetry and Its Applications, Dr. Philippe Blondel (Ed.), ISBN: 978-953-307-959-2, InTech, Available from: <http://www.intechopen.com/books/bathymetry-and-its-applications/the-geomorphology-and-nature-of-seabed-seepage-processes>

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