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ORIGINAL

Numerical simulation of upwelling currents in pockmarks, and data from the Inner Oslofjord, Norway

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Abstract The deflection of oceanic or tidal currents into pockmarks has been studied by both general three-dimensional computational fluid dynamics simulations and acoustic measurements in a number of pockmarks in the Inner Oslofjord, Norway. The modeling demonstrates upstream convergence of flow lines, followed by upwelling over the pockmark. This upwelling is an effect of deflected regional currents, not of expulsion of fluids or gas from the seafloor, and is sufficiently strong to prevent the settling of fine particles. The field measurements, although noisy at low vertical velocities, are consistent with the hypothesis of upwelling. The reduction in sedimentation rate inferred over the pockmarks (relative to that of the flat surrounding seabed) can explain the maintenance, or even deepening of pockmarks in the absence of fluid or gas seepage. The current pattern may also have consequences for the marine biology of pockmarks.

Introduction

Pockmarks are circular to elongated depressions in the seafloor, ubiquitous especially on the continental shelf throughout the world (Hovland and Judd 1988; Hovland et al. 2002). Ranging from less than 1 m to more than 1 km in diameter, these features are considered to form mainly as a result of sudden or gradual release of gas (usually methane; Scanlon and Knebel 1989), meteoric groundwater (Khandriche and Werner 1995), or overpressured pore water (Harrington 1985).

Deflection of oceanic currents in pockmarks is a critical issue for a number of reasons. A fundamental problem in pockmark research is age estimation, usually involving consideration of relative rates of sedimentation or erosion inside and outside the pockmark. Does the pockmark act as a sediment trap, or do currents keep the pockmark open long after fluid expulsion or seepage has ceased? Elongated pockmarks are often aligned along prevailing current directions, which may indicate that the pockmarks were initially circular, but have been deformed by sediment transport, deposition, and erosion (Josenhans et al. 1978; Hovland 1983; Bøe et al. 1998).

Coarse sediment is often found in the center of pockmarks (Manley et al. 2004; Webb et al. 2009). In some cases, this is due to authigenic carbonate in methane seep settings, or may be explained as a winnowed lag deposit caused by the expulsion or seepage of fluids. However, such lag deposits can also be due to currents, as well as to the accumulation of anthropogenic and other debris, as sometimes observed in pockmarks (e.g., Manley et al. 2004; Webb et al. 2009).

Currents are known to influence the distribution of benthic organisms, both by affecting larval settlement, and by controlling the transport of nutrients to suspension feeders such as corals, sea anemones, and crinoids. The distribution of benthic organisms around a pockmark may therefore reflect hydrodynamic patterns affected by the pockmark's geometry (Webb et al. unpublished data; Wildish et al. 2008). Furthermore, the frequently observed

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association between pockmarks and high densities of fish (Hovland and Judd 1988; Dando et al. 1991) may partly be connected with current patterns.

Although long-term measurements of physical parameters such as pressure and temperature in pockmarks are available (e.g., Marinaro et al. 2006), pockmark currents have been measured directly only rarely. In fact, to our knowledge there is only one published study on current measurements in pockmarks. Manley et al. (2004) carried out long-term ADCP measurements from a moored instrument in a pockmark in Lake Champlain, USA/Canada, and also provide an interesting discussion of possible effects of currents on pockmark sedimentation. They suggest that a cyclostropic rotational flow may be induced as the water column is stretched vertically when advected across the pockmark, and furthermore that an inward and downward flow may be set up around the perimeter. This could bring particles to the center of the pockmark, where the fines could get resuspended.

This paper presents numerical modeling of currents as deflected by a generic pockmark. We have also attempted to validate the modeling results using current measurements in pockmarks in the Inner Oslofjord, Norway. The morphology and sedimentology of these pockmarks have been described by Webb et al. (2009). No direct evidence of gas seepage from Oslofjord pockmarks has so far been detected, but there are weak indications of freshwater flux (Hammer and Webb, personal observation). The aim of this paper is not to address the formation or maintenance of the Inner Oslofjord pockmarks in particular, but rather to use these as convenient structures for validating the numerical modeling. Many of these pockmarks are near-perfectly circular, large, and in areas of relatively strong tidal current.

Materials and methods

Hydrodynamic conditions (the pressure and flow velocity fields) in a synthetic, generic pockmark geometry were simulated in three dimensions using the SAGE adaptive mesh Navier-Stokes solver (Science Applications International Corporation, San Diego, CA, 2005). The code was run using 32 processor nodes on an HP BL 460c cluster provided by the NOTUR network in Norway. Horizontal domain size was 100×100 m. Water depth outside the model pockmark was set at 60 m, typical of the Inner Oslofjord pockmarks (Webb et al. 2009). The mesh was automatically adapting down to a minimum cell size of 63×63×63 cm near the seafloor. The pockmark was modeled using a rotated cosine function, giving a diameter of 40 m and a maximum depth of 7 m. These dimensions are typical for pockmarks in general (Hovland and Judd 1988), and for the Inner Oslofjord pockmarks in particular (Webb et al. 2009). Inflow from the southern edge, and outflow from the northern edge of the model pockmark were based on a parabolic velocity profile approximating the steady-state flow inside the domain. The exact form of this profile was uncritical, because the model pockmark was placed at considerable distance (30 m) from the inflow and outflow boundaries. Surface current velocity was set at 20 cm/s, which is high but not uncommon for the tidal currents of the Inner Oslofjord (cf. during the measurements in multiple pockmarks mentioned below, we observed surface current speeds varying between ca. 10 cm/s and 30 cm/s). The program run was terminated at 30 s simulated time (roughly 10,000 CPU h), when the flow field had reached steady state.

The pockmarks investigated in this paper are shown in Fig. 1 and Table 1. In pockmark 186, current velocity profiles were measured using a Nortek Aquadopp acoustic Doppler current profiler (ADCP) with 1-MHz transducers. The instrument was mounted on an aluminum frame, raising the transducers 25 cm above the seafloor, and set up to collect data through a vertical column with 0.5-m cells starting at 45 cm above the seafloor. The range was 8 m, and each measurement was averaged over 8 min. The instrument was deployed at six sites within pockmark 186 (Fig. 2), at 56 m water depth north of Nesodden in the Inner Oslofjord (Webb et al. 2009). This pockmark was selected because of its regular circular shape, substantial depth (5.8 m) relative to its diameter (31 m), and flat surrounding seafloor. The complete operation took slightly less than 4 h (11:10 A.M. to 3:00 P.M. on 29 April 2008). In this time period, tidal current speed remained fairly constant (around 20 cm/s at the surface), but the current rotated from SSE to ESE.

For comparison of upwelling inside and outside of pockmarks, the vertical current component was measured in the center of nine other pockmarks in the Oslofjord, as well as at adjacent control sites situated on flat seafloor 100–150 m outside each pockmark (Table 1). The measurements were made from aboard the RV *Trygve Braarud*, by means of a ship-mounted Nortek Continental ADCP with 190-kHz transducers and 2-m cell size. We selected pockmarks in relatively shallow water (less than 50 m), in order to minimize the measurement area encompassed by the three divergent beams of the ADCP. Surface current velocities were less than 20 cm/s at all sites. Measurements from a cell ca. 4 m above the seafloor were averaged over 5 min. Vertical currents inside and outside of pockmarks were compared by means of a paired t test, using the software PAST (Hammer et al. 2001).

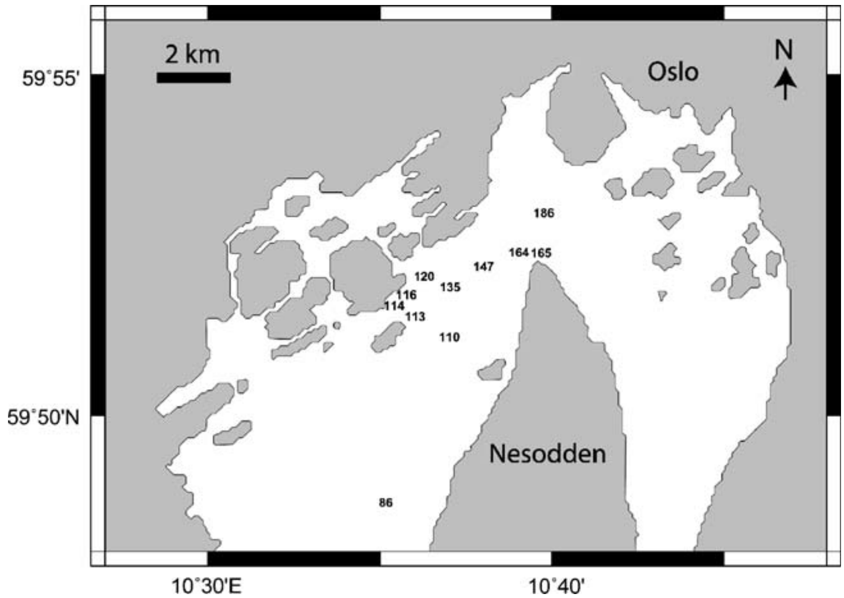


Fig. 1 Locations of the Inner Oslofjord pockmarks listed in Table 1

Results

The results of the hydrodynamic modeling are shown in Figs. 3, 4, 5, and 6, revealing several interesting phenomena. As expected, overall current velocities decrease substantially in the sheltered area inside the model pockmark. There is no clear flow separation or formation of an eddy—the dominant mode is laminar flow subparallel to the seafloor (Fig. 3), with water masses first flowing down into the pockmark, and then escaping up.

In a top view (Fig. 4), however, currents are clearly deflected in the horizontal plane above the model pockmark, showing marked convergence upstream and divergence downstream. The velocity field 1.5 m above seafloor (Fig. 5) shows the low velocity down in the pockmark, and high velocities around the rim. The converging water masses escape partly through an updraft, with its focus inside the pockmark, but displaced slightly downstream. The vertical component of current velocity, v_z, reaches 0.5 cm/s near the bottom of the model pockmark, but minor upwelling can be traced high into the water column, nearly to the surface (Fig. 6).

In pockmark 186, the horizontal components of measured current profiles generally align along the regional tidal current direction, which varied through the measurement period as the tide was turning (data not shown). The vertical component was positive at all six measurement sites, but varied depending on location within the pockmark. In positions to the left

Table 1 Pockmarks in the Inner Oslofjord, Norway, investigated in the present study

Pockmark	Lat. N	Long. E	Water depth (m)	Pockmark depth (m)	Observed vertical current (m/s)	
					Inside	Outside (control)
86	59°48.736′	10°35.212′	45.4	7.1	-	-
110	59°51.167′	10°37.079′	46.8	8.1	0.23	0.20
113	59°51.466′	10°36.081′	40.6	5.5	0.18	0.08
114	59°51.699′	10°35.472′	27.8	5.3	0.08	0.06
116	59°51.753′	10°35.751′	34.4	5.2	0.15	0.10
120	59°52.060′	10°36.341′	40.5	4.5	0.17	0.08
135	59°51.901′	10°37.092′	31.9	5.9	0.05	0.02
147	59°52.199′	10°38.082′	31.3	5.8	0.09	0.06
164	59°52.413′	10°39.312′	26.8	5.4	0.08	0.04
165	59°52.403′	10°39.521′	28.1	4.1	0.07	0.05
186	59°52.990′	10°39.830′	56.3	5.8	-	-

Pockmark 86 was used only for Fig. 8. Pockmark 186 was studied by multiple ADCP measurements inside the structure. The vertical currents in the remaining pockmarks were measured by ADCP inside and outside each pockmark

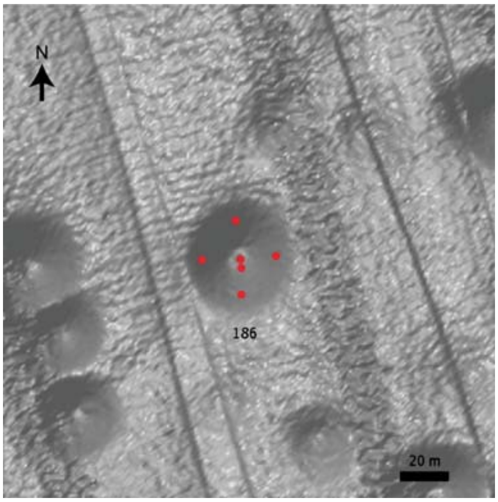


Fig. 2 Sonar bathymetry in the vicinity of pockmark 186 (data provided by the Norwegian Geological Survey). *Red dots* ADCP deployment sites. The surrounding pockmarks are not among those mentioned in this paper. *Smaller ripples* and *straight lines* are surveying artifacts. Depth of seafloor outside pockmarks ca. 56 m. Depth of pockmark 186 is 5.8 m

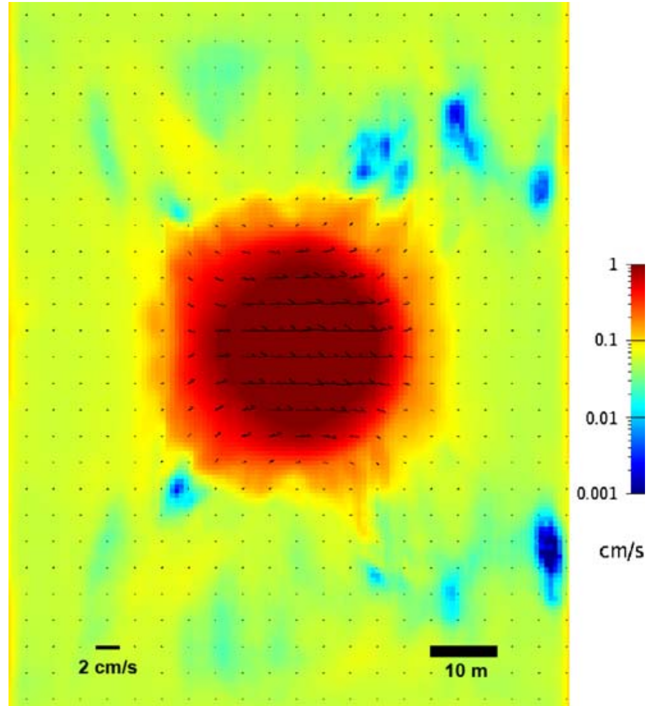


Fig. 4 Current speed and vectors from numerical simulation, in a horizontal plane (i.e., not parallel to the seafloor) immediately above and in the vicinity of the model pockmark. Scale bar at *lower left* refers to vector lengths. Note convergence of flow upstream (*left*), and divergence downstream (*right*) of the pockmark

(Fig. 7a), upstream (Fig. 7b), and upstream right (Fig. 7c) of the pockmark (relative to the current direction), upwelling was generally less than 2 cm/s, except very close to the seafloor. The smallest overall upwelling, less than 1 cm/s above 2 m from the seafloor, was observed in the upstream position (Fig. 7b). Maximum upwelling (>3 cm/s) was recorded at the center and downstream sites (Fig. 7d, e). The center downstream location (Fig. 7f) showed intermediate upwelling.

The results of ship-mounted ADCP measurements over other pockmarks and control sites (Table 1) reveal that the vertical component was positive in all cases, but significantly stronger inside the pockmarks (average 174%; paired t test $p<0.01$). Both sets of ADCP measurements were, however, noisy relative to the small vertical velocities. There was correlation between water depth and vertical velocities at control sites (Spearman's rank correlation $r_S=0.75$, $p=0.02$).

Discussion

The main result of this study is the considerable upwelling reconstructed over the model pockmark, potentially affecting sedimentation. The field measurements were noisy, and the deeper water at pockmark locations relative to outside may have contributed to

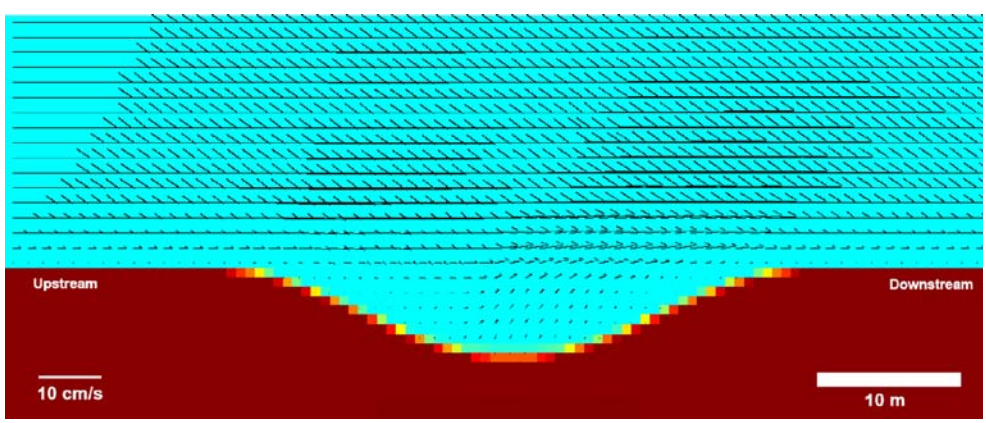


Fig. 3 Current vectors from numerical simulation of the model pockmark (lateral view). The overall current direction is from *left to right*. Scale bar at *lower left* refers to vector lengths

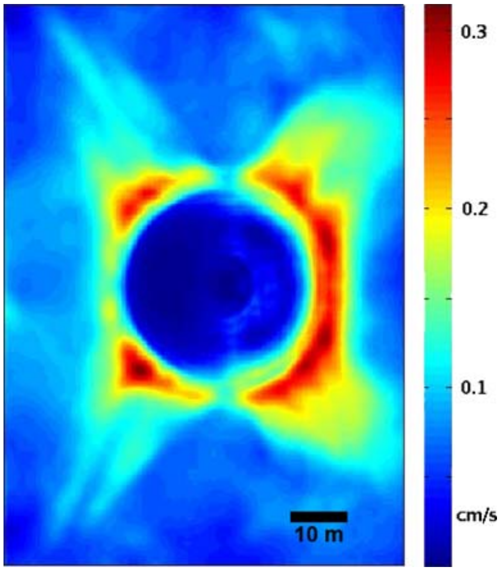


Fig. 5 Current speed from numerical simulation, 1.5 m above the seafloor in and around the model pockmark. Orientation as in Fig. 4. Note localized areas of strong current (*red*) around the rim

higher measured velocities inside pockmarks through the observed correlation between water depth and vertical velocity (the reason for this effect is unknown). The detailed measurements in pockmark 186 are in general accordance with the upwelling hypothesis, except that the upwelling in the center downstream position (Fig. 7f) is somewhat smaller than expected from the modeling results. We therefore consider the ADCP results to be consistent with, rather than confirming, the upwelling hypothesis.

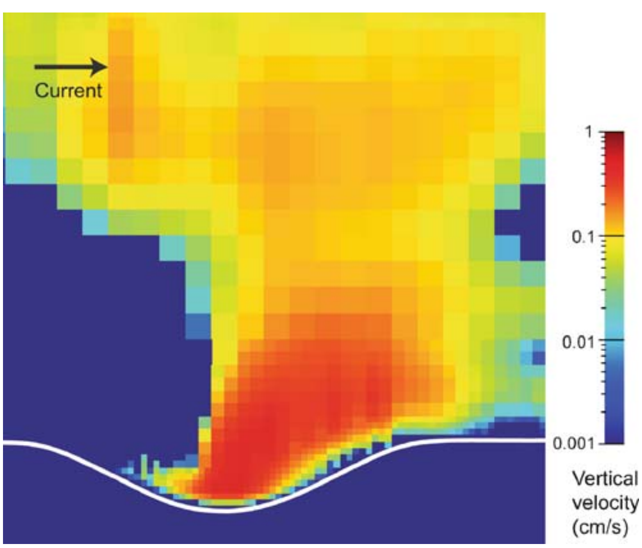


Fig. 6 Vertical component (v_z) of current velocity (cm/s) from numerical modeling, showing upwelling (lateral view). Seabed indicated by *white line*

Stokes' law (Lamb 1994) gives the terminal settling velocity V_s for a particle of diameter D:

$$V_s = \frac{\left(\rho_p - \rho_f\right) g D^2}{18\mu}$$

Using a particle density ρ_p=2.65 g/cm^3, fluid density ρ_f=1.03 g/cm^3, dynamic viscosity μ=0.01308 g/cm per second (in water at 10°C), and a vertical current velocity of 0.5 cm/s, as seen in the simulation, we find that spherical particles with a diameter less than about D=85 µm (that is, clay, silt, and even very fine sand) would be unable to settle through the water column near the center of the pockmark. This effect could produce a lag deposit consisting of coarser sediment, in accordance with observations by Manley et al. (2004) in Lake Champlain, and Webb et al. (2009) in the Inner Oslofjord. However, some proportion of fine particles could still settle by flocculation (e.g., Kranck 1975).

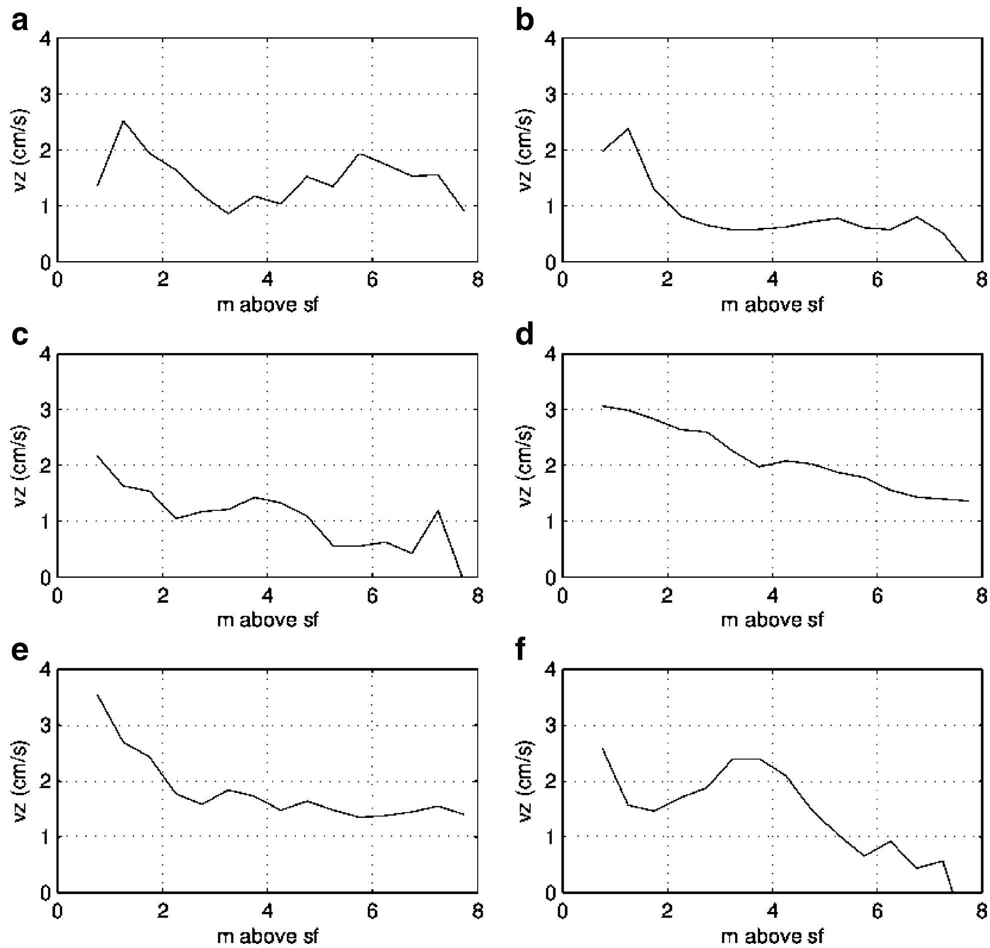
Clearly, the overall reduction in horizontal current velocity inside the pockmark will lead to higher sedimentation rates, especially from bed load. This will, however, be counteracted by the updraft in the center of the pockmark. The net sedimentation rate will be controlled by the balance of these two processes, and is therefore likely to vary depending on particular conditions controlled by, for example, pockmark shape, regional current velocity, grain size distribution of bed load and suspended sediments, and cohesiveness of the sediment.

The lack of flow separation (Fig. 3) may be ascribed to the very smoothly curving edge of the model pockmark.

The convergence of flow upstream of the pockmark (Fig. 4) is another interesting result from the simulation. This effect is due to the increase in depth, causing a vertical elongation of the water column resulting in a pressure drop. Any natural water current will have a small net angular momentum. As water masses converge upstream of the pockmark, it could be theorized that the preservation of angular momentum would dictate acceleration in the rotational flow, and the formation of a vortex (cf. Manley et al. 2004). Because no angular momentum was imposed, the phenomenon could not arise in the simulations shown here, but pockmark vortices in nature remains a possibility.

Current patterns are also of interest because they have profound effects on the distributions of many marine organisms, both direct and indirect—for example, by affecting larval settlement, and the supply of nutrients and oxygen (e.g., Rosenberg 1995). From the results presented above (cf. Fig. 5), we would predict higher densities of benthic suspension feeders (e.g., corals, sea anemones, and crinoids) in and around the high-velocity areas of a pockmark, i.e., on the rims and slopes, rather than in the center. However, the nature of the substrate is probably

Fig. 7 Vertical component (v_z) of ADCP measurements at various locations within pockmark 186 (cf. *red dots* in Fig. 2). The positions in the pockmark relative to the background current direction at the time of measurement are as follows: **a** left, **b** upstream, **c** upstream right, **d** downstream right, **e** center, **f** downstream center (*sf* seafloor)



another key factor determining the distribution of organisms within pockmarks (e.g., Gray 1974). In the center, carbonate rocks and anthropogenic debris often provide a hard surface for organisms to encrust or attach to. Such objects are also likely to increase the complexity of current flow patterns. If we exclude the centre, compared to the surrounding seabed we still see much higher abundances of fauna, especially suspension feeders, on the rims and slopes of pockmarks in the Troll Field, North Sea (Webb et al., unpublished data). As the substrate in these habitats is comparably soft sediments, these differences in faunal abundances are most likely to be a result of altered current flow patterns in pockmarks. The pockmarks studied in the Troll Field showed an increase in the abundance of fauna inside, including high abundances of suspension-feeding anemones on the slopes. One pockmark had large colonies of the tree-like soft coral *Paragorgia arborea* in its center, this being one of the key habitat-forming “bubblegum” corals worldwide. The presence of corals in the center of pockmarks could be due to the nature of the substrate, or possibly to the upwelling current. Hovland (2005) also reported that 33 pockmarks in the Kristin field off the coast of mid-Norway had coral reefs in their center or along their inside rim. These coral species are typically found at locations exposed to currents, implying that the pockmarks are associated with increased flow. Wildish et al. (2008) reported high densities of holothurians in some pockmarks

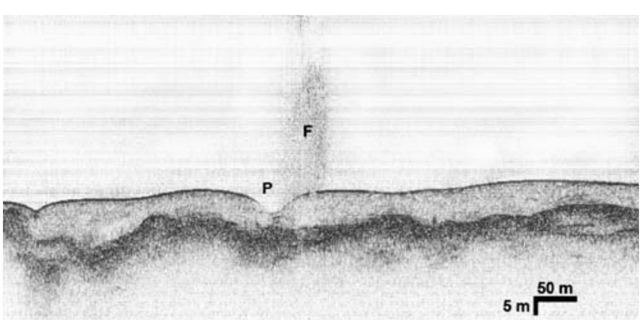


Fig. 8 Accumulation of fish above the downstream edge of pockmark 86, Inner Oslofjord, as revealed by subbottom profiling (6 kHz). *P* Pockmark, *F* fish

in the Bay of Fundy, Canada, and suggested a connection with special hydrodynamic conditions causing resuspension of sediment.

Fish are known to congregate in areas of upwelling (e.g., Genin 2004), and also near pockmarks (Hovland and Judd 1988; Dando et al. 1991). In the course of several years of fieldwork in the Oslofjord, we have frequently observed shoals of fish in the water column directly above and to the sides of pockmarks (Fig. 8), consistent with the presence of an updraft current.

Conclusions

From the modeling and field evidence, we here suggest that currents may be deflected by the pockmark in a way that produces a positive vertical current component from the pockmark, possibly but not necessarily associated with rotation. This upwelling phenomenon could lead to reduced sedimentation rate, and winnowing of the fine fraction inside the pockmark. To our knowledge, this scenario has not been proposed previously. It provides a model that could at least partly explain the lack of infill in pockmarks even where no active seepage is observed (e.g., Ussler et al. 2003). The lower relative sedimentation rate inside the pockmark could even make it deepen over time. We do not consider that this effect could initiate a pockmark, but it could explain the lack of infill in old, inactive pockmarks.

Future modeling work should include the simulation of flow patterns in pockmarks with other types of geometry, most notably elongate and trench pockmarks (Hovland 1983; Bøe et al. 1998; Webb et al. 2009). Also, a more complete model simulating current flow and sediment transport, deposition, and erosion in a changing geometry is necessary in order to understand the development of pockmarks over time, including elongation in the direction of current flow (Josenhans et al. 1978; Hovland 1983; Bøe et al. 1998). Such simulation is, however, extremely computer intensive. More accurate field measurement is also necessary. Hovland et al. (2002) made a plea for long-term monitoring of temperature, pressure, and fluid flow in pockmarks (cf. Marinaro et al. 2006). Such studies should ideally also include measuring of current patterns and sedimentation rates.

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References

Bøe R, Rise L, Ottesen D (1998) Elongate depressions on the southern slope of the Norwegian Trench (Skagerrak): morphology and evolution. Mar Geol 146:191–203

Dando PR, Austen MC, Burke RJ, Kendall MA, Kennicutt MC, Judd AG, Moore DC, O'Hara SCM, Schmaljohann R, Southward AJ (1991) Ecology of a North Sea pockmark with an active methane seep. Mar Ecol Prog Ser 70:49–63

Genin A (2004) Bio-physical coupling in the formation of zooplankton and fish aggregations over abrupt topographies. J Mar Syst 50:3–20

Gray JS (1974) Animal-sediment relationships. Oceanogr Mar Biol Annu Rev 12:223–261

Hammer Ø, Harper DAT, Ryan PD (2001) PAST: paleontological statistics software package for education and data analysis. Palaeontol Electronica 4(1)

Harrington PK (1985) Formation of pockmarks by pore-water escape. Geo-Mar Lett 5:193–197. doi:10.1007/BF02281638

Hovland M (1983) Elongate depressions associated with pockmarks in the western slope of the Norwegian Trench. Mar Geol 51:35–46

Hovland M (2005) Pockmark-associated coral reefs at the Kristin field off Mid-Norway. In: Freiwald A, Roberts JM (eds) Cold-water corals and ecosystems. Springer, Berlin Heidelberg New York, pp 623–632

Hovland M, Judd AG (1988) Seabed pockmarks and seepages. Graham & Trotman, London

Hovland M, Gardner JV, Judd AG (2002) The significance of pockmarks to understanding fluid flow processes and geohazards. Geofluids 2:127–136

Josenhans HW, King LH, Fader GB (1978) A side-scan sonar mosaic of pockmarks on the Scotian Shelf. Can J Earth Sci 15:831–840

Khandriche A, Werner F (1995) Freshwater induced pockmarks in Bay of Eckernfoerde, Western Baltic. In: Mojski JE (ed) Proc 3rd Marine Geological Conf The Baltic. Panstwowy Instytut Geologiczny, Warzawa, pp 155–164

Kranck K (1975) Sediment deposition from flocculated suspensions. Sedimentology 22:111–123

Lamb H (1994) Hydrodynamics, 6th edn. Cambridge University Press, Cambridge

Manley PL, Manley TO, Watzin MC, Gutierrez J (2004) Lakebed pockmarks in Burlington Bay, Lake Champlain: I. Hydrodynamics and implications of origin. In: Manley TO, Manley PL, Mihuc TB (eds) Lake Champlain: Partnerships and research in the new millennium. Springer, Berlin Heidelberg New York, pp 299–330

Marinaro G, Etiope G, Bue NL, Favali P, Papatheodorou G, Christodoulou D, Furlan F, Gasparoni F, Ferentinos G, Masson M, Rolin J-F (2006) Monitoring of a methane-seeping pockmark by cabled benthic observatory (Patras Gulf, Greece). Geo-Mar Lett 26:297–302. doi:10.1007/s00367-006-0040-4

Rosenberg R (1995) Benthic marine fauna structured by hydrodynamic processes and food availability. Neth J Sea Res 34:303–317

Scanlon KM, Knebel HJ (1989) Pockmarks in the floor of Penobscot Bay, Maine. Geo-Mar Lett 9:53–58. doi:10.1007/BF02262818

Ussler W, Paull CK, Boucher J, Friederich GE, Thomas DJ (2003) Submarine pockmarks: a case study from Belfast Bay, Maine. Mar Geol 202:175–192

Webb KE, Hammer Ø, Lepland A, Gray JS (2009) Pockmarks in the Inner Oslofjord, Norway. Geo-Mar Lett 29:111–124. doi:10.1007/s00367-008-0127-1

Wildish DJ, Akagi HM, McKeown DL, Pohle GW (2008) Pockmarks influence benthic communities in Passamaquoddy Bay, Bay of Fundy, Canada. Mar Ecol Prog Ser 357:51–66