Marine Geology 346 (2013) 262–273

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Sediment mapping and long-term monitoring of currents and sediment fluxes in pockmarks in the Oslofjord, Norway

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ARTICLE INFO

Article history:
Received 28 November 2012
Received in revised form 23 September 2013
Accepted 29 September 2013
Available online 11 October 2013

Communicated by J.T. Wells

Keywords:
pockmarks
ADCP
sediment traps
sediment cores
Oslofjord

ABSTRACT

Pockmarks in the Oslofjord, Norway, show no evidence of recent expulsion of gas or water, but have still experienced reduced sedimentation rates through the Holocene. They are therefore suitable model systems for studying the currents and sedimentation in pockmarks. Mapping of sediment in a single pockmark using a large number of precisely positioned cores shows thickening of an unconsolidated, almost flocculent layer inside the pockmark. X-ray fluorescence logging of anthropogenic metals indicates higher sedimentation rates and mass accumulation rates inside the pockmark with respect to the surrounding seafloor. Furthermore, the cores taken near the pockmark centre contained relatively coarser material than those from outside the depression. Sediment traps collected substantially more sediments inside than outside of the pockmark when positioned close to the seafloor. This agrees with resuspension of sediments from the seafloor being enhanced inside the pockmark. Moreover, the traps deployed in the pockmark intercepted relatively coarser sediments. Acoustic backscatter near the seabed varies in a diurnal cycle, not related to the tide. This is interpreted as a probable result of vertical migration of zooplankton or fish. Inside the pockmark there is also a diurnal cycle in current velocity with high values in the daytime, possibly because of swimming fish. The data indicate that pockmarks collect particles, which may be largely due to deposition of sediments transported as bedload. This process should be dominant for pockmarks found in proximity to fluvial coarse-grained sediment input. The suspended fine material, however, is kept in suspension by turbulence and possibly biological activity, and can be transported away before settling. Whether an inactive pockmark will behave as a sediment depocentre or will be maintained by the action of currents, is likely to depend on the relative importance of bedload versus suspended load transport.

1. Introduction

The pockmarks in the Inner Oslofjord, Norway, were described by Webb et al. (2009). They identified over 500 pockmarks, ranging from 20 to 50 m in diameter and 2–10 m in depth. The Inner Oslofjord is marine, but with reduced salinity in the surface waters and reduced oxygen levels in deeper basinal parts. The water circulation is estuarine with a halocline at about 20 m water depth (Gade, 1968). The restricted character of the water masses is partly caused by a sill at the entrance of the fjord (Gade, 1968). The tidal amplitude in the area is low, with a mean range of 52 to 80 cm, but the tide is still the main driver of currents.

Webb et al. (2009) found no signs of recent expulsion of methane or freshwater in the pockmarks, and there is no known source of methane in the relatively thin (<50 m) glacial and postglacial sediments or in the underlying Lower Paleozoic bedrock. In spite of the lack of evidence for active fluid expulsion, pockmarks were found to contain coarser sediment than the surrounding seabed, and also to have relatively low sedimentation rates. This was confirmed by analysis of long piston cores retrieved inside and outside a pockmark (Hammer and Webb, 2010).

It might be expected that in the absence of gas or water release, the bathymetric depression and low current velocity (Hammer et al., 2009) would make pockmarks act as sediment depocentres, with elevated sedimentation rates and accumulation of fine material. Over time, this would cause infilling and disappearance of inactive pockmarks. In the Oslofjord, where some pockmarks fill in slowly or not at all, and contain coarser material, the opposite seems to be the case. Similar results have been reported from other areas. In the Belfast Bay, Maine, pockmarks do not seem to fill in, although no active seepage was observed (Ussler et al., 2003). Brothers et al. (2011) discuss the Belfast Bay case in detail, and suggest that the pockmarks may be kept open by current activity. A similar suggestion was made by Manley et al. (2004) for the pockmarks in Lake Champlain, USA/Canada. Hammer et al. (2009) made preliminary, short-term current measurements in Oslofjord pockmarks, and carried out simple, 3D numerical fluid dynamics modelling of currents in a pockmark. The results were consistent with the hypothesis that deflection of currents

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http://dx.doi.org/10.1016/j.margeo.2013.09.012

by a pockmark could contribute to reduced sedimentation rates. This question is of great importance for assessing whether pockmarks are currently active, or if not, for dating their release of fluids.

In this paper, new data are presented on currents and sedimentation in Oslofjord pockmarks. The easy access to these pockmarks, extending into the harbour of Oslo and many of them found in relatively shallow water (30–70 m depth), together with their large number and varied morphology, make them convenient models for understanding pockmark processes and dynamics. It is the aim of this work to assess whether, and how, inactive pockmarks in shallow water may be maintained by the action of currents. To achieve this goal, hydrodynamic conditions are investigated in pockmarks relatively to the surrounding seabed, while differences in past and present sedimentation rate and grain size are estimated or measured.

2. Methodology

The bathymetric maps used here are based on multibeam data on a 1 m grid produced by the Norwegian Geological Survey. Two pockmarks (numbered 120 and 114 by Webb et al., 2009) were selected for this study based on their regular morphology, relatively large depth compared with diameter, and position away from the main shipping routes. Their positions and other data are given in Table 1 and Fig. 1. The fieldwork campaigns were conducted with the University of Oslo's RV *Trygve Braarud*.

2.1. Coring and core analysis, Pockmark 120

In Pockmark 120, 26 short gravity cores were taken, diameter 60 mm, core recovery varying from ca 50 to 70 cm. The exact locations of the cores (Fig. 2a) were determined using acoustic positioning of a transducer on the corer (Sonardyne Wideband Sub-Mini Ultra Short Base-Line system).

X-ray tomography was carried out shortly after sampling with a Siemens Somatom wholebody computerised tomography (CT) scanner at the Norwegian University of Life Sciences in Ås, Norway, at the resolution of 1 mm. X-ray density was measured along the core in order to give an undisturbed density log before opening it (Boespflug et al., 1995). Density is given in CT numbers, averaged over the 40 central pixels of the core and with a 3-point running average.

The cores were split and logged further at the Department of Earth Science, University of Bergen, Norway. Gamma density and magnetic susceptibility (MS) were measured with a multi-sensor core logger at the resolution of 5 mm. Magnetic susceptibility is reported following SI conventions. Element geochemistry was logged with the ITRAX X-ray fluorescence (XRF) core scanner (Croudace et al., 2006) using a Mo-anode X-ray tube at 30 kV voltage and 40 mA current. Spatial resolution was 1 mm and exposure time 10 s. Relative abundance is given in counts per second (cps). Noise in the resulting spectra was reduced by running a reference spectrum through a batch of 10 analyses at the time.

Pore water was collected at 20 and 40 cm core depth using Rhizon samplers (Rhizosphere Research Products, Netherlands), which are 5 cm porous polymer tubes fitted to spring-loaded syringes. The extracted pore water was analysed for anions and cations. Ion chromatography analysis was used for the anions Cl^- and SO_4^{2-}, while inductively coupled plasma mass spectroscopy for the cations Na^+, Mg^{2+}, Si^{4+}, K^+, Ca^{2+}, Sr^{2+} and Ba^{2+}.

Because of core disturbance after splitting, and variation in the thickness of the split core, the CT density is used rather than gamma density for estimating sediment density. Given that the mineralogy is relatively constant along and among the cores, a constant mean atomic number can be assumed (Boespflug et al., 1995). One sample from each core at 25–30 cm core depth, of known volume, was weighed before and after drying to obtain its true wet density and porosity. Together with the zero CT number of water, this was used to produce a linear calibration curve from CT number to wet density and porosity.

A sample extracted from the 20–25 cm core-depth interval of core PM120-13 (located near the pockmark centre, Fig. 2a) was wet-sieved at 63 μm, and the coarse fraction analysed for sediment composition.

Grain size analysis was carried out on the 25–30 cm core-depth samples with a Beckman Coulter LS 13 320 laser diffraction particle size analyser at the Department of Geosciences, University of Oslo, Norway. In addition, the total dry weight of the25–30 cm core-depth samples was measured after freeze-drying the samples. The samples were then wet-sieved at 63 μm, and the coarse fraction was dried in an oven at approximately 40 °C and weighed.

2.2. Acoustic current measurement and sediment traps, Pockmark 114

Time series of the current velocity were measured using a Nortek Continental acoustic Doppler current profiler (ADCP) with 190 kHz transducers, along with a Nortek Aquadopp acoustic Doppler current meter (ADCM) with 2 MHz transducers. The instruments were moored on the seabed, one inside Pockmark 114 and one at control site about 90 m away from the pockmark deepest point (Fig. 2b). Two deployments were carried out, from November 2009 to March 2010 (ADCM inside the depression and ADCP outside) and from December 2011 to March 2012 (ADCP inside and ADCM outside). The ADCP measurement cell size was set at its minimum value of 2 m (sensitivity to currents is highest in the middle of the cell). The elevation of the instruments above the seabed was about 1 m for the ADCP and around 0.4 m for the ADCM. Taking into account blanking distances of 2 and 0.35 m for ADCP and ADCM, respectively, the lowest cell of the ADCP allowed measurements at ca 4 m above seabed, whereas the ADCM at ca 0.75 m. The sampling rate was 6 min, and the data are presented here with a one hour time average to reduce noise.

Two tube sediment traps provided by the Norwegian Institute of Water Research, Oslo, Norway, were deployed inside and outside of Pockmark 114. Each trap consisted of two plastic cylinders, 55 cm long and 13 cm in diameter, collecting settling particulate matter into individual sample cups. Two deployments were carried out, from November 2009 to November 2010 (nearly 13 months) with the trap openings at ca 1 m above seafloor (ASF), and from April to November 2011 (about 7 months) with the trap openings at ca 2 m ASF. During the first deployment, the reference trap was positioned around 40 m NW of the deepest point of the pockmark in order to avoid flow disturbance at the location where the ADCP was moored (Fig. 2b). The second deployment was performed at the latter location, i.e. about 90 m SW of the pockmark deepest point. The recovered samples were analysed for grain size with a Beckman Coulter LS 13 320 laser diffraction particle size analyser at the Department of Geosciences, University of Oslo, Norway.

2.3. Data analysis

Gridding of sediment thickness and coarse fraction content was done using the v4 algorithm in Matlab. Spectral analysis of ADCM data

Table 1
Details of the two pockmarks studied. Pockmark numbers refer to the database of Webb et al. (2009), used also in Hammer et al. (2009) and Hammer and Webb (2010). Coordinates are WGS84. Pockmark diameter and depth are according to the automatic morphometric techniques of Webb et al. (2009), giving smaller diameters than visual impression.

Pockmark	Latitude	Longitude	Diameter [m]	Depth [m]	Water depth [m]	Data collected
120	59°52.058′N	10°36.341′E	24	4.5	45.1	Gravity cores
114	59°51.999′N	10°35.472′E	23	5.3	33.2	ADCP, ADCM, sediment traps