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HIGH-RESOLUTION 3D SEISMIC INVESTIGATIONS OF HYDRATE-BEARING FLUID-ESCAPE CHIMNEYS IN THE NYEGGA REGION OF THE VØRING PLATEAU, NORWAY

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ABSTRACT

Hundreds of pockmarks and mounds, which seismic reflection sections show to be underlain by chimney-like structures, exist in southeast part of the Vøring plateau, Norwegian continental margin. These chimneys may be representative of a class of feature of global importance for the escape of methane from beneath continental margins and for the provision of a habitat for the communities of chemosynthetic biota. Thinning of the time intervals between reflectors in the flanks of chimneys, observed on several high-resolution seismic sections, could be caused by the presence of higher velocity material such as hydrate or authigenic carbonate, which is abundant at the seabed in pockmarks in this area. Evidence for the presence of hydrate was obtained from cores at five locations visited by the Professor Logachev during TTR Cruise 16, Leg 3 in 2006. Two of these pockmarks, each about 300-m wide with active seeps within them, were the sites of high-resolution seismic experiments employing arrays of 4-component OBS (Ocean-Bottom Seismic recorders) with approximately 100-m separation to investigate the 3D variation in their structure and properties. Shot lines at 50-m spacing, run with mini-GI guns fired at 8-m intervals, provided dense seismic coverage of the sub-seabed structure. These were supplemented by MAK deep-tow 5-kHz profiles to provide very high-resolution detail of features within the top 1-40 m sub-seabed. Travel-time tomography has been used to detail the variation in Vp and Vs within and around the chimneys. Locally high-amplitude reflectors of negative polarity in the flanks of chimneys and scattering and attenuation within the interiors of the chimneys may be caused by the presence of free gas within the hydrate stability field. A large zone of free gas beneath the hydrate stability field, apparently feeding several pockmarks, is indicated by attenuation and velocity pull-down of reflectors.

Keywords: hydrate, chimney, high-resolution 3D seismic

INTRODUCTION

In the southeast part of the Vøring plateau, on the Norwegian continental margin (Figure 1), there are hundreds of pockmarks and mounds that seismic reflection data, where they exist, show to be the seabed terminations of chimney-like structures [1,2,3,4]. These chimneys were first interpreted as clay diapirs [5,2], from relatively poor resolution seismic reflection profiles, but more recent, higher resolution seismic data has shown that there is little evidence of large volumes of mobilised mud in these features [3,6,7,8]. These features do not exhibit the subsidence of near-surface strata beneath erupted mud that is characteristic of mud volcanoes, and in many cases the near-surface strata are bent upward in the flanks of the mounds in which many of the pockmarks occur. They are very similar in their seismic characteristics to

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chimneys in the accretionary complex off Vancouver Island, Canada [9,10,11]. The pockmarks are, at present and were in the past, the sites of methane seeps colonised by chemosynthetic biota, and within the pockmarks there is extensive development of authigenic carbonate, expressed variously as platforms, mounds and fields of blocky rubble [12,13,14,15,16,17]. Often the authigenic carbonate has cemented the fossil biota.

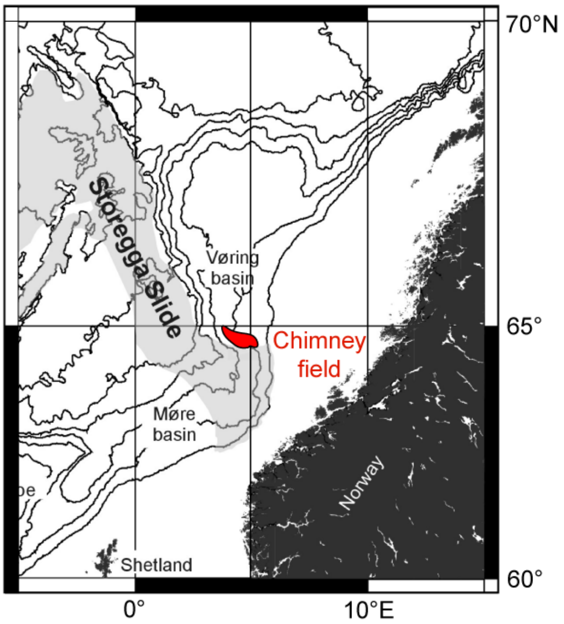

Figure 1. Location of the field of fluid-escape chimneys in the south east of the Vøring plateau.

A bottom-simulating seismic reflector (BSR) is widespread in the area [2,4,6,18,19,20,21,22,23]. There are numerous indicators of the presence of free gas beneath the base of the gas hydrate stability zone (GHSZ). The migration of the free gas to form BSRs is stratigraphically controlled, restricted to the more permeable lithological units. The chimneys have been identified as pathways for gas to migrate to the seabed [2,4,6,7,12], although, to the knowledge of the authors, no plumes of bubbles of free gas have been observed at any of the pockmarks in this area.

The chimneys exhibit a range structural styles and levels of emplacement. In seismic sections, they typically display a near-vertical zone of weak and/or incoherent reflections. The strata in the flanks of many of the chimneys bend upward. The cause of this bending is, in part, deformation associated with the formation of the chimney. The seabed itself is commonly pushed upward around the top of the chimney. A contributory cause of the upward bending, as seen on a seismic section, is velocity ‘pull-up’ produced by the presence of high-velocity material in the flanks of the chimneys. This produces the appearance of a differential bending effect, in which the degree of bending increases with depth. The travel time between reflectors decreases closer to the centre of the chimney. Other chimneys show no bending of strata, even though they lie beneath well-defined pockmarks. The width of the chimneys, including their flanks, is up to 500 m, but most are much narrower, and the width of the central zone of incoherence and attenuation is usually only between a half and two thirds of the total width of a chimney. Chimneys of only a few metres width are shown in the 5-kHz and 3.5-kHz profiler records. Although on vertically exaggerated seismic sections the chimneys appear to be narrow and near vertical, the width of 300-m–wide chimney is about equal to its height above the base of the GHSZ. The chimneys originate from beneath the base of the GHSZ, commonly at depths that are indeterminate from the seismic sections. The true depth extent of the chimneys can be difficult to establish, because strong attenuation in the upper part of the chimney produces an acoustic shadow zone beneath. Seismic surveys with large shot-receiver offset can image beneath shallow zones of attenuation. Some chimneys do not reach the seabed, and terminate at the tops of buried pull-up features. In some cases, it is clear that they are old features, as subsequent sediment layers fill the palaeo-topography, with local onlap against the former pockmark feature.

The purpose of the seismic experiments conducted in June 2006 from the RV Professor Logachev during Leg 3 of the TTR16 cruise was to determine the three-dimensional distribution of the seismically fast material, which could be hydrate or carbonate, and any free gas that may be present within two chimneys for which there was evidence of active or recent fluid flow. One of these chimneys, CNE03, showed bending of strata. The other, G11, did not [Figure 2]. Verification of seepage in the pockmarks above these chimneys, in addition to that provided previously by Hovland and others at G11 [5,15], was provided by an investigation of the seabed geology, seep activity, chemistry and biological communities, using the

ROV Victor deployed from the NO "Pourquoi pas?" in May-June 2006 [17].

The seismic experiments were supported by surveys with a deep-towed 100-kHz side-scan-sonar and 5-kHz sub-bottom-profiler and by sampling with a gravity corer and a TV-guided grab, from the CNE03 and G11 pockmarks and from the Tobic feature, which is a pockmark feature with extensive development of authigenic carbonate crust that was first investigated by TTR Cruise 8 in 1998 [13], and its near neighbours, Sharic and Bobic. Methane hydrate was discovered in five cores from these features. Immediately after bringing the gravity corer on board, very small crystals of gas hydrate less than a millimetre in width were observed in the sediment in the core catcher. These decomposed rapidly within several tens of seconds, producing a crackling noise and bubbling in sediment with the release of gas and water from the hydrate, leaving a "Gorgonzola cheese" texture that was also found in lowest sections of these cores. Large crystals of hydrate were discovered in two of the cores, in which hydrate also formed thin sheets extending across the core [24].

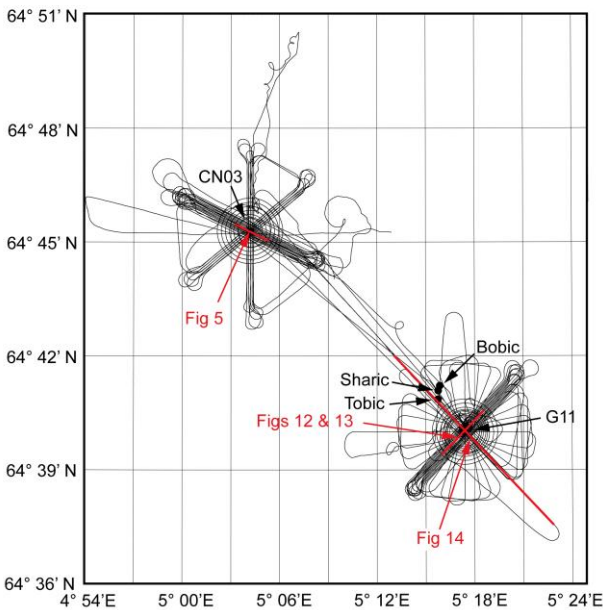

Figure 2. Seismic track across the CNE03 and G11 pockmarks.

SEISMIC EXPERIMENTS

The seismic experiments were anticipated to provide a much higher resolution 3D definition of seismic properties in the fluid-escape chimneys than previous work on such features. The basis of the experimental design was to place an array of 4-component OBS (ocean-bottom seismic recorder with a hydrophone and 3 orthogonal geophones) over the top of each of the two chimneys, CNE03 and G11, and to shoot to them from a grid of shot lines, along which seismic reflection profiles were simultaneously acquired with a towed streamer [Figure 2]. The spacing of the OBS, 16 at CNE03 and 14 at G11, was about 100 m [Figure 3]. The seismic sources were mini-GI guns, deployed as a single gun in true GI mode for maximum resolution and as two guns in harmonic mode to give better penetration. The shot spacing for the single-gun lines was ~8 m and that of the two-gun lines was ~12 m. The separation between single-gun lines was 50 m and for the two-gun lines it was 100 m.

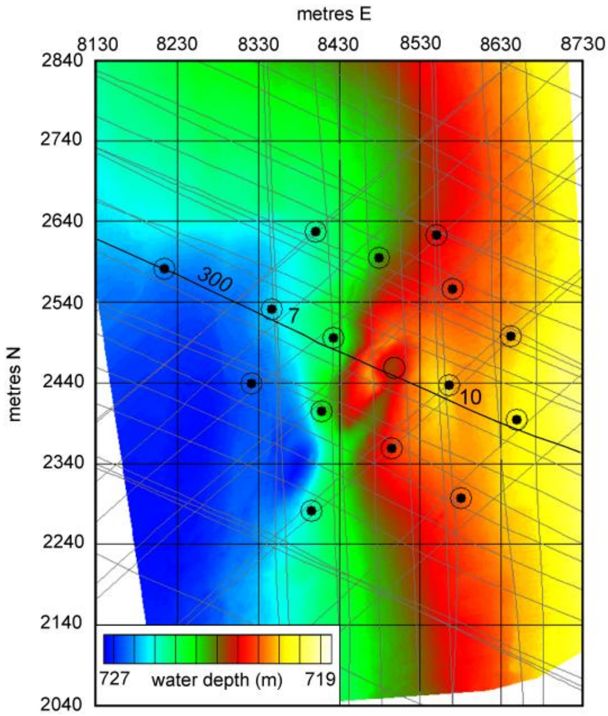

Figure 3. Bathymetry of the area of the CNE03 pockmark, with the acoustically relocated positions of OBS shown by black dots. OBS 7 and 10 are labelled. Shot lines are shown in grey. Shot line 300 is shown in black. Bathymetry was acquired with the ROV Victor during the Vicking cruise [17], © Ifremer.

To keep the OBS array correctly positioned and not distorted in shape, the placement of the OBS on the seabed needed to be precise in relation to the size of the features, 250 m wide, in a water depth of about 725 metres. This was achieved by lowering the OBS on a wire to within 50 metres of the seabed before they were released. The dynamic positioning of the Professor Logachev, combined with underwater acoustic location of an acoustic transponder clipped to the wire, ensured that the OBS was within 25 metres of its planned location, at the time of its release. Detailed bathymetry of the two target sites, with a precision of 0.5 m, came from microbathymetric data that were provided by Martin Hovland of Statoil for the G11 pockmark and were acquired with the ROV Victor for pockmark CNE03, during the Vicking cruise of the Pourquoi pas? [17].

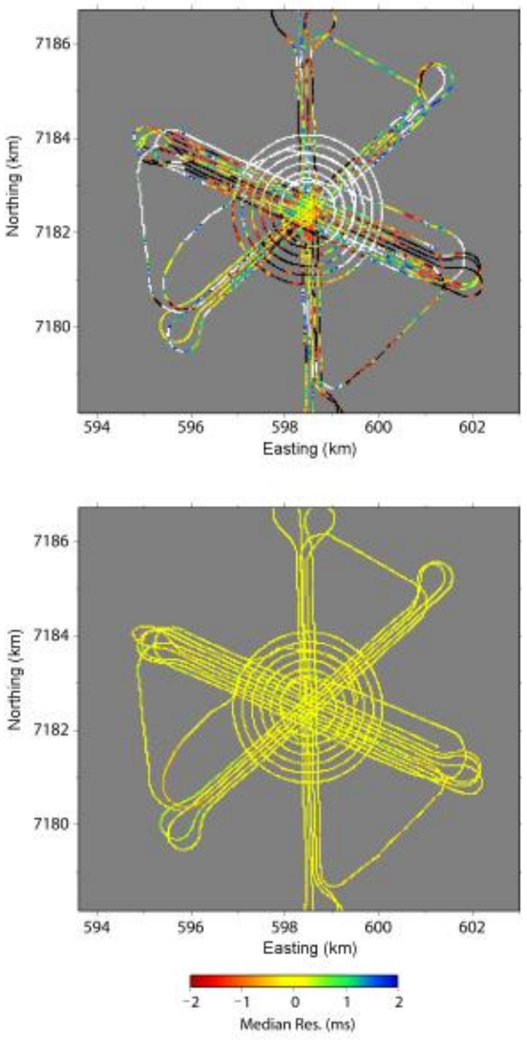

Figure 4. The effect of acoustic relocation of shots upon the median travel-time residuals of the direct wave for all OBS at pockmark CNE03. Top: residuals before shot relocation. Bottom: residuals after shot relocation.

Following acoustic relocation using the direct-wave travel times between the shots and the OBS, the nearly all the median residuals between measured and predicted travel times from each shot to all the OBS in each array were between –0.5 and +0.5 ms [Figure 4]. At a shot-OBS offset of 500 m, a change in the expected direct-wave travel time of 0.5 ms is produced by a change in range of 1.35 m.

CNE03 POCKMARK

The CNE03 pockmark is mounded feature with a central crater [Figures 3 & 5]. The strata in the flanks of the chimney beneath the pockmark bend upward towards its centre, in which there is a zone of attenuation and acoustic scattering. The bending is, in part, a structural effect related to the formation of the chimney. The seabed itself has been displaced upward, and the shallowest strata are offset by a fault that downthrows to the NW. The time intervals between some reflectors decrease progressively as they bend upward. If the cause of this is geological, it might imply that the chimney grew over a long period with progressive uplift, so that layers continually thinned on to a positive bathymetric feature. The absence of any onlap of strata on to the flanks of the chimney, or other changes in the character of the strata, and the degree of uplift the present seafloor, with different patterns of sedimentation in the top few metres of sediment either side of the pockmark, which is not shown by the deeper strata, indicate that the progressive growth model is unlikely to be an important for this pockmark and that the chimney is young in comparison with most the strata that it affects. It is more likely that the thinning is caused by the increase in content of a seismically fast material, such as hydrate or carbonate, towards the centre of the chimney.

An evaluation of the time-thinning of the upper sediment intervals shown in the 5-kHz section [Figure 6] indicates a progressive increase of average velocity from about 1530 m/s, at the outer flank, to about 1820 m/s, at the inner flank of the chimney in the interval between the orange reflector (25 ms) and the turquoise blue reflector (50 ms), an increase of 19%. If this increase is caused by the presence of hydrate, then a concentration of about 35% of pore space is predicted for model in which hydrate is both pore-filling and frame-forming, using the approach of Chand et al. [25].

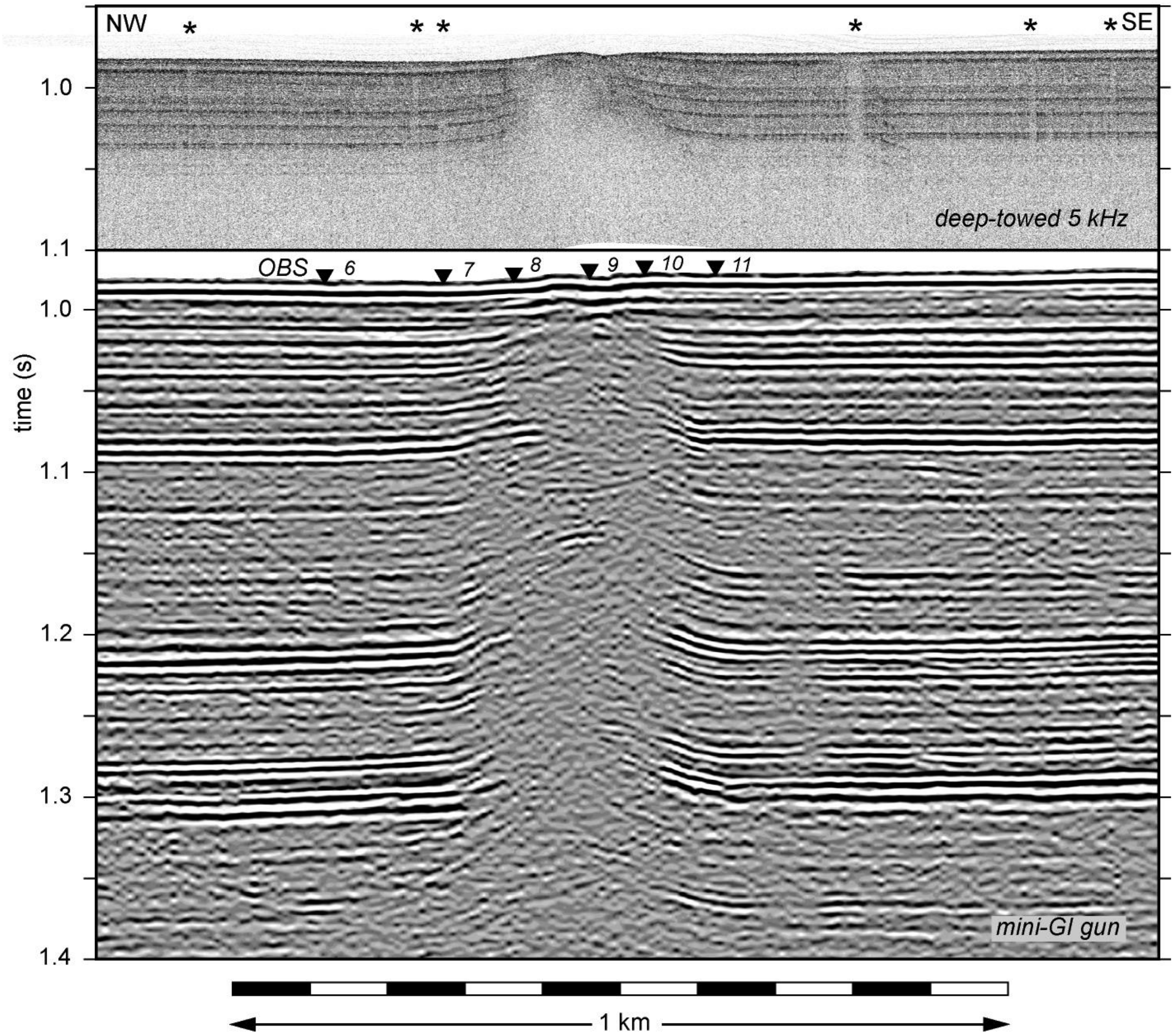

Figure 5. Seismic sections acquired with a 5-kHz deep-towed-profiler (upper) and a min-GI-gun (lower) along part of shot line 300 across the CNE03 pockmark, displayed at the same scale. The positions of OBS are shown by inverted triangles. The section from the mini-GI gun is migrated; that for the 5-kHz profiler is not. For the locations of the line and OBS, see Figures 2 and 4. The upward bending of strata in the chimney is evident on both sections. The 5-Khz section also shows several small-scale 'chimneys' (stars indicate the positions of some of the larger of these) and displacement of near-seabed strata across the pockmark that is caused by faulting. Shallow scattering between OBS 8 and 9 indicates the possibility of fast material close to the seabed.

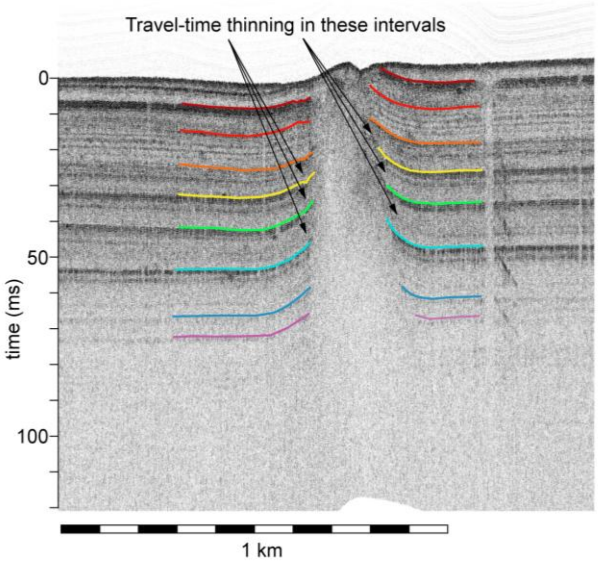

Figure 6. Thinning of the travel-time thickness of sedimentary intervals is shown by the upward bending strata in the flanks of the CNE03 chimney. This could be caused by a progressive increase in seismic velocity of 18% towards the centre of the chimney.

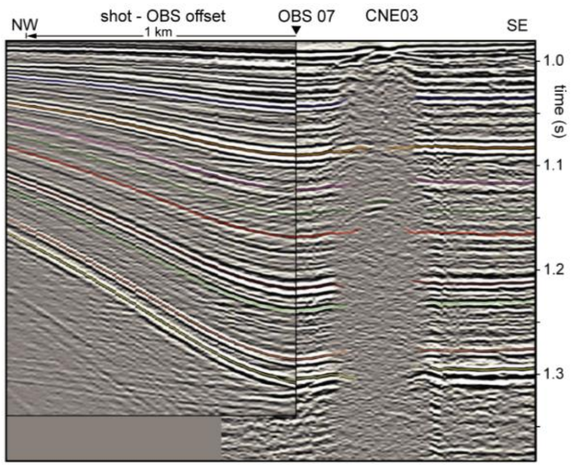

Figure 7. Part of the record section of upgoing waves (left), obtained by summing the scaled vertical geophone and hydrophone components of OBS C07 for shot line 324 at the CNE03 pockmark, matched at zero offset to the position of OBS C07 projected on to the seismic section from shot line 324 (right). The OBS data have been reduced to flatten the direct arrival. See Figure 3 for the location of OBS 07. Some of the reflectors are highlighted in colour to show the correlation between the two data types.

These travel-time anomalies are indicative of the presence of material of high seismic velocity in the chimney and the purpose of the seismic experiment was to derive the 3D distribution of seismic velocity from modelling and inversion of travel times from both the data recorded by the OBS and by the seismic streamer. This requires good correlation between the seismic records from both data types to ensure that the reflection times from the same horizons are chosen in the different data types. After applying PZ summation to the OBS data to separate the upgoing waves, a good match is obtained with the streamer data [Figure 7].

The record from the OBS clearly show the effect of velocity heterogeneity [Figure 8], and preliminary 2D modelling shows that the chimney has a higher seismic velocity at the same depth below the seabed in the top 80 m than sediments of the surrounding area. Further 2D and 3D modelling should elucidate the distribution of velocity variation in detail.

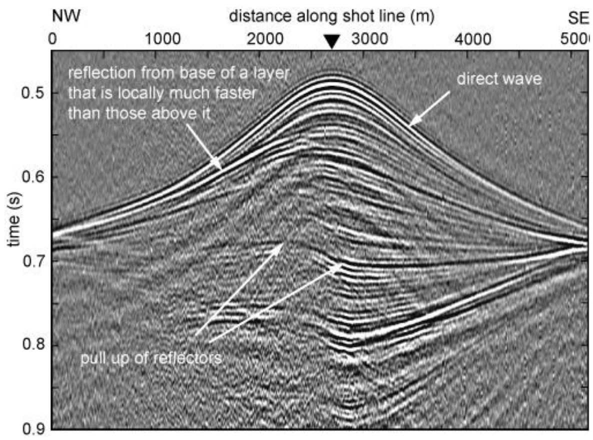

Figure 8. Record section of upgoing waves for OBS 10 at CNE03, from the summation of the hydrophone and vertical geophone records. The section is reduced to flatten a reflector with a travel time at zero offset of 0.7 s and an average seismic velocity of 1500 m/s. The black triangle marks the position of the OBS.

In addition to the *P* waves, the OBS recorded *S* waves created by conversion from *P* waves on reflection at interfaces. These *PS* or converted waves can provide much additional information on the properties of sediment. In weakly compacted sediment they are much more sensitive to the state of compaction than *P* waves, because they are independent of bulk modulus, which in high porosity sediment is dominated by that of water. The cementation of grains has a pronounced effect on *S*-wave velocity. *S* waves, through the phenomenon of *S*-wave splitting, are very sensitive to seismic anisotropy. Azimuthal anisotropy can be created by aligned vertical, or near-vertical cracks. This can be detected by a number of techniques, one of which is to measure the azimuthal variation in the amplitude and travel time of the radial and transverse horizontal components [26]. The OBS at CNE03 show much larger than normal variations in travel time, and only have one minimum and one maximum, whereas anisotropy produces two maxima and minima. This pattern of travel-time variation [Figure 9] is caused by lateral heterogeneity of seismic velocity.

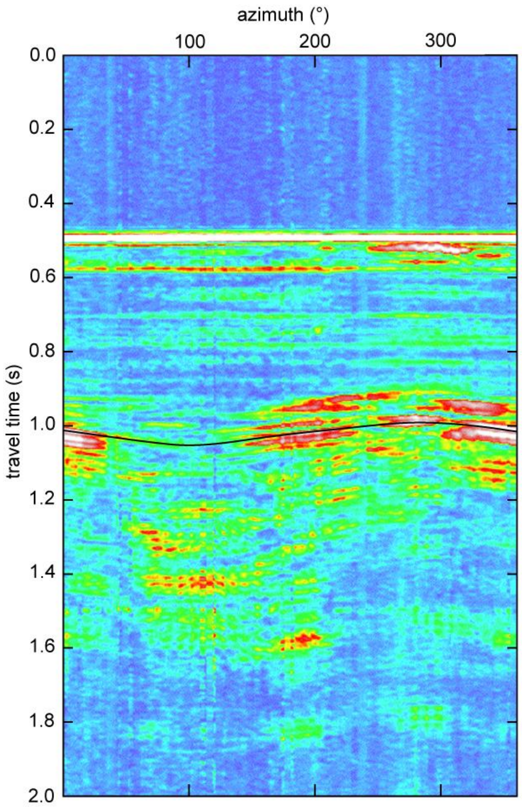

Figure 9. Azimuthal variation in the absolute (envelope) amplitude of the radial horizontal component of OBS C10 at pockmark CNE03 from shots at an offset of about 700 m. The direct arrival through the water is at 0.5 s. At times greater than 0.9 s, there is an azimuthal variation in travel time, the minimum occurring at 280°. The variation is illustrated by the black line at about 1.0 s. The difference between maximum and minimum travel times is about 70 ms.

By plotting the directions from which the arrivals for the same reflector have their minimum travel, one can gain a qualitative indication of the position of the fast material. For CNE03, these fast-direction arrows point towards the central region of the chimney [Figure 10]. Much of the variation in travel time will have been acquired in the downgoing *P*-wave paths, which are more oblique and cross more of the chimney than the steep upgoing *S*-wave paths. The much slower *S*-wave velocity, however, means that even moderate azimuthal heterogeneity in the vicinity of the OBS has a strong effect on travel time.

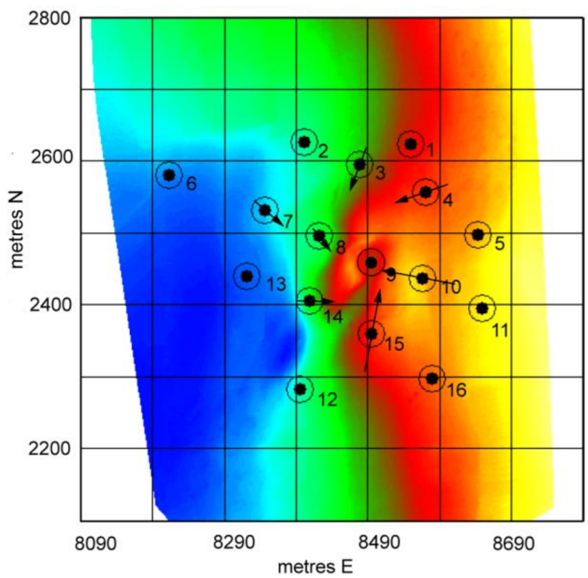

Figure 10. Plot of the directions from which the earliest S-wave arrivals from the same reflector come into each OBS at the CNE03 pockmark. The arrows point in the direction of the minimum travel time, and the length of the arrows are proportional to the difference between the minimum and maximum travel times. The largest is about 80 ms. It is clear from the directions of the arrows that the central region of the pockmark contains faster material at the same depth than in the surrounding area.

G11 POCKMARK

The G11 pockmark, which lies in a group of nearby pockmarks, is expressed bathymetrically as a depression without any peripheral uplift [Figure 11] [12,15]. The seismic sections show that there is no upward bending of reflectors [Figures 12,13,14]. The shallowest sediments show

evidence of collapse of the margins of the pockmark. [Figure 12] Within the pockmark, there is extensive development of authigenic carbonate, which forms ridges, and local colonisation of seeps by bacteria and chemosynthetic fauna [12,15,17].
At G11, the chimney is expressed seismically by strong attenuation of reflectors and some scattering. The base of the chimney lies within or below a zone containing free gas that is beneath a layer with a chaotic internal structure, which is likely to have its origin as a glacigenic debris flow, although deformation of its top surface indicates that it was, at least, partially remobilised during the subsequent deposition of sediment over it. The bright reflections from the layers containing free gas become attenuated laterally beneath the slope of the headwall of the Storegga slide, where they cross the base of the GHSZ, producing a 'truncation' BSR that is typical of this area [2,4,6,18,19,20,21,22,23]. The base of the GHSZ lies within the chaotic unit across much of the section [Figure 12], but does not display a BSR. The bright reflectors, and presumably most of any free gas that is present, lie beneath base of the chaotic unit, which, if it is typical of the other glacigenic diamictons of this region of the Norwegian margin, will have very low permeability [4].

The G11 chimney does not show the strong velocity increase exhibited by the CNE03 chimney. Preliminary results of modelling show that seismic velocity increases from 1500 m/s at the seabed to 1770 m/s at the base of the chaotic unit, beneath which there is a decrease of velocity in the gas charged zone. Evidence for the presence of gas is also shown in the seismic sections [Figures 12 & 14]. At the top of the gas zone, the reflections from the gas charged layers are bright, but, with increasing depth, the attenuation produced by the gas causes the reflectors to become weaker, to have a lower dominant frequency and to become separated further in time. (The degree of separation indicates a reduction in velocity of 35%.) The area underlain by the thick gas zone is not completely defined by the seismic sections from the cruise. It extends southwest beneath the headwall of the Storegga slide. In the area of the survey of G11, it is nearly 5 km across, and does not extend north of 64° 40.5'N or south of 64° 38.0'N. It centre is about 2 km south of G11.

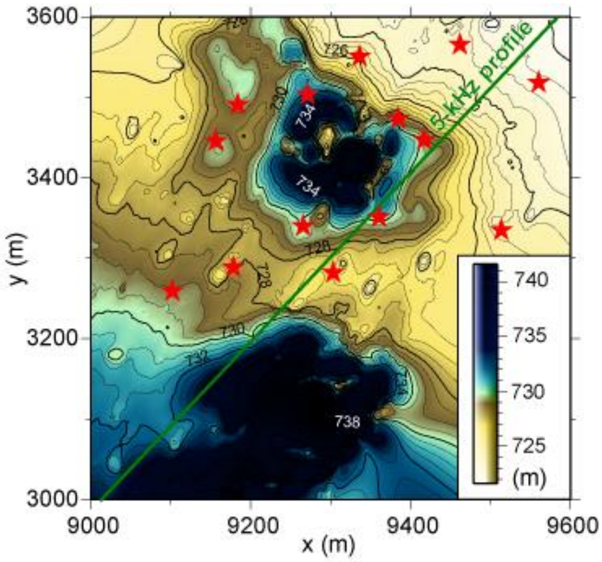

Figure 11. Bathymetry of the area of the G11 pockmark (data - courtesy of M. Hovland, Statoil). Contours at 0.5 m intervals. The acoustically relocated positions of OBS shown by red stars. The line of the 5-kHz profile of Figure 12 is shown in green.

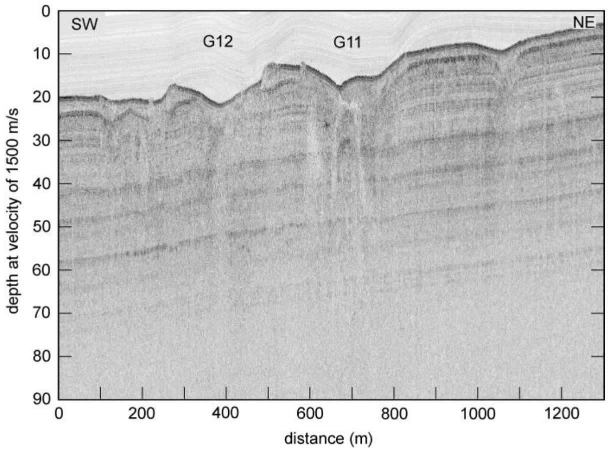

Figure 12. Section from deep-towed 5-kHz profiler across the G11 and G12 pockmarks. (See Figure 13 for close, parallel seismic section with mini GI gun.) The section, which does not cross the central carbonate platforms of either pockmark, shows collapse of the flanks of the pockmark and infilling by the most recent sediment layer. Notably, the strata are not bent upward around the pockmarks, like those of CNE03 or of the Tobic group of pockmarks, 2 km to the NW of G11. (See Figure 14.)

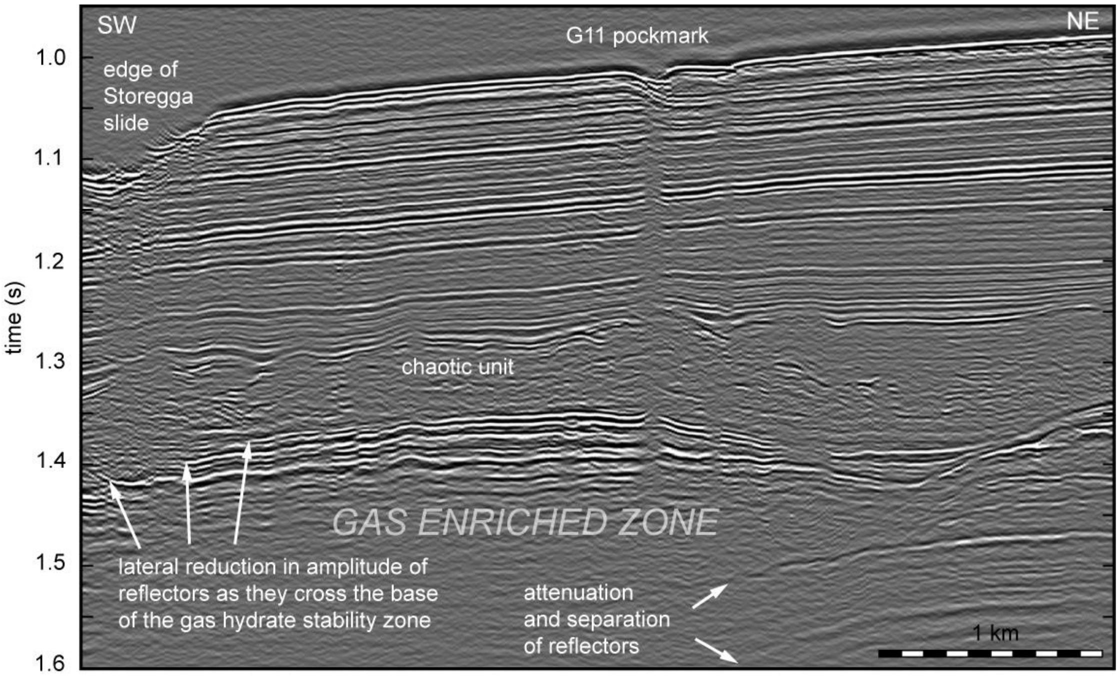

Figure 13. Migrated seismic section through the G11 pockmark and its underlying chimney, which extends downward at least as far as a zone of gas-charged layers beneath a unit with chaotic internal structure. At the left of the section, bright reflections from layers containing free gas become attenuated laterally where they cross the base of the GHSZ, beneath the slope of the headwall of the Storegga slide.

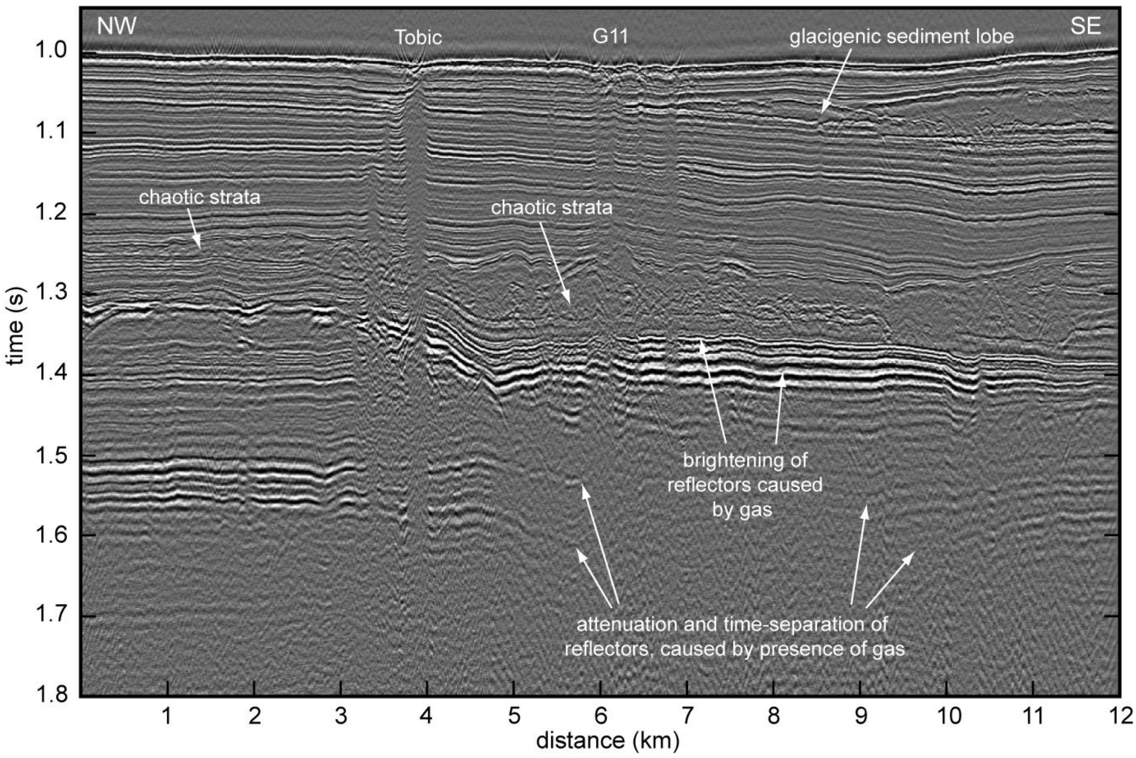

Figure 14. Seismic section through G11 and edge of Tobic pockmarks, showing their geological context in relation to units of chaotic strata (glacigenic debris flows) and zones of free gas beneath the GHSZ. The section has been migrated at 1475 m/s. Note that while the strata in the flanks of the chimney at the Tobic pockmark are bent upward, those around the G11 pockmark and its near neighbours are not.

DISCUSSION

While the fluid-escape chimneys of the Nyegga region exhibit a wide range of form and size, the property that they have in common that enables their identification in seismic sections is the downward-extending zone of attenuation. The cause of this attenuation is probably not the presence of free gas, at least not in the uppermost 300 m, which lie within the GHSZ. Although free gas occurs in the GHSZ in highly dynamic systems such as those of Hydrate Ridge [e.g. 27], where free gas enters the water at the seabed, it is difficult to conceive of how the free gas would not be converted to hydrate in more slowly advecting systems, such as those of the Nyegga area appear to be. Small-scale scattering could be the primary cause of the seismic attenuation. Disruption of strata at a small scale or many localised, small bodies of hydrate that are probably fracture filling could produce the scattering. Such bodies of hydrate could be formed and sustained by methane taken out of solution, as the solubility of methane decreases towards the seabed in the GHSZ. The abundant evidence for the presence of free gas beneath the GSHZ implies that methane would be at saturation concentration in water when it entered the base of the GHSZ on its upward path through a chimney.

While it appears likely that, at present, advection of gas in solution by water flowing through the chimneys is the principal mechanism by which methane and other gases are brought to the seabed, this, as remarked by Hovland et al. for the G11 pockmark [12], cannot provide the mechanism for the formation of the chimneys, especially those, such as CNE03, which have upward displacement of strata in their flanks. A more forceful process, almost certainly involving strongly overpressured free gas, seems to have been necessary to create the pathways, through which methane-rich pore water has subsequently been channelled.

ACKNOWLEDGEMENTS

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SOME PRELIMINARY CONCLUSIONS

Although the analysis of the data through modelling and inversion is not complete, it is already evident that within the CNE03 chimney there is material that gives it a higher seismic velocity then the surrounding sediments. This could be carbonate or hydrate. Coring of hydrate from this feature [24] favours the presence of hydrate, and if this is so then the increase in seismic velocity in the flanks of the chimney could be explained by hydrate occupying up to 35% of pore space, on average. The bending of strata in the flanks is partly deformational in origin, and this suggests that the chimney was created by some forceful process, even if it has subsequently acted as a pathway for fluid outflow.

At the G11 pockmark, there is no upward bending of the strata in its flanks. The pockmark and neighbouring pockmarks are underlain a zone of locally higher content of free gas, about 5 km across, into which the chimneys beneath the pockmarks penetrate. The origin of the chimneys was different in some respects to that of chimneys like CNE03, but they also act as pathways for the outflow of methane-rich fluid. In addition to the large chimneys, which are commonly topped by pockmarks or mounds, the high-resolution seismic sections show that there are many other smaller chimney-like structures, which should not be overlooked in assessing the budget of fluid outflow and methane transport in this area.

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