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A GEOPHYSICAL STUDY OF A POCKMARK IN THE NYEGGA REGION, NORWEGIAN SEA

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ABSTRACT

Over the last decade pockmarks have proven to be important seabed features that provide information about fluid flow on continental margins. Their formation and dynamics are still poorly constrained due to the lack of proper three dimensional imaging of their internal structure. Numerous fluid escape features provide evidence for an active fluid-flow system on the Norwegian margin, specifically in the Nyegga region. In June-July 2006 a high-resolution seismic experiment using Ocean Bottom Seismometers (OBS) was carried out to investigate the detailed 3D structure of a pockmark named G11 in the region. An array of 14 OBS was deployed across the pockmark with 1 m location accuracy. Shots fired from surface towed mini GI guns were also recorded on a near surface hydrophone streamer. Several reflectors of high amplitude and reverse polarity are observed on the profiles indicating the presence of gas. Gas hydrates were recovered with gravity cores from less than a meter below the seafloor during the cruise. Indications of gas at shallow depths in the hydrate stability field show that methane is able to escape through the water-saturated sediments in the chimney without being entirely converted into gas hydrate. An initial 2D raytraced forward model of some of the P wave data along a line running NE-SW across the G11 pockmark shows, a gradual increase in velocity between the seafloor and a gas charged zone lying at ~300 m depth below the seabed. The traveltime fit is improved if the pockmark is underlain by velocities higher than in the surrounding layer corresponding to a pipe which ascends from the gas zone, to where it terminates in the pockmark as seen in the reflection profiles. This could be due to the presence of hydrates or carbonates within the sediments.

Keywords: gas hydrates, chimney, high-resolution 3D seismic

INTRODUCTION

Fluid escape features such as seismic wipe-outs, seeps, and pockmarks are often associated with gas hydrate bearing sediments in continental margin settings worldwide [1,2]. Pockmarks are seabed culminations of fluid/gas escape chimneys which appear as cone-shaped circular or elliptical depressions [3,4,5] . They were first discovered off Nova Scotia, Canada and classified as seabed gas and porewater escape features by King and MacLean [5]. They vary in size ranging from a few metres to 300 m or more in diameter and from 1 m to 80 m in depth. Pockmarks generally concentrate in fields extending over several square kilometres where they often appear as isolated patches.

Pockmarks are often underlain by wipe-outs or pipes, which are narrow (150-500 m) vertical zones of low reflectivity, and occur because of

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vertical fluid or gas expulsion [6,7]. In the deeper part of seismic sections, these pipes are sometimes characterised by upward bending marginal reflectors (pull up), possibly suggesting vertical sediment movement [4,8] or perhaps the presence of high velocity material near the walls of the chimney. Over the last decade pockmarks have proven to be important seabed features that provide information about fluid flow on continental margins. However their formation and dynamics are still poorly constrained due to the lack of proper three dimensional imaging of their internal structure.

As part of the HERMES (Hotspot Ecosystem Research on the Margins of the European Seas) integrated project to study gas-fluid seeps and the benthic communities that are associated with them, a high resolution seismic experiment was conducted to investigate the 3D structure of two such features in the Norwegian Margin and hence to determine the distribution of free gas and gas hydrate in and around the gas/fluid escape chimney. These chimneys may be of global significance for the escape of gas, especially methane from the sediments to the water column at continental margins and also as habitats for chemosynthetic communities. This paper deals with the initial 2D modelling results for the G11 pockmark [3].

GEOLOGICAL SETTING

The Nyegga Region [Figure 1] lies at the border between the More and the Voring Basin in the southeast part of the Voring plateau, on the Norwegian continental margin [9,10]. This region developed as a result of several repeated rifting episodes until the Late Palaeocene/Early Eocene continental break up and subsequent thermal subsidence [9,11]. Episodes of moderate compression between the late Eocene and Mid Miocene times led to the development of N-S oriented dome structures, which are known to be potential hydrocarbon reservoirs, e.g. Ormen Lange gas reservoir, Helland-Hansen Arch [12,13].

The stratigraphy consists of: Holocene sediments overlying interbedded Pleistocene glacial diamictons and hemi-pelagic silty/clayey sediments of the Naust formation, covering the Miocene/early Pliocene hemipelagic oozes of the Kai formation and early Eocene/Miocene Brygge formation [14,15,16]. Polygonal fault systems are abundant within the Kai formation [4].

A prominent bottom-simulating reflector (BSR) occurs in the region [3,8,10,17] and there are numerous indicators of the presence of free gas beneath the base of the gas hydrate stability zone (GHSZ). The presence of gas hydrates in this area had never been verified by sampling until the recent TTR16 cruise [18].

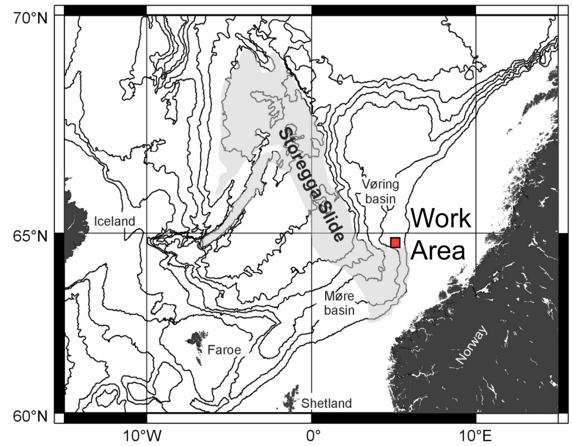

Figure 1. Location of the Nyegga area, at the southern end of the Vöring plateau, just north of the Storegga slide (From [25]).

A belt of fluid escape features is associated with gas hydrates in the Nyegga region as given evidence by 2D, 3D seismic reflection surveys. Gay et al., [19] observed a large number of pockmarks with an average density of 0.14 pockmarks per km² to the north of the Storegga slide between the More and Voring basin. Most of these pockmarks occur immediately above vertical pipes or chimneys which extend down to and in some cases, beyond the BSR [3,9,17]. The source region of the pipes are suggested to be both near the BSR and the polygonal faults in the Kai formation through which hydrocarbons are thought to seep from the deep reservoir domes in the region [4,10,20]. Some of these pockmarks are associated with micro-seepage of light hydrocarbon gases (C1-C5) and a distinct fauna with local bacterial mats and tubeworms [3]. Petrography and geochemistry of carbonate blocks from them suggest precipitation of methane derived aragonite within the sediments [21].

SEISMIC SURVEY, DATA AND METHODS

During the months of June-July 2006 a high-resolution seismic experiment using Ocean Bottom Seismometers (OBS) was carried out on RV Professor Logachev TTR Cruise16-leg 3 to investigate the detailed 3D structure of the G11 pockmark in the Nyegga region. The G11 pockmark is about 250 m wide and situated at water depths of ~ 725 m. It has a rugged topography with irregular ridges divided by a central sediment basin and carbonate piles. The carbonate blocks and the surrounding are partly colonised by various fauna, including small tubeworms and bacterial mats.

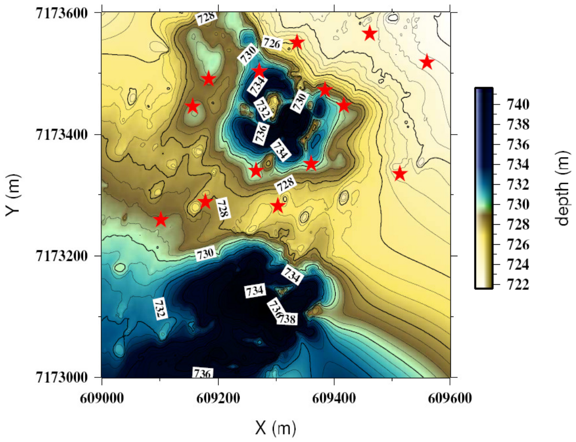

Figure 2. Bathymetry of the area of the G11 pockmark (data - courtesy of M. Hovland, Statoil), contours at 0.5 m intervals, with the acoustically relocated positions of OBS shown by red stars.

An array of eight 4-component and six 2-component OBS were placed on the top and within the immediate vicinity of the pockmark with a spacing of ~100 m [Figure 2]. A new technique of deployment using acoustic navigation enabled a more precise positioning of the OBS on the sea bed. The OBS were lowered with a wire to within 50 metres of the seabed before they were released. This was achieved through the dynamic positioning of the Professor Logachev, coupled with underwater acoustic location of a transponder clipped to the wire, 50 metres above the OBS, so that, at the point of its release, the OBS was within 25 metres of its planned location. The accuracy of location was about ± 10 metres. The bathymetry of the target sites, were known with a precision of 0.5 m, from microbathymetric maps, that were provided by Martin Hovland, Statoil.

Eight of the instruments recorded at 2500 Hz sampling rate while the other six recorded at 500 Hz. To give the highest frequency, and near 3-D seismic coverage of the upper 200 m of the subsurface, a single gun with a 13 cu in. generator and 35 cu in injector was fired in true GI mode every 4 s corresponding to distances of ~ 8 m. In a second survey, to ensure penetration of ~500 m and P-S conversions, two 24/24 cu in. GI guns were used, increasing the power of the source but reducing its resolution at shot intervals of 6 s corresponding to distances of ~12 m. The shot interval was limited by the capacity of the compressors and hence it was not possible to shoot under 6 s. The shots were fired from the mini guns towed at ~ 1.5 m water depth on a grid of lines of minimum length 5000 m at 100 m (for 4 s shot intervals) and 50 m line spacing (for 6 s shot intervals) [Figure 3]. The frequency range of the airgun array was 20-300 Hz, with maximum energy of acquisition centered around 150 Hz. An unconventional pattern of circular lines were shot at 6 s interval to cover a full range of offsets and azimuths for the OBS array. The shots were also recorded on a short near-surface hydrophone streamer to provide zero offset seismic reflection images of the sub-seabed structure.

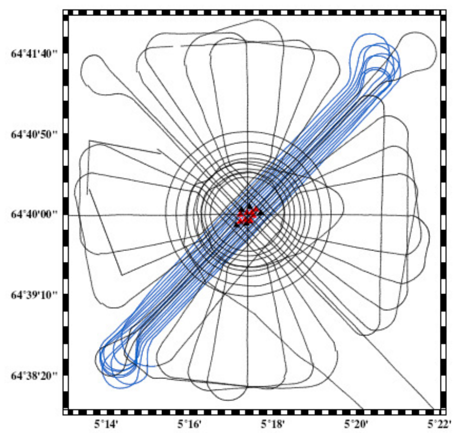

Figure 3: The layout of the seismic experiment. Black lines where shot at 6 s intervals and the blue lines at 4 s intervals. The OBS array is located in the centre.

The high resolution nature of the experiment required that the shot positions and OBS positions are as precise as possible (accuracy of ~1 m or less). Using the water wave arrivals across survey lines and performing a simple least squares inversion optimization to minimize the residuals between the picked direct-wave arrival times and those calculated from the shot positions, the OBS were relocated.

Although the relative positions of the towing position and the gps antennae and the length of the tow cable to the guns were known, the effects of wind and current on the position of the guns relative to the ship were sufficiently variable to make it impossible to determine the shot position with sufficient accuracy. At a shot-OBS offset of 500 m, an error in range of 2.7 m produces a change in the expected direct-wave travel time of 1 ms. After the locations of the OBS had been established, the direct-wave travel times were used to relocate the positions of the shots, using an inversion code [22] that minimises the squares of the residuals subject to a smoothness constraint that limits the variation in the distances between consecutive shots from exceeding that for which it is possible for the ship to accelerate or decelerate. After shot relocation, the great majority of the median values of the residuals between the measured and predicted travel times from each shot to all the OBS in the array were between –0.5 and +0.5 ms [Figure 4].

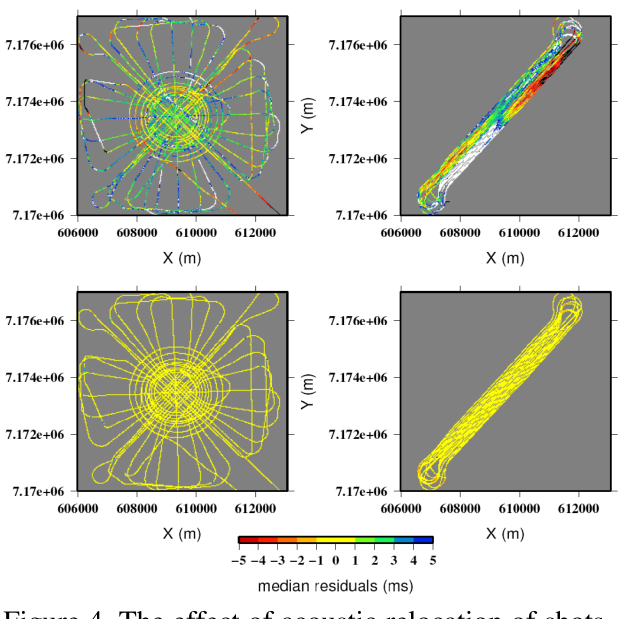

Figure 4. The effect of acoustic relocation of shots upon the median travel-time residuals of the direct wave for all OBS at pockmark G11. Upper left: 6-second shots before shot relocation. Lower left: 6-second shots after shot relocation. Upper right: 4-second shots before shot relocation. Lower right: 4-second shots after shot relocation.

All the OBS recorded good data, imaging reflectors down to depths greater than ~ 1500 ms and showing arrivals with offsets of ~6 km. The ship's engine noise is obvious on all the records from all OBS, increasing to high levels at near offsets when the ship is closest to the OBS. Much of it was removed by separating the up-going wavefield [Figure 5], which contains the reflected seismic arrivals, from the down-going wavefield, which contains the strongest ship's noise. This was achieved by summing the hydrophone and vertical geophone components, after scaling the components to have the same amplitude/frequency response. The method works because the up-going and down-going components have different signs in the record of the geophone but the same sign in the record of the hydrophone. Consequently, up-going waves are reinforced and down-going waves are suppressed. Subtracting the two components reinforces the down-going wave field.

The OBS and reflection data reveal many interesting features of the subsurface geology of the chimney. 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. 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 [25].

The bright reflections 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 [8,10,19,23,24,25]. The base of the GHSZ lies within the chaotic unit across much of the section [Figure 6], but does not display a BSR.

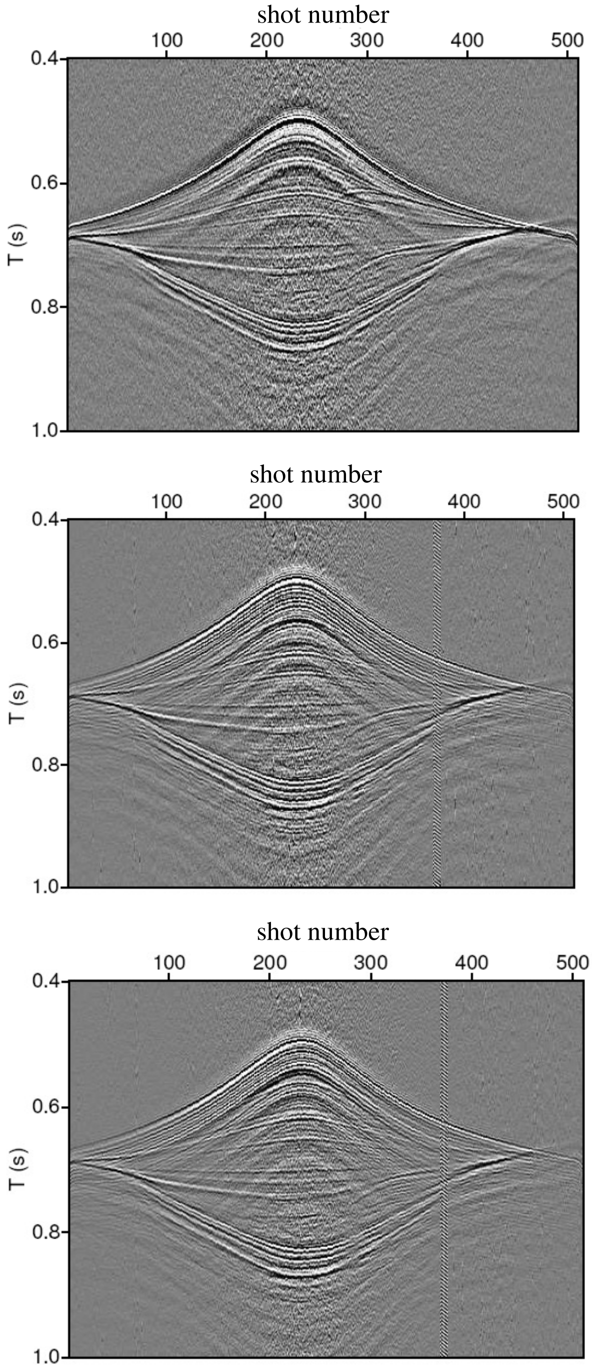

Figure 5. Top: hydrophone record from OBS 06, middle: vertical geophone record. Bottom: hydrophone and geophone summed to give up-going waves. The data is reduced by applying a horizontal move out velocity of 1500 m/s. The signal-to-noise ratio of the seismic events in the up-going wavefield is noticeably better than in either the hydrophone or geophone records from which it is derived.

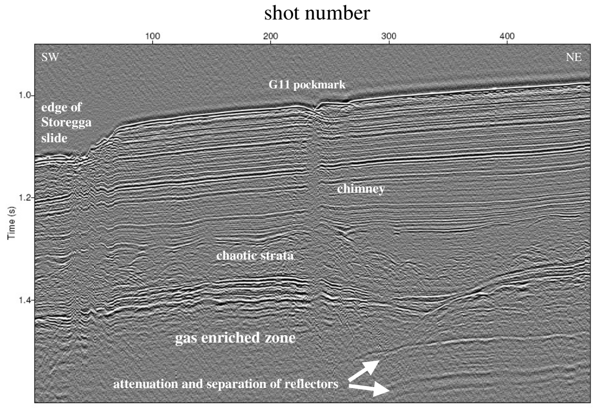

Figure 6. Unmigrated seismic section through the G11 pockmark and its underlying chimney. At the left of the section, bright reflections from layers containing free gas become attenuated laterally where they cross the base of the GHSZ, beneath the slope of the headwall of the Storegga slide (modified from [25]).

MODELLING

Travel-time modelling using a ray tracing software Rayinvr [26] was carried out using five OBS lying along line 360 [Figure 7] which crosses the pockmark to determine the velocity structure beneath the line as an initial test of the sensitivity of the model to the data. An initial 2D analysis of data is useful in determining a rough velocity model, which can then be used as the starting model for performing 3D tomographic inversion.

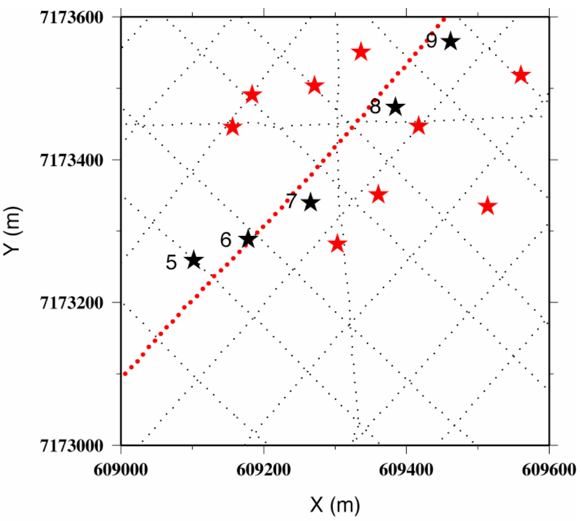

Figure 7. Chart in UTM coordinates of the relocated OBS positions (stars) and shot lines with the two 24/24 mini GI guns. The OBS used for the test model are shown in black and shot line 360 is shown in red.

Approximately 6500 P-wave travel time picks from seven prominent [Figure 8] reflectors lying above the gas charged zone were made on the OBS records and streamer data. The observed travel time picks were then used to invert for velocity and depth by ray tracing using Rayinvr. An initial 2D velocity model was defined, and ray traced from each source through the model. The shapes of the layer boundaries in the initial model were taken from the seismic reflection section 360. The Chi-square error value, which represents the squared difference between the calculated travel times and the times picked from the observed data normalised by their assigned error, was minimised by the inversion to find the best fitting values for parameters defining the model such as seismic velocity and the positions of the vertices defining the layer boundaries.

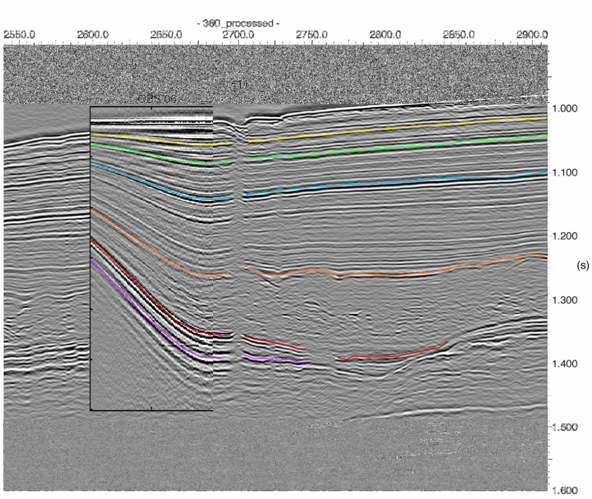

Figure 8. Part of the up-going wavefield section of OBS 06 for shot line 360 at pock mark G11, matched at zero offset to the position of OBS 06 projected on to the seismic section from shot line 360. The prominent reflectors are marked on both profiles.

DISCUSSION

Preliminary results from the modelling show a gradual increase in seismic velocity between the seafloor and the gas charged zone lying at ~300 m depth below the seabed. The model has 9 layers: the water column and 7 sediment layers [Figure 9]. Sediment velocities range from 1.54 km/s at the seabed to 1.67 km/s just above the zone with chaotic internal structure [Figure 6]. Velocity is constrained only in regions crossed by the seismic rays [Figure 10].

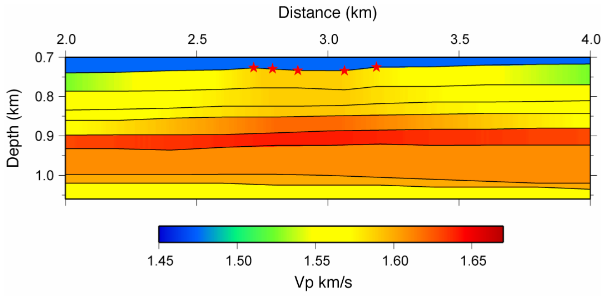

Figure 9. Preliminary model of the velocity structure of the G11 chimney, derived from 2D ray-tracing inversion. The positions of the five OBS used for this model are shown by the red stars.

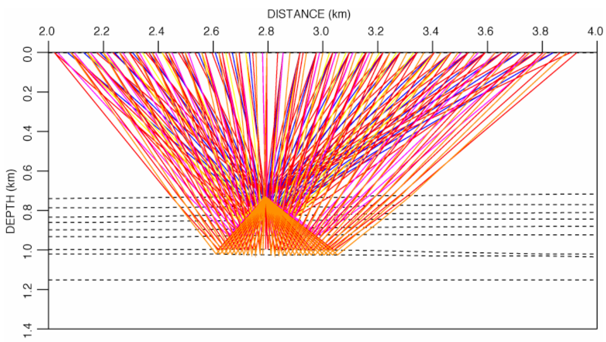

Figure 10. Top: Rays traced between the shots on line 360 and OBS 06 (See Figure 7 for location) through a preliminary 2D velocity model for the G11 chimney. The layer boundaries are indicated by dashed lines.

The velocity model, although not at its final form, indicates that in the region with good ray coverage the velocity of the chimney beneath the pockmark is about 10% higher than that of the surrounding area.

CONCLUSIONS

It has been demonstrated by this experiment that it is feasible to conduct a high-resolution experiment over a chimney like structure. New techniques of OBS deployment helped to attain accurate positioning of the instruments in the pockmark, avoiding seabed obstacles such as carbonate piles. It was also possible to relocate the shot and OBS positions to less than a metre accuracy allowing high resolution analysis of seismic velocities.

Although the modelling and inversion of the data from the G11 pockmark is not complete, the preliminary velocity and depth model suggests that there is higher velocity material within the chimney compared to the surrounding sediments. This could be due to the presence of hydrates within the sediments or carbonate.

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