TTR16-Leg 3

A Seismic Investigation of the G11 and CN03 Pockmarks in the Nyegga Region on the Northern Headwall of the Storegga Slide

Seismic Reflection Line Acquisition and Processing

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Introduction

As part of the HERMES (Hotspot Ecosystem Research on the Margins of European Seas) project, supported by the European Commission FP6 project HERMES (GOCE-CT-2005-511234), UNESCO/IOC TTR program and StatoilHydro, two high-resolution seismic investigations were carried out in June 2006 as part of TTR16 - Leg3 cruise aboard the Russian research vessel the Professor Logachev, see Fig 1. The aim of the cruise was to investigate the 3D structure of gas/fluid-escape chimneys beneath two actively seeping pockmarks (G11 and CN03) in the Nyegga region on the northern headwall of the Storegga Slide, see Fig 2.

Figure 1: The Russian research vessel the Professor Logachev coming into dock in Brest, France at the start of the cruise.

The chimneys, beneath the pockmarks, are considered to represent a class of feature that allow the escape of gas from beneath continental margins, typically from large natural gas reservoirs. Communities of chemosynthetic biota that are dependent, directly or indirectly, on the methane that flows through them are often found close to and within the pockmarks. Chimneys may be a more important source of methane to biota than mud volcanoes, which, although individually much larger features, are far fewer in number than the chimneys, of which there are many hundreds off Norway alone.

The long-suspected presence of hydrate was confirmed on the cruise by the presence of gas hydrate recovered from cores at five locations visited including the G11 and CN03 pockmarks. Locally negative polarity and high amplitude of reflectors in the flanks of chimneys and scattering and amplitude blanking is thought to be caused by the presence of free gas.

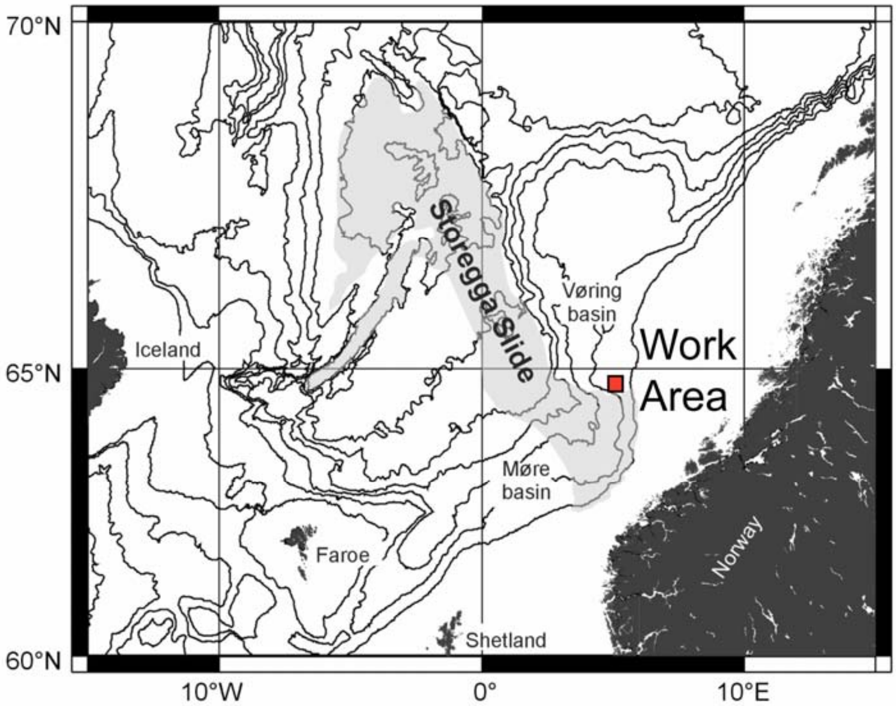

Figure 2: Map illustrating the location of the seismic investigations on the northern headwall of the Storegga Slide.

This document briefly documents the acquisition and processing applied to a series of reflection lines acquired using a short offset streamer and high frequency deep towed profiler.

Streamer Reflection Lines

Seismic reflection data from two channels of the Logachev's hydrophone streamer, see Fig 3, were recorded using a CODA-DA200 (Data Acquisition) system, a 12-bit stand alone module. The two seismic channel inputs from the ship's streamer were connected to the system and each input digitally sampled. Navigation data were input into the DA system once per second via NMEA string from a CSI Wireless DGPS receiver, and stored in SEG-Y headers in units of 0.001°. Unprocessed data were recorded on the PC hard disk in a 2-byte integer SEG-Y format and backed up onto DVD RAM disks at the end of each profile.

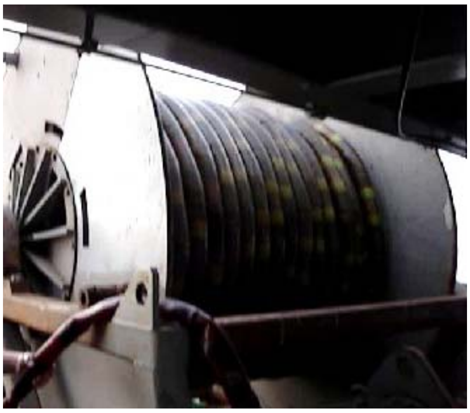

Figure 3: Russian oil filled streamer on the aft deck of the Professor Logachev. Only 2 of the 3 channels were working during the cruise.

The acoustic source consisted of an airgun array with three S.S.I (Seismic Systems Incorporated) 70 cu in mini-GI guns towed about 36 m behind the ship at a depth of approximately 1.5m, see Fig 4.

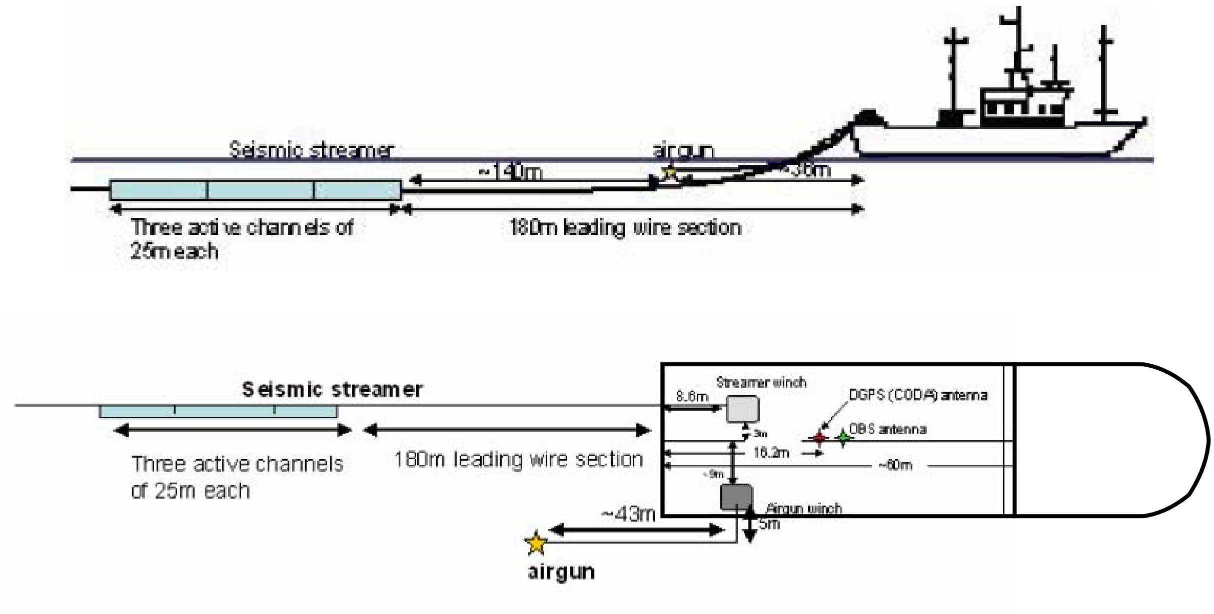

Figure 4: Schematic illustrating streamer airgun configuration.

The GI gun, see Fig 5, is made of two independent airguns, the generator, which produces the primary pulse, and the injector, which is used to control the oscillation of the bubble produced by the generator. The volume of both the generator and injector could be changed from 13 cu in up to 35 cu in, thereby enabling control of the duration of the injection or its timing. This adaptability allowed the use of the guns in two different modes during the investigation. In the true GI mode, the volume of the generator/injector was 13/35 cu in, whereby the injector was tuned to totally suppress the oscillation of the bubble and only one gun was used normally with a shot interval of 4 s, the minimum interval required for the injector chamber to recharge. In the harmonic mode (24/24 cu in), the timing of injection was adjusted to reduce the bubble oscillations to provide a better primary to bubble ratio. Two guns were used in this case with a shot interval of 6 s; the shot interval was limited by the capacity of the compressors. The air pressure for both the modes was 2000 PSI. The GI gun trigger box and the CODA recording system were both triggered on the exact second using a TTL pulse from a Zypher GPStarplus clock. Typically, the clock was operating with a time factor merit of 4 throughout the cruise, giving an accuracy of less than 1 micro-second. The GI guns were tuned so that the firing pulse for the generator was 10 ms after the trigger time from the GPStarplus clock. The actual rising edge of the first pulse of the air gun signal was 18 ms after the trigger time from the GPStarplus clock. The time of this pulse varied over a period of the order of 10 shots in a saw-tooth pattern, with a maximum shift of around 1 ms. The frequency range of the airgun was 30-300 Hz, with a variation of amplitude less than 6 dB. The maximum energy of the source was centred around 150 Hz. Above 300 Hz, its amplitude decreased by a further ~7 dB to 400 Hz before reaching a plateau between 400 and 800 Hz.

Figure 5: Mini GI-gun setup used as the seismic source for the streamer lines.

The seismic streamer contained three 25m-long active sections, of which the front two were used, carrying 37 hydrophones per section at a spacing of 0.6 m. CODA channel 1 recorded the nearer of these two sections and channel 2 the farther. Because of the high intensity of acoustic noise generated by the ship, channel 2 generally provided better data. The streamer had no tow cable but instead was towed from a passive section that remained partly wound on the winch drum. There was no mechanism for controlling the depth of the streamer. The streamer was negatively buoyant, and had to be towed at 4 knots or above to keep it within 4 m of the surface: observations of the sea-surface ghost in the recorded data suggested that the streamer depth was generally in the range of 2-7 m, sinking during turns.

The streamer channels were connected via BNC leads to the recording system via transformers (to electrically decouple the streamer from the system), but no pre-amplifiers were available. The CODA channels were both set to a maximum gain

(1.25 v range), but nevertheless the recorded signals were relatively weak, with maximum peak-to-peak amplitudes of around 70 units for the single gun source and 200 units for the two-gun source, compared to a maximum peak-to-peak range of 4096 units for the recording system. Hence only a small proportion of the dynamic range of the recording system was used, and weaker signals were poorly represented. The quality of reflection images does not appear to have been noticeably degraded by this limitation. Significant 50 Hz electrical noise was observed on both channels. Later in the cruise, it was recognised that this noise could be reduced by more effective shielding of the signal cables.

For a number of reasons, the actual positions of the shots were not known accurately from the navigational data alone. Ideally, a differential GPS system mounted on the guns float would have been used, but such a system was not available. Although the relative positions of the towing arm 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.

Fortunately, the seismic reflection streamer data benefited from being able to precisely re-locate all of the shot positions using the ocean bottom seismometers (OBS), also deployed, which simultaneously record the shots. This was done by firstly re- locating the OBS and then using direct-wave travel times to relocate the positions of the shots, using an inversion code, written by James Hobro, 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. This ultimately allowed the location of the shots to be determined to within approximately 1 m, see Fig 6. Common mid-point (CMP) locations were determined from the shot positions and the acquisition geometry. Variations in the streamer length and tow gun length throughout the acquisition period meant that the final CMP locations were more erroneous than the shot positions.

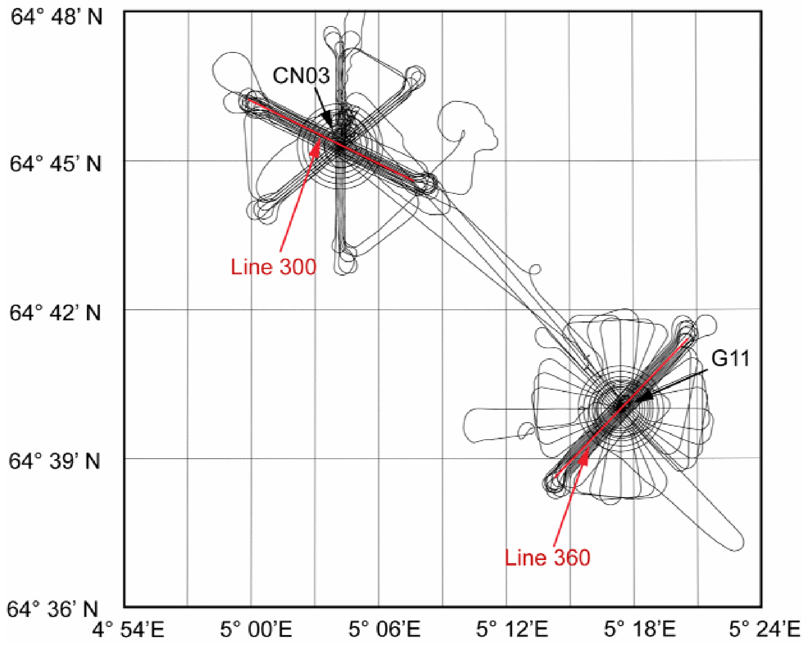

Figure 6: Shooting pattern used for the two separate investigations over the G11 and CN03 pockmarks.

In addition to the normal processing for such lines, corrections were required for the jitter (fluctuations) in the shot times, introduced by the gun firing system, which could vary by up to 1 ms, and for variation in the depth of the streamer. For the shot-time variation the direct wave arrivals to the streamer on successive records were analysed to derive the time variation. For the variation in streamer depth, the period of the sea-surface ghost was derived from the frequency spectrum of each record and the time shifted by half the period, effectively putting the streamer at zero depth for the purpose of travel-times. The ghost period was also used to design a trace-by-trace de-ghosting filter. Details of the processing sequence applied to examples of reflection sections are given below:

Processing Steps

1. Removal of CODA DC offset (constant of 2057).

2. Time-dependent band-pass filtering from 40,90,400,700 to 10,60,400,700 applied between 1 and 2 s (TWT) respectively. Before and after these times filter settings remain constant.

3. Trace-by-trace analysis, via manual picking rather than cross correlation, of the direct wave of the streamer to find the inter-trace variation in arrival time to remove the jitter caused by variation in shot time, see Fig 7.

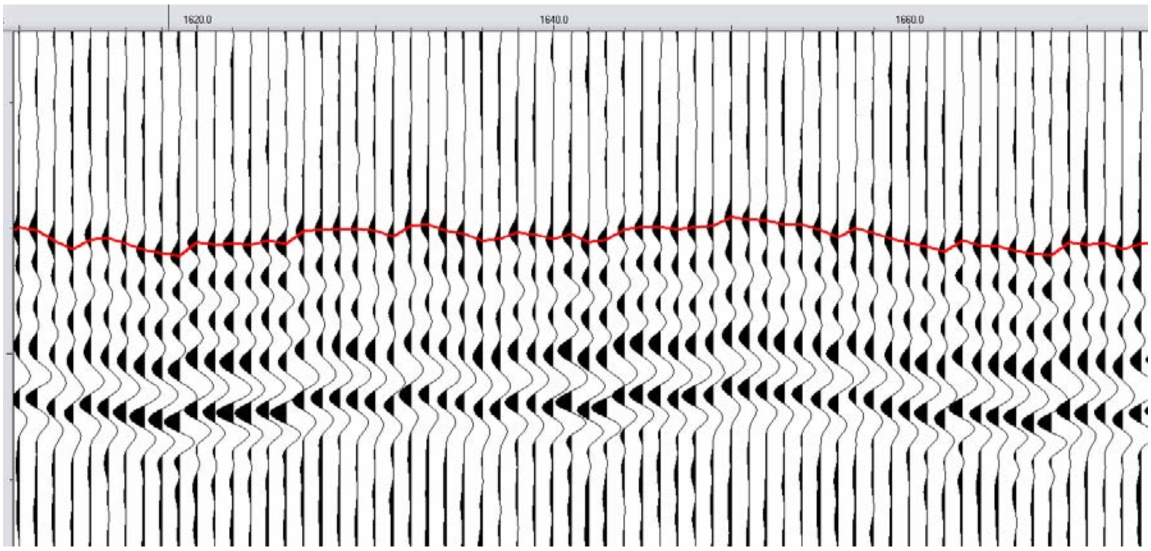

Figure 7: Typical direct arrival picked in order to analyse the “jitter” variations in the firing trigger and correct for them.

4. Computation of frequency spectrum for each trace and picking of the first notch to determine the period of the sea surface ghost to the hydrophone streamer, see Fig 8.

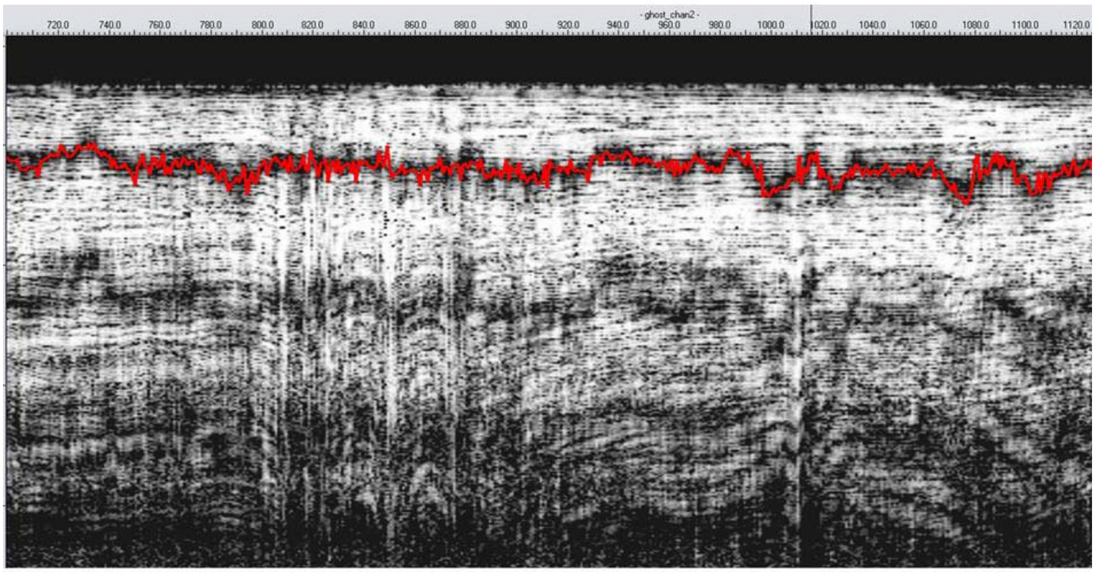

Figure 8: Each trace in the streamer section is converted to the frequency domain using a standard Fourier transform. The traces in the frequency domain are then imagined to be in the time domain and are input into Kingdom. The frequency notch created by the interference of the sea-surface ghost was then picked allowing the precise frequency of the notch to be determined from both channels for each and every shot in the survey. This frequency allowed determination of the streamer depth and provided deconvolution de-ghosting parameters.

5. Static shift of each trace to allow for variations in streamer depth derived from the period of the sea-surface ghost obtained in step 4.

6. Cross-correlation analysis of the trace-by-trace variation in the time of the sea floor using a smoothing routine (with very fine lateral resolution) that retains the shape of the topographic features of the sea floor but removes residual static errors.

7. Trace-by-trace wave-shaping deconvolution that best minimises the ghost to leave just the primary reflection. Parameters for the filter were based on the waveforms of the ghost and seafloor with a separation time defined by the ghost period picked in step 4.

8. Trace-by-trace Wiener-based predictive-error deconvolution (using a minimum lag based on the notch derived times and a maximum lag of 0.05 s) to remove any remnant ringing.

9. Conversion of navigational data to UTM coordinate system and correction for layback so that all traces are positioned at common mid-points.

10. NMO applied to both channels followed by Stolt migration using the following parameters T=1,1.1,1.2,1.3,1.4,1.5 V=1470,1500,1550,1600,1650,1750. (Stolt (FK) migration was applied, because it is quick and the detailed variation in velocity is not yet known. A more sophisticated technique will be applied once the velocity field has been better determined.)

11. FK filtering to suppress 50 Hz noise using the following parameters in the FK domain Slope=-0.0004, -0.00001, 0.00001, 0.0004

12. Stacking of channel 1 and 2, depending upon the similarity (measured using semblance) of channel 1 to channel 2. This was determined on a trace by trace basis. If channel 1 was not sufficiently similar to channel 2 then only channel 2 was used as channel 1 was generally of lower quality.

The improvement of applying these processing steps is illustrated in Fig 9.

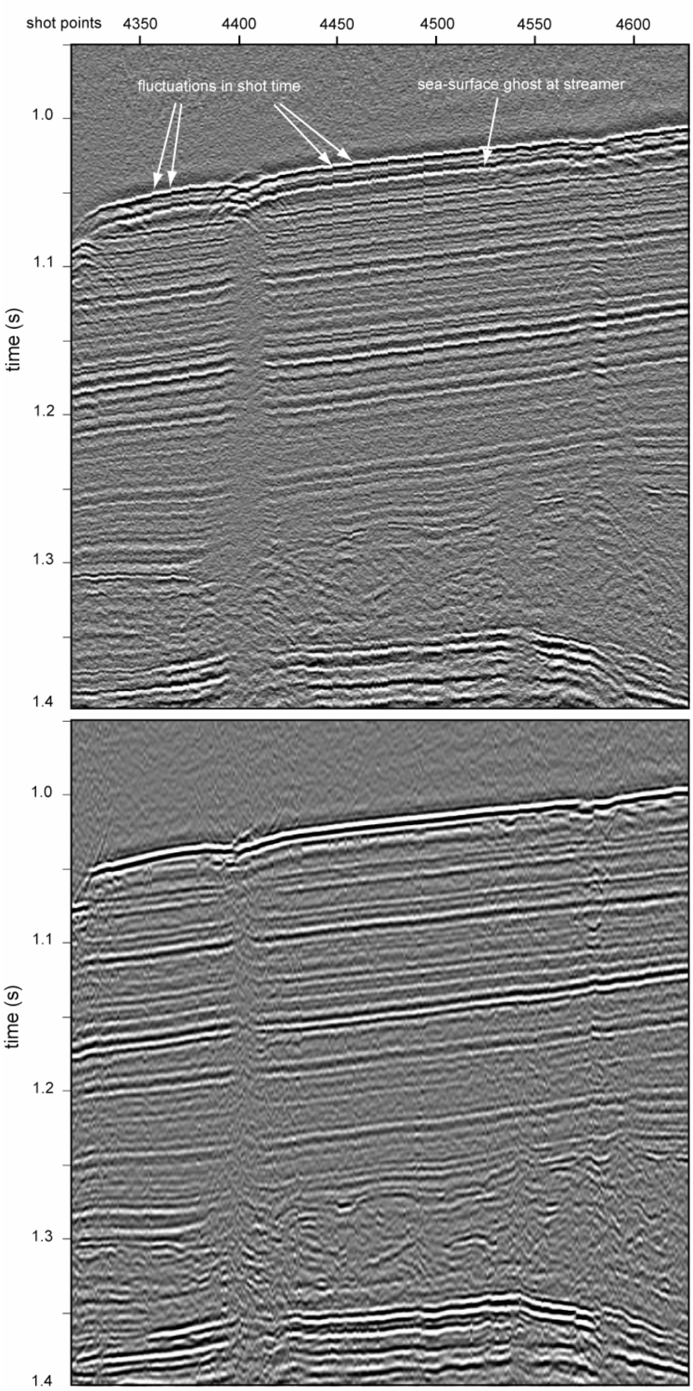

Figure 9: Comparison of a section from a line shot with two 24/24 cu in. mini GI guns with only the first two stages of the processing sequence applied (upper) with same section after application of the whole processing sequence (lower). The increase in resolution from suppression of the sea-surface ghost, improvement in reflector continuity from correction of shot time fluctuation and general improvement in signal-to-noise ratio are evident. The lower frequency content of the fully processed section was produced by the application of a lower high-cut filter at the stage of migration.

The processed seismic reflection sections, both migrated and un-migrated, were placed in Kingdom projects for the purpose of interpretation and picking of reflectors and arrival times. Kingdom is a seismic interpretation suite produced by Seismic Micro Technologies Inc. The following figures (Fig 10 to 12) show screen shots of the streamer sections and local bathymetry for reference.

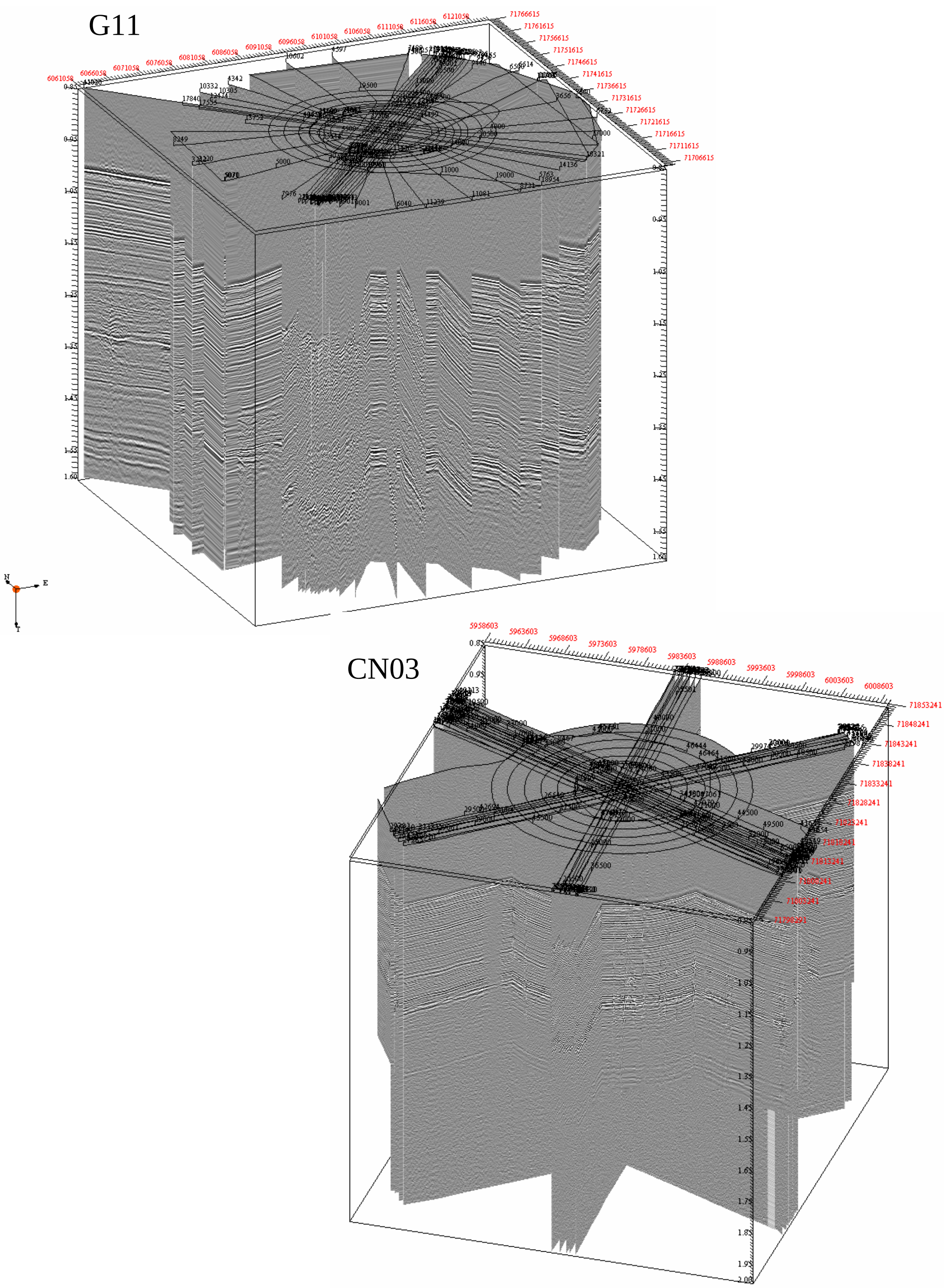

Figure 10: Perspective views of all the seismic reflection sections through the areas of the CN03 and G11 pockmarks.

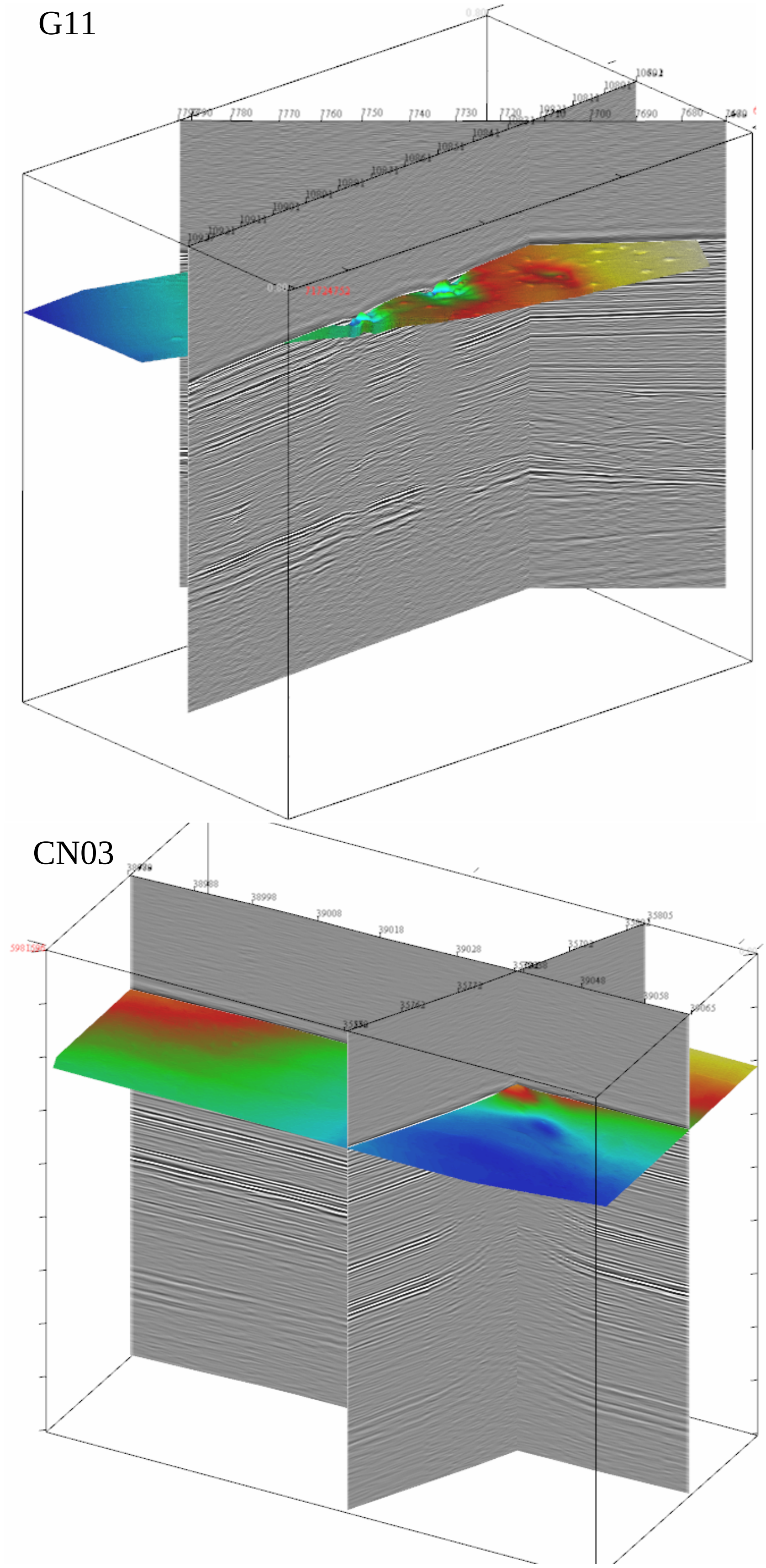

Figure 11: Perspective view of reflection lines for both the G11 and CN03 pockmarks. The high resolution bathymetry acquired by Ifremer (ROV Victor in the Viking cruise) and Statoil generally showed a good correlation with all the reflection lines and the topography caused by the pockmarks.

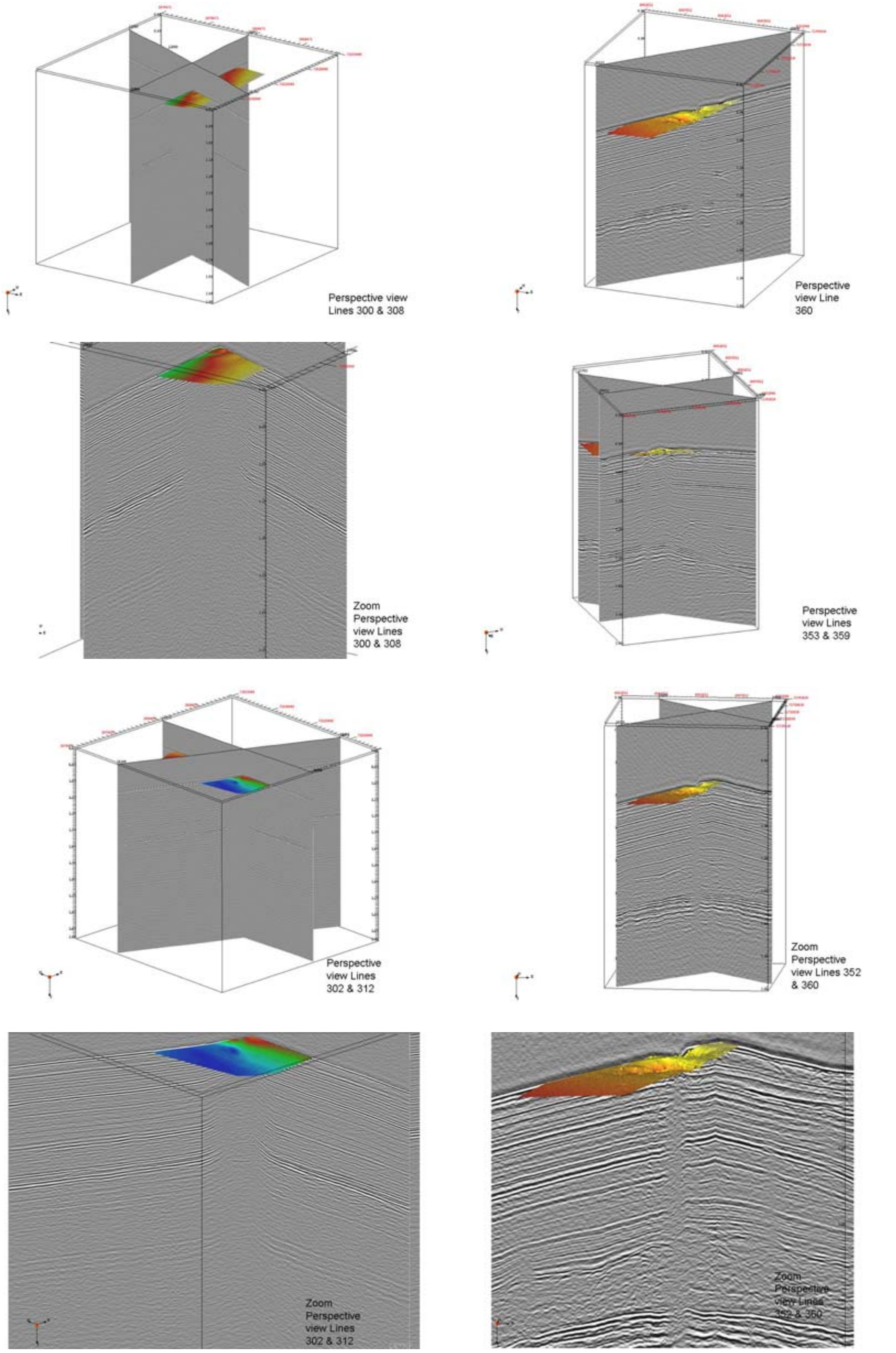

Figure 12: Screen shots from Kingdom showing perspective lines through the CN03 (left column) and G11 (right column) pockmarks illustrating the generally good agreement between intersecting lines and the bathymetry. Generally it was found that the CMP locations were better constrained at the CN03 pockmark when compared to the G11 pockmark.

Side-Scan Sonar and Deep Tow Profiler Lines

The MAK-1M deep-towed hydro-acoustic system contains a side-scan sonar operated at frequencies of 30 and 100 kHz, with a total swath range of up to 2 km (1 km per side and 350 m per side respectively) and a sub-bottom profiler, operated at a frequency of 5 kHz. The side-scan sonar represents the acoustic image of the sea bottom, and the profiler represents the acoustic section of the upper sediments.

The underwater vehicle was towed by the vessel with an electrical deep-tow cable. A depressor weight was used to stabilize the depth of the tow-fish. During TTR16, the tow-fish was towed at a nearly constant altitude of about 100 m above the seafloor at a speed of 1.5-2 knots for 30 kHz surveys and about 50 m above seafloor for 100 kHz ones. These two options represent the operating modes of the MAK-1M complex: long range survey and detailed high-resolution survey. Resolution of the sonar along the track depended upon the speed of the ship. The position of the tow-fish was achieved using a short-base line underwater navigation system. The data from the tow-fish was transmitted on board through the cable, recorded digitally, and stored in SEG-Y format, with a trace length of 4096 2-byte integer samples per side. The trace length of the profiler record was the same. Time-variant gain was applied to the data while recording in order to compensate the recorded amplitudes for the irregularity of the directional pattern of the transducers as well as to account for the spherical divergence of the acoustic pulse.

Onboard processing of the collected data included slant-range-to-ground (SLT) correction of the sonographs, geometrical correction of the profiles for recovery of the real sea-floor topography, and smoothing of both types of records. Individual lines were geometrically corrected for the towing speed of the fish.

Eight MAK lines (140-147) were run during the cruise. The sub-seabed penetration was up to 70 m providing good quality records. Seven of the lines were run with the 100-kHz sonar 50 m above seabed. One line (146) was run with a 30-kHz sonar 100m above seabed.

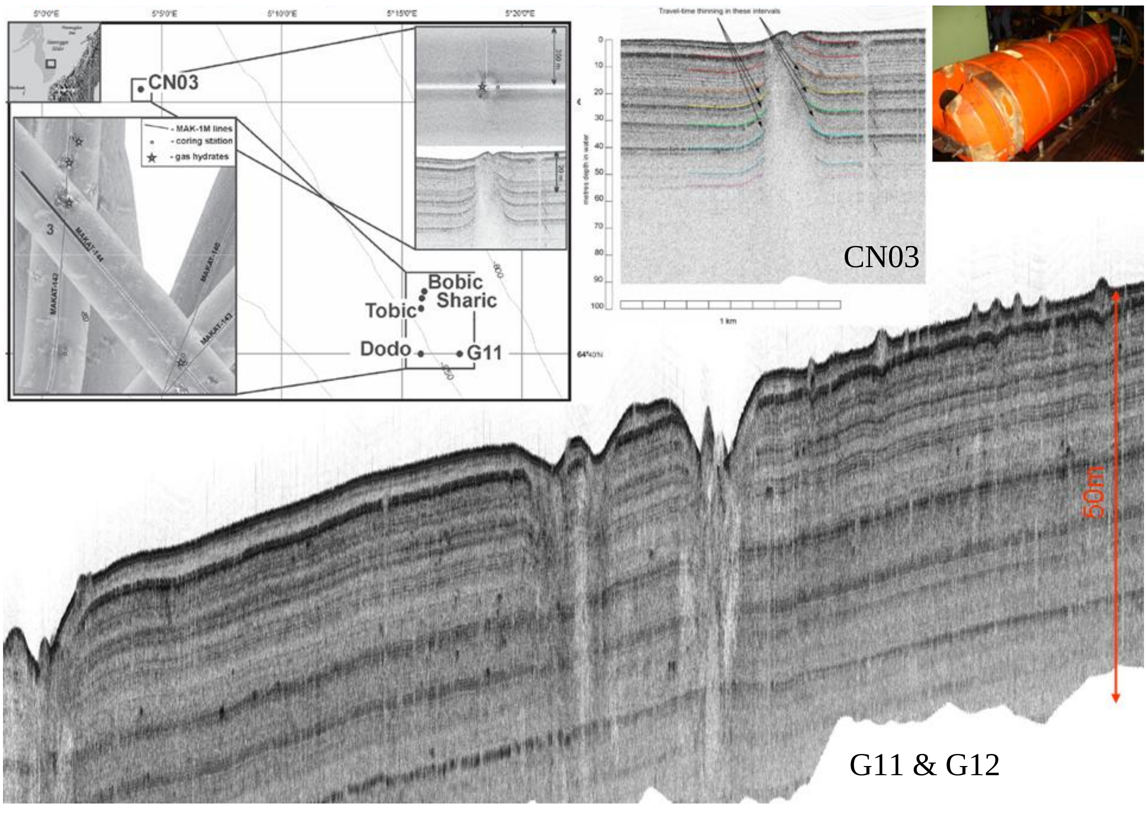

Figure 13: Typical side scan sonar and profiler images acquired from the cruise.

A Very Brief Interpretation

The NW European continental margin contains a diverse range of fluid and gas migration pathways. These pathways typically connect hydrocarbon reservoirs to the seabed, and vary in scale considerably from sub-seismic micro-fractures to larger scale features, such as mud volcanoes. Between these end members, gas, fluid and sediment are transported through a range of structures collectively known as ``chimneys''.

Larger chimneys sometimes create depressions or pockmarks in the sea floor and are often linked to large natural gas reservoirs including for example the Troll Field, the Gullfaks Field, and the Britannia Field. Seismic investigations such as the TTR16 cruise have shown that these pathways are, where pressure and temperature conditions allow, also associated with natural gas hydrate accumulations.

Pockmarks and chimneys with horizontal dimensions of meters to hundreds of meters are especially prevalent in the Nyegga region. Seismic imaging reveals distinct vertical zones with an absence or attenuation of reflectors, in which upward fluid or gas flow appears to have been concentrated. Although some of these features reach diameters up to a few hundred meters the majority of chimneys are much smaller and are only visible in higher resolution seismic data, specifically higher frequency sub-bottom profiler images.

The reflection data clearly indicates that the chimneys are formed in response to significant gas and fluid leakage from the underlying Helland Hansen arch whose apex is situated directly beneath the Nyegga region. Where fluids and gas enter the shallow sub-surface, within the free gas zone and hydrate stability zone, the inter-bedding of glacial and inter-glacial lithologies can be seen to control their migration significantly.

The formation of chimneys and focussed methane input to the seafloor is considered, therefore, to be formed by the upward migration of gas, fluids (from thermogenic sources) and re-mobilised sediment by elevated differential pore-fluid pressures.