Investigation of the origin of shallow gas in Outer Moray Firth open blocks 15/20c and 15/25d

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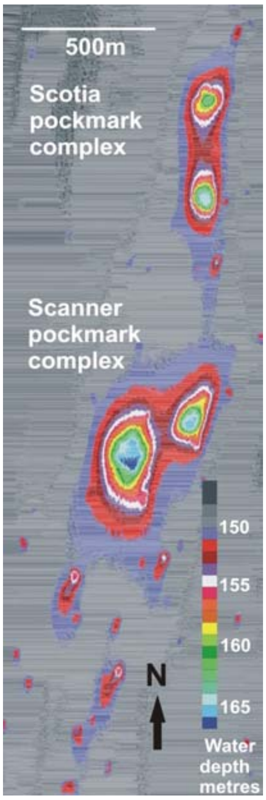

Frontispiece: Sea bed topography associated with actively seeping pockmarks in block 15/25d

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1 EXECUTIVE SUMMARY

This report briefly describes the evidence for the origin of shallow gas in Outer Moray Firth open blocks 15/20c and 15/25d. Sea floor pockmarks are known to occur within these blocks, and they indicate the seepage of gas from shallow levels into the local water column. An environmental concern is that any industry activity in these blocks must not plumb into any component of the system that is sustaining the gas seepages at sea bed. The conclusions of this study are:

1. Interpretation of the available BGS shallow seismic data and commercial site investigation data shows that gas is seeping from sea bed in three large active pockmark complexes in approximately 150 m or more water depth: the Challenger Pockmark Complex in the north of block 15/25d, the Scanner Pockmark Complex in the south of block 15/25d and the Scotia Pockmark which is adjacent to the north-east of the Scanner Pockmark Complex.

2. A review of the peer-reviewed scientific publications indicates that the majority of the arguments based on isotope analyses of gas and authigenic carbonate are for a predominantly biological origin for the gas seeping from the active pockmarks. However, biogenic isotopic signatures in the Gulf of Mexico and the North Sea are thought to have been generated when thermogenic hydrocarbons in shallow sediments were re-cycled by bacteria to produce ‘secondary’ methane with an identical isotopic signature to biogenic methane. Thus, the isotopic data derived from the Scanner Pockmark Complex do not provide a secure basis for determining whether the gas escaping from the pockmarks in block 15/25 is primarily biogenic or thermogenic in origin.

3. Interpretations completed during this project indicate that gas seeping to sea bed in the largest pockmarks is reservoired within the uppermost part of the Aberdeen Ground Formation, where it is preserved between buried sub-glacial channels. The gas seepages at sea bed are fed from an almost continuous blanket of buried gas-charged sediments situated between the sub-glacial channel margins at approximately 280-300 ms two-way time (around 120 m below sea bed) in the northern part of block 15/25d.

4. An empirical conclusion from distribution patterns observed in the interval between sea bed and 400 ms two-way time is that loss of shallow gas from the gas-charged interval at approximately 280-300ms two-way time will cut off the supply of shallow gas to the active pockmarks. Dry well 15/25b-1A, located immediately to the north of the Scanner Pockmark Complex, appears to have been drilled on the margin of the shallow gas reservoir. A recommendation is that future development operations should not disturb the shallow gas reservoir.

5. All of the hydrocarbon discoveries made within and around the study area are oil. The nearest Upper Jurassic Kimmeridge Clay Formation principal thermogenic gas kitchen lies some 30 km to the south-east, in the Fisher Bank Basin. Gas has been proved to have migrated up into Mid-Eocene sandstones (e.g. Alba Field) in that basin. Although it is possible that further vertical migration might have been achieved through minor faults and fractures in the Late Eocene to Pliocene, no evidence was observed in the 3D data to connect the location of the active pockmarks with supply from the thermogenic gas kitchen. For example, no gas chimneys have been observed within the Tertiary section on 3D seismic data across the study area.. Although no major faults have been found in 3D seismic data that transect the entire Eocene to Pliocene interval, minor polygonal faulting has been observed within the upper part of the Hordaland Group.

6. The regional perspective is that shallow gas has accumulated on the unconformity at the near base Pleistocene (Crenulate Reflector). Lateral gas migration of the requisite 30 km from the principal thermogenic gas kitchen might then have occurred up-dip along the Crenulate Reflector into the study area. The unconformity may also be the focus for the transfer into the study area of shallow gas generated within the Plio-Pleistocene section, ascending from the Neogene basin to the south-east. Since numerous wells have previously penetrated the Crenulate Reflector down-dip from the study area, it is suggested if suitable precautions are taken, drilling operations in these areas should not significantly affect the supply of shallow gas to the active pockmarks.

7. The only recognisable fault to cut the Mid-Late Miocene to Pliocene interval and the gas-charged Crenulate Reflector in the study area is a small throw, NE-SW trending fault that runs directly beneath, and parallel to the southern margin of a sub-glacial channel. Regional studies demonstrate that this fault uniquely defines the northern boundary of the gas-charged sediments occurring between sub-glacial channels in the top of the Aberdeen Ground Formation. A suggestion is that the fault is the conduit for gas transferred from depth to the overlying gas-charged sediments and upwards thereon to the active pockmarks. A recommendation is that future drilling operations should not disturb the fault. Particular care should also be taken to prevent of loss of gas from the Crenulate Reflector in the study area.

2 INTRODUCTION

The study area covers two part-blocks within the eastern part of the Witch Ground Graben within the UK Central North Sea (Fig. 1). Both blocks are open at the conclusion of this report, but may be offered for licensing within the 23rd Round during 2005.

Two wells, 15/25b-1A and 15/25-5, are located within the study area (Fig. 1). Well 15/25-1 found poor oil shows within the Upper Jurassic Piper Formation. Well 15/25c-5 was redesignated as a development well for the Blenheim Field (Fig. 1) which has now ceased production from its Paleocene Forties Formation reservoir.

The study area lies entirely within the mapped limit of sea-bed pockmarks as determined by Fyfe *et al*. (2003), and well 15/25b-1A was drilled close to the north-east of a major pockmark complex (Fig. 1).

The Department of Trade and Industry (DTI) has a policy that Strategic Environmental Assessments (SEA) will be undertaken prior to future wide-scale licensing of the UK Continental Shelf (UKCS) for oil and gas exploration and production. This policy implements the EU Strategic Environmental Assessment Directive (2001/42/EEC). This project falls within the DTI SEA2 (north) area for which the Technical Reports to accord with the EU SEA Directive have been completed (Dando 2001, Judd 2001). The presence of shallow gas in the subsurface of these two blocks is well documented. This study follows on from the DTI 2001 SEA research on pockmarks, and has a focus aimed at investigating shallow subsurface gas seepages in blocks 15/20c and 15/25d are.

Outer Moray Firth blocks 15/20c and 15/25d have been excluded from recent licensing rounds for environmental reasons because of the presence of pockmarks on the sea floor, indicating active seepage of gas from shallow levels into the local water column. The environmental concern is that any industry activity in these blocks must not plumb into any component of the system that is sustaining the gas seepages at sea bed. If the gas is migrating along a conduit from deeper levels, then the blocks should remain to be excluded from future licensing rounds.

The study comprised three main tasks:

1. A desk study based on publications in the literature and unpublished reports to determine whether or not there is already a consensus on the derivation of the gas seepages in blocks 15/20c and 15/25d
2. A quick interpretation of available BGS shallow seismic data and commercial site survey data to determine the extent of the gas in the shallow subsurface.
3. Quick interpretation of appropriate horizons on the PGS MegaSurvey for indications of gas seepages from deeper levels. Use of seismic attribute analysis to map the locations of Tertiary channels that might be acting as migration conduits into the area. Investigate for gas chimneys, faults extending to shallow levels, amplitude anomalies, evidence for sediment remobilisation and any other evidence for upward gas migration into the shallow subsurface.

A full digital data catalogue is presented in Appendix A.

3 DESK STUDY AND SHALLOW SEISMIC INTERPRETATION

3.1 Published literature

A consensus of published scientific opinion was sought on the origin of shallow gas in the project area. Bibliographical references in the public domain were retrieved using the on-line Georef, Web of Science and Work ISI Proceedings search engines. The references were compiled in Endnote and then reviewed for relevance before retrieval. Publications cited in this report are listed in section 6. Other publications from the scientific literature associated with North Sea pockmarks have been compiled as a supplementary bibliography in section 7 of this report.

3.2 BGS regional seismic reflection surveys and commercial site investigation reports

Data on the locations of the commercial site investigation survey reports and BGS regional surveys held in the BGS archives were compiled using the BGS Arc8 GIS system. Those located within blocks 15/20c and 15/25d are shown on Figure 2. Three anomalously large pockmarks or pockmark complexes have been documented within the study area (Fig. 2, Judd 2001).

The BGS air-gun, sparker, boomer, and side-scan survey records and site investigation report data were only available in hardcopy format. Interpretations of shallow gas distributions were compiled on hardcopy maps, digitised and then converted to ArcGIS shapefiles.

On boomer 1.5 kHz profiles, disturbed and chaotic acoustic facies occurring with high amplitude reflection anomalies are interpreted as evidence for shallow gas seepage and the presence of gas charge (Fig. 3). Sparker 500 Hz profiles, providing data up to 400 ms below sea level, show similar disturbed and chaotic acoustic facies occurring with high amplitude reflection anomalies that are interpreted as due to gas charge (Fig. 4). When calibrated by sea bed photography, patterns of structured high backscatter at sea bed are interpreted from side-scan sonar records as likely areas of gas bubbles and authigenic carbonate hardgrounds. Images of strings of mid-water high backscatter recorded on side-scan sonar are also interpreted as evidence for ascending shallow gas plumes (Fig. 3).

3.3 Results

An overall planar sea bed consists of very soft muds at approximately 150 m or more below mean sea level. The sea bed has been cratered by pockmarks with a population density of more than 15 per km^2. Pockmarks average approximately 1-2 m depth from shoulder to axis and 100 m diameter. Because these pockmarks yielded no evidence at the time of surveys for modern gas expulsion, they are termed ‘inactive’. The distributions of the inactive pockmarks have not been mapped for this project. At more than 500 m maximum diameter, the Challenger, Scanner and Scotia pockmark complexes are anomalously large compared to the average size of the surrounding inactive pockmarks (Figs. 2-4). Due to shaping by tidal near-bed currents are elongated along a NE axis (frontispiece). Photographs and side-scan sonar images have recorded the seepage of methane gas bubbles from sea bed to sea water from the anomalously large pockmarks (Fig. 3). The nematode species *Astomonema southwardorum* is exclusively associated with the actively seeping pockmarks (Dando *et al*. 1991). The bivalve species *Thyasira sarsi* is also found within actively seeping pockmarks, and is also typical of enriched sediments including oily cuttings piles (Dando *et al*. 1991, J. Hartley pers. comm.). Other unusual biota are methane-oxidising bacteria. These build up slabs of methane-derived authigenic carbonate which are exposed as hardgrounds in the Scotia Pockmark Complex (Fig. 3) and also in the Scanner and Challenger pockmark complexes.

Isotopic ratios derived from the methane-derived authigenic carbonate have been used to infer whether the gas utilised by the bacteria has a biogenic or thermogenic origin, thereon leading to estimates for the depth of origin of the gas seeps at sea bed. For example, the gas utilised by bacteria to form the authigenic carbonate in the Scanner pockmark complex has a biogenic isotopic signature consistent with an origin from bacterial oxidation of Cenozoic lignite or peat in the relatively shallow section of the basin (Dando 2001). Isotopes from a carbonate slab in an adjacent region of the North Sea (Norwegian block 25/7) also indicate an origin from bacterial oxidation of shallow seepages of predominantly biogenic methane. However, shows of minor amounts of higher hydrocarbon gases (up to C5) at this Norwegian site are also consistent with input to the seepages from thermogenic sources (Hovland et al., 1987). Most importantly, biogenic isotopic signatures in the Gulf of Mexico and the North Sea are thought to have been generated when thermogenic hydrocarbons in shallow sediments were re-cycled by bacteria to produce 'secondary' methane with an identical isotopic signature to biogenic methane (Thompson, 1996; Brekke, 1997). Thus, the isotopic data derived from the Scanner pockmark complex do not provide a secure basis for determining whether the gas escaping from the pockmarks in block 15/25 is primarily biogenic or thermogenic in origin (Judd 2001).

The published evidence in blocks 15/20c and 15/25d for sea water, sea bed and sub-sea bed shallow gas occurrences and sources is summarised below in Table 1.

	UKCS blocks 15/20c and 15/25d			
FEATURE	**UNUSUAL BIOTA**	**METHANE GAS/ BIOGENIC OR THERMOGENIC ISOTOPIC SIGNATURE**	**METHANE-DERIVED AUTHIGENIC CARBONATE HARDGROUNDS / ISOTOPIC SIGNATURE**	**UNDERLYING GAS SOURCE**
1. Sea water in study area	No	Yes: recorded on seismic reflection records and gas samples / mid-water isotopic signatures not tested for biogenic or thermogenic signatures	No	Challenger, Scotia and Scanner pockmark complexes
2. Sea bed: inactive pockmarks	No	No gas emission from inactive pockmarks	No	Historical connection with sea bed fluid expulsion not proven whether gas or liquid
3. Sea bed: Challenger complex of large pockmarks (Judd, 2001)	Yes (Dando, 2001)	Yes, recorded on seismic reflection records / biogenic isotopic signature not reported	Yes / biogenic isotopic signature not reported	Indirect evidence from seismic reflection records for connection to underlying gas charges (Judd, 2001)
4. Sea bed: Scanner / Scotia large pockmarks (Judd, 2001)	Yes (Dando, 2001)	Yes, recorded on seismic reflection records and photographs / biogenic isotopic signature (Judd, 2001)	Yes / biogenic isotopic signature (Dando, 2001)	Indirect evidence from seismic reflection records for connection to underlying gas charges (Judd, 2001)
5. Witch Ground Formation (Stoker et al. 1985)	Not observed	Yes / anomalously high concentrations of 'thermogenic' methane adsorbed onto clay minerals in sub-sea bed sediments (Faber and Stahl, 1984), now interpreted as biogenic methane produced by oxidation of thermogenic methane (Judd, 2001). Diagnostic evidence from acoustic facies for sub-sea bed gas ascent (Judd, 1997)	Not observed sub-sea bed	Evidence from acoustic facies for connection to gas charge in top Aberdeen Ground Formation and top Ling Bank Formation (Judd 2001).

	UKCS blocks 15/20c and 15/25d			
FEATURE	**UNUSUAL BIOTA**	**METHANE GAS/ BIOGENIC OR**	**METHANE-DERIVED**	**UNDERLYING GAS SOURCE**

		THERMOGENIC ISOTOPIC SIGNATURE	AUTHIGENIC CARBONATE HARDGROUNDS / ISOTOPIC SIGNATURE	
6. Top Aberdeen Ground Formation and top Ling Bank Formation (Stoker et al. 1985)	Not observed	Yes / isotopic signature not tested	Not observed	Overall connectivity of gas migration implied from stacked configuration of gas sources and gas-charged intervals (Fyfe et al., 2003)
7. Crenulate Reflector (Holmes, 1977)	Not observed	Yes / isotopic signature not tested	Not observed	Trapping of basin-margin gas ascending upslope from the east implied by distribution of high amplitude reflectors (Holmes, 1977)

Table 1 Summary of published evidence for sea bed and sub-sea bed gas levels and likely gas sources.

The features reviewed in Table 1 occur in Holocene to Pleistocene sediments in the range of approximately 200-520ms twt below mean sea level. The Crenulate Reflector has not been securely dated, but as it occurs just above a 2.6 Ma magnetic polarity event recorded in shallow sediments (Holmes 1997), it is probably near base Pleistocene where the base Pleistocene has an age of approximately 2.6 Ma.

The most important derivations from Table 1 are:

- controversy based on geochemistry over whether the major component of gas expelled from the pockmarks originates from biogenic sources at relatively shallow depths, thermogenic sources, or from mixtures of these,
- the regional perspective that gas is probably being transferred from deep basin systems into the project area via the Crenulate Reflector.

Interpretations of the 1.5 kHz deep-tow boomer seismic reflection profiles illustrate that the nearest sub-sea bed gas charge under the active pockmarks lies within the Aberdeen Ground Formation (Figs. 3 & 4), and perhaps also within the Coal Pit Formation (Fig. 3), and is largely restricted to inter-channel areas (Fig. 5).

The lateral distribution of gas-charged sediments interpreted from the deep-tow boomer profiles appears to be closely related to the distribution of sub-glacial channels mapped on deep 3D seismic data (section 4; Fig. 5). The two largest pockmarks in the study area are located close to the margins of the sub-glacial channels, such that pathways of active seepage above sub-glacial channel margins may be postulated. These seepages are sourced from the gas charged sediments observed across most of the inter-channel area over a vertical interval ranging from approximately 280-300 ms two-way time below sea bed (Figs. 3 & 4). The pathway connecting sea bed to the gas-charged interval is shortened by up to approximately 17m or more over the largest pockmarks. If it is presumed that the shortened pathway may be part of the reason why gas seepages have been stable for sufficient time to have deposited large slabs of authigenic carbonate, then it would be important not to cause pathway shortening during future oil and gas exploration and development activity.

4 INTERPRETATION OF 3D SEISMIC MEGASURVEY

The 100 m bin version of PGS's *mcns_100* 3D dataset (MegaSurvey) was used to interpret the 2045 km2 study area blocks. Horizons were interpreted on a 50 line/trace increment (approx. 500 m) grid, and autotracked ('zapped') where appropriate.

The interpretation was carried out on a workstation, using Landmark's SeisWorks 2003.12.03 software, utilising the *Northsea* Openworks project (Central Meridian of 3°E; UTM Zone 31), and SeisWorks 3D project *mcns_100*.

A total of 3 horizons were interpreted regionally across the seismic dataset (Figs. 6 & 7):

Horizon	Horizon name in SeisWorks	Reflection signature
Sea bed	*Zap_proj0422_seabed*	Minimum (hard kick)
Base Ling Bank/ Coal Pit Fm	*proj0422_base_ling_bank_fm*	Maximum (soft kick)
Base Pleistocene (Crenulate Reflector)	*proj0422_horz1*	Minimum (hard kick)

MegaSurvey horizon interpretations provided by PGS that were used in this study include: top Hordaland Group, top Sele Formation, top Chalk, top Lower Cretaceous, base Cretaceous unconformity and top Rotliegend Group (Fig. 6).

An additional horizon at the base of a Mid-Late Miocene-Pliocene prograding wedge unit (Prograding Wedge A, Figs 6 & 7) was picked and autotracked ('zapped') in order to generate a StratAmp RMS amplitude extraction across the lower part of the prograding wedge unit where some isolated high amplitude reflections had been observed.

4.1 Sea bed

The pockmarks cannot be discerned from the 3D seismic data on the sea bed horizon. An example of the detailed seabed topography associated with the active Scotia and Scanner pockmark complexes is illustrated on the frontispiece.

4.2 Base Ling Bank / Coal Pit Formation unconformity

The base Ling Bank and Coal Pit formations horizon is an unconformity surface that results partly from sub-glacial channel scouring, and several major channels can be identified within the study area (Fig. 8). The Ling Bank Formation is largely constrained within the channels, and is overlain by the Coal Pit Formation. Three main trends of sub-glacial channels can be observed: NE-SW, NW-SE and N-S. The horizon is poorly imaged on the 3D seismic data, especially within the deep channels, and it is unsuitable for zap interpretation. A better quality image of the unconformity from the Andrew Field area is presented in Figure 16.14 of Fyfe *et al*. (2003). The sub-glacial channels can be discerned easily on 3D seismic time-slices through the interval between 276-400 ms two-way time (Fig. 9).

4.2.1 High amplitude reflections

Locally, the uppermost part of the Aberdeen Ground Formation in the intervening areas between the sub-glacial channels exhibits a high amplitude response (Fig. 7). The lateral distribution of these anomalously high amplitude reflections has been determined from an RMS amplitude extraction from the interval 50-150 ms below the sea bed (Fig. 10). The largest area of high amplitudes lies within a triangular area between two intersecting sub-glacial channels in the north of block 15/25d, and another area lies in an inter-channel area to the south-west in block 15/25c (Fig. 10). This seismic response is at the same stratigraphic level, and has a similar geographic distribution to the high-amplitude reflectors mapped on shallow seismic profiles (Fig. 5). The three large pockmark complexes within the study area all overlie this area of anomalously high amplitudes in the Aberdeen Ground Formation (Fig. 10).

4.3 Near base Pleistocene and Mid-Late Miocene-Pliocene (Nordland Group)

A near base Pleistocene horizon, designated the Crenulate Reflector by Holmes (1977), appears from the 3D seismic data to be broadly conformable with underlying beds across the study area (Figs. 6 & 7), but overlying reflectors onlap it from the east (Fig. 6), and regionally it is an unconformity. The horizon dips gently down to the south-east across the study area, and is cut by a single fault which trends NE-SW across block 15/25d (Figs. 7, 11 & 12).

The near base Pleistocene horizon was used to constrain a StratAmp extraction of RMS amplitudes on the MegaSurvey (*mcns_100*) across most of the Mid-Late Miocene-Pliocene interval (window of base Pleistocene +20 ms to near base Pleistocene +420 ms). The resulting amplitude map shows predominantly high amplitudes (Fig. 13a), which probably arise from high amplitude reflections in the upper part of prograding wedge B (see Fig. 6). A wedge-shaped area of lower amplitudes extends southwards from the NE-SW trending minor fault which crosses block 15/25d (Fig. 13a). Localised high amplitude reflections were noted within prograding wedge A in the south-east of block 15/25d (Fig. 13c), and these are thought to perhaps represent a high-porosity sand channel system such as that illustrated by Fyfe *et al.* (2003, their Fig. 16.15) in the Nordland Group of block 16/17. A StratAmp extraction of RMS amplitudes was generated across the basal part of the prograding wedge unit A (window base prograding wedge –60 ms to base prograding wedge –20 ms) to determine the lateral distibution of the anomalously high amplitude reflections. The result found a group of en-echelon, linear amplitude anomalies trending NNE-SSW across the south-eastern part of block 15/25d. Since these anomalies are parallel to the regional slope of the prograding wedge unit, they are unlikely to represent a channel complex such as that located in block 16/17 (Fyfe *et al*. *op. cit.*). The anomalies more likely represent toe-of-slope sand bodies.

4.4 Potential sources of shallow gas in Aberdeen Ground Formation

4.4.1 Biogenic methane

Primary biogenic methane is likely to have been generated from woody material and lignite beds within the Mid-Late Miocene to Pleistocene section (Fyfe *et al*. 2003). It is controversial, however, as to the proportion of secondary biogenic methane that could have originated from the biogenic transformation of ascended thermogenic fluids (Judd 2001).

The unconformity which approximates the base of the Pleistocene (Crenulate Reflector) may act as a focus for gathering of biogenic methane formed in the underlying interval where it is more deeply buried to the south-east of the study area. The near base Pleistocene unconformity rises up to the north-west across block 15/25d.

A NE-SW trending minor fault cuts across the north of the block and through the Crenulate Reflector. The minor fault is also parallel to one of the overlying major sub-glacial channels (Fig. 5). This relationship may be critical in providing a mechanism for the vertical transfer of gas up into the gas charged interval at the top of the Aberdeen Ground Formation.

4.4.2 Thermogenic methane and potential migration routes

Huge quantities of gas have been generated from mudstones of the Kimmeridge Clay Formation, the world-class, principal oil and gas source rock of the Central and Northern North Sea (Kubala *et al*. 2003). All of the hydrocarbon discoveries made within and around the study area are oil, reservoired principally within Paleocene and Jurassic sandstones. The nearest Upper Jurassic Kimmeridge Clay Formation principal gas kitchen lies some 30 km to the south-east, in the Fisher Bank Basin. Gas has been proved to have migrated up into Mid-Eocene sandstones (e.g. Alba Field) in that basin. Further vertical migration might have been achieved through minor faults and fractures in the Late Eocene to Pliocene. Lateral gas migration of the requisite 30 km might then have occurred up-dip along the near base Pleistocene unconformity into the study area. Gas generated within the deepest parts of the Witch Ground Graben to the south-west (i.e. in blocks 15/29 and 15/30, see Fig. 17.33 of Kubala *et al*. 2003) could also have migrated north-eastwards into the study area at Jurassic levels (see Fig. 17.26 of Kubala *et al*. 2003), but migration patterns in the Paleocene across this area have been determined to be from south-east to north-west (see Fig. 17.28 of Kubala *et al*. 2003), and this may have caused gas to be swept north-westwards out of the study area before it could rise to Pleistocene levels.

No gas chimneys have been observed within the Tertiary section on 3D seismic data across the study area.

Minor faulting observed within the upper part of the Hordaland Group is poorly resolved on the decimated 3D seismic data, and is inferred by analogy to be polygonal. Fyfe *et al*. (2003, their Fig. 16.19) note that the Eocene, Oligocene and lower Miocene shale-prone sequences within the basin centre are commonly deformed by abundant small, normal faults with a mappable polygonal nature. No faults have been found on the 3D seismic data that transect the entire Eocene to Pliocene interval. The only recognisable fault to cut the Mid-Late Miocene to Pliocene interval is a NE-SW trending fault that runs across the northern part of block 15/25d, underlying the southern margin of a parallel sub-glacial channel. The fault has a maximum heave of 10 ms, and soles out within the lower part of the Mid-Late Miocene to Pliocene interval.

5 CONCLUSIONS

The conclusions of this study are:

1. Interpretation of the available BGS shallow seismic data and commercial site investigation data shows that gas is seeping from sea bed in three large active pockmark complexes in approximately 150 m or more water depth: the Challenger Pockmark Complex in the north of block 15/25d, the Scanner Pockmark Complex in the south of block 15/25d and the Scotia Pockmark which is adjacent to the north-east of the Scanner Pockmark Complex.

2. A review of the peer-reviewed scientific publications indicates that the majority of the arguments based on isotope analyses of gas and authigenic carbonate are for a predominantly biological origin for the gas seeping from the active pockmarks. However, biogenic isotopic signatures in the Gulf of Mexico and the North Sea are thought to have been generated when thermogenic hydrocarbons in shallow sediments were re-cycled by bacteria to produce 'secondary' methane with an identical isotopic signature to biogenic methane. Thus, the isotopic data derived from the Scanner Pockmark Complex do not provide a secure basis for determining whether the gas escaping from the pockmarks in block 15/25 is primarily biogenic or thermogenic in origin.

3. Interpretations completed during this project indicate that gas seeping to sea bed in the largest pockmarks is reservoired within the uppermost part of the Aberdeen Ground Formation, where it is preserved between buried sub-glacial channels. The gas seepages at sea bed are fed from an almost continuous blanket of buried gas-charged sediments situated between the sub-glacial channel margins at approximately 280-300 ms two-way time (around 120 m below sea bed) in the northern part of block 15/25d.

4. An empirical conclusion from distribution patterns observed in the interval between sea bed and 400 ms two-way time is that loss of shallow gas from the gas-charged interval at approximately 280-300ms two-way time will cut off the supply of shallow gas to the active pockmarks. Dry well 15/25b-1A, located immediately to the north of the Scanner Pockmark Complex, appears to have been drilled on the margin of the shallow gas reservoir. A recommendation is that future development operations should not disturb the shallow gas reservoir.

5. All of the hydrocarbon discoveries made within and around the study area are oil. The nearest Upper Jurassic Kimmeridge Clay Formation principal thermogenic gas kitchen lies some 30 km to the south-east, in the Fisher Bank Basin. Gas has been proved to have migrated up into Mid-Eocene sandstones (e.g. Alba Field) in that basin. Although it is possible that further vertical migration might have been achieved through minor faults and fractures in the Late Eocene to Pliocene, no evidence was observed in the 3D data to connect the location of the active pockmarks with supply from the thermogenic gas kitchen. For example, no gas chimneys have been observed within the Tertiary section on 3D seismic data across the study area.. Although no major faults have been found in 3D seismic data that transect the entire Eocene to Pliocene interval, minor polygonal faulting has been observed within the upper part of the Hordaland Group.

6. The regional perspective is that shallow gas has accumulated on the unconformity at the near base Pleistocene (Crenulate Reflector). Lateral gas migration of the requisite 30 km from the principal thermogenic gas kitchen might then have occurred up-dip along the Crenulate Reflector into the study area. The unconformity may also be the focus for the transfer into the study area of shallow gas generated within the Plio-Pleistocene section, ascending from the Neogene basin to the south-east. Since

numerous wells have previously penetrated the Crenulate Reflector down-dip from the study area, it is suggested if suitable precautions are taken, drilling operations in these areas should not significantly affect the supply of shallow gas to the active pockmarks.

7. The only recognisable fault to cut the Mid-Late Miocene to Pliocene interval and the gas-charged Crenulate Reflector in the study area is a small throw, NE-SW trending fault that runs directly beneath, and parallel to the southern margin of a sub-glacial channel. Regional studies demonstrate that this fault uniquely defines the northern boundary of the gas-charged sediments occurring between sub-glacial channels in the top of the Aberdeen Ground Formation. A suggestion is that the fault is the conduit for gas transferred from depth to the overlying gas-charged sediments and upwards thereon to the active pockmarks. A recommendation is that future drilling operations should not disturb the fault. Particular care should also be taken to prevent of loss of gas from the Crenulate Reflector in the study area.

6 REFERENCES

BREKKE, T, LONNE, O., & OHM, S. E. 1997. Light hydrocarbon gases in shallow sediments in the northern North Sea. *Marine Geology*, Vol. 137, 81-108.

DANDO, P. R. 2001. A review of pockmarks in the UK part of the North Sea, with particular respect to their biology. *UK Department of Trade and Industry Strategic Environmental Assessment Technical Report*, TR_001.

DANDO, P. R, AUSTEN, M. C., BURKE, R. A., KENDALL, M. A., KENNICUTT, M. C., JUDD, A. G., MOORE, D. C., O'HARA, S. C. M., SCHMALIJOHANN, R., & SOUTHWARD, A. J. 1991. Ecology of a North Sea pockmark with an active methane seep. *Marine Ecology Progress Series*, Vol. 70, 49-63.

FABER, E., & STAHL, W. 1984. Geochemical Surface Exploration for Hydrocarbons in North Sea. *The American Association of Petroleum Geologists Bulletin*, Vol. 68, 363-386.

FYFE, A., GREGERSEN, U., JORDT, H., RUNDBERG, Y., EIDVIN, T., EVANS, D., STEWART, D., HOVLAND, M., & ANDRESEN, P. 2003. Oligocene to Holocene. In: EVANS, D., GRAHAM, C., ARMOUR, A., and BATHURST, P. (eds) *The Millennium Atlas; Petroleum Geology of the Central and Northern North Sea.* Geological Society, London, 279-287

HOLMES, R. 1977. Quaternary deposits of the central North Sea.5. The Quaternary geology of the UK sector of the North Sea between 56° and 58°N. *Report Institute of Geological Sciences.*, Vol. 77/14.

HOLMES, R. 1997. Quaternary stratigraphy: the ofshore record in Gordon, J E , ed, Reflections on the ice age in Scotland. An update on Quaternary Studies. *Scottish Association of Geography Teachers*. Glasgow, Scottish National Heritage 72-94.

HOVLAND, M, TALBOT, M R, QVALE, H, OLAAUSSEN, S, & AARSBERG, L. 1987. Methane-related carbonate cements in pockmarks of the North Sea. *Journal of Sedimentary Petrology*, Vol. 5, 881-892.

JUDD, A., DAVIES, G., WILSON, J., HOLMES. R., BARON, G. & BRYDEN, I. 1997. Contributions to atmospheric methane by natural seepages on the UK continental shelf. *Marine Geology*, Vol. 137, 165- 189.

JUDD, A G. 2001. Pockmarks in the UK sector of the North Sea. *UK Department of Trade and Industry Strategic Environmental Assessment Technical Report*, TR_002.

KUBALA, M., BASTOW, M., THOMPSON, S., SCOTCHMAN, I. & OYGARD, K. 2003. Geothermal regime, petroleum generation and migration. In: EVANS, D., GRAHAM, C., ARMOUR, A., and BATHURST, P. (eds) *The Millennium Atlas; Petroleum Geology of the Central and Northern North Sea.* Geological Society, London, 289-315

THOMPSON, K F M. 1996. Postulated generation of bacterial methane from seepage petroleum in sea floor sediments of the Gulf of Mexico. In: D. Scumacher and M.A. Abrahms (eds.) Hydrocarbons migration and its near-surface expression. *AAPG Memoir*, Vol. 66, 331-334.

STOKER, , M S, LONG, D. AND FYFE, J.A. 1985. A revised Quaternary stratigraphy for the North Sea. *Report of the British Geological Survey* 17.

7 BIBLIOGRAPHY

Excludes references listed in section 6 above.

ANDREWS, I J, LONG, D, RICHARDS, P C, THOMSON, A R, BROWN, S, CHESHER, J A, and MCCORMAC, M. 1990. United Kingdom offshore regional report: the geology of the Moray Firth. *HMSO for the British Geological Survey*.

BAUER, C, and FICHLER, C. 2002. Quaternary lithology and shallow gas from high resolution gravity and seismic data in the central North Sea. Petroleum Geoscience Vol. 8, 229-236.

DANDO, P R. 1992. RRS Challenger cruise 82 12-31 July 1991. *Marine Biological Association of the UK*.

DANDO, P R, AUSTEN, M C, BURKE, R A, KENDALL, M A, KENNICUTT, M C, JUDD, A G, MOORE, D C, O'HARA, S C M, SCHMALIJOHANN, R, and SOUTHWARD, A J. 1991. Ecology of a North Sea pockmark with an active methane seep. *Marine Ecology Progress Series*, Vol. 70, 49-63.

DANDO, P R, and HOVLAND, M. 1992. Environmental effects of submarine seeping natural gas. *Continental Shelf Research*, Vol. 12, 1197-1208.

FLUIT, C, and HULSCHER, S. 2002. Morphological response to a North Sea bed depression induced by gas mining. Journal of Geophysical Science Vol. 107, art. no.-3022.

HOVLAND, M. 1993. Submarine gas seepage in the North Sea and adjacent areas. In: PARKER, J R (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Graham & Trotman, London, 1333-1338.

HOVLAND, M. 2002. On the self-sealing nature of marine seeps. in *Gas in marine sediments; contributions from the 5th international conference organized by the Shallow Gas Group.* JUDD ALAN, G, and CURZI, P V (editors). (Pergamon. Oxford, United Kingdom. 2002.)

HOVLAND, M. 2003. Geomorphological, geophysical, and geochemical evidence of fluid flow through the sea bed. in *Proceedings of Geofluids IV.* VERWEIJ, J M, DOUST, H, PEACH, C J, SPIERS, C J, and SWENNEN RUDY, A J (editors). (Elsevier. Amsterdam-New York, International. 2003.)

HOVLAND, M, and JUDD, A G. 1988. *Sea bed Pockmarks and Seepages*. (London: Graham and Trotman.)

HOVLAND, M, and RISK, M. 2003. Do Norwegian deep-water coral reefs rely on seeping fluids? in *Geosphere-biosphere coupling; cold seep related carbonate and mound formation and ecology.* VAN WEERING TJEERD, C E, DULLO WOLF, C, and HENRIET JEAN, P (editors). (Elsevier. Amsterdam, Netherlands. 2003.)

HOVLAND, M, and SOMMERVILLE, J H. 1985. Characteristics of two natural gas seepages in the North Sea. *Marine and Petroleum Geology*, Vol. 2, 319-326.

HOVLAND, M, and THOMSEN, E. 1989. Hydrocarbon-based communities in the North Sea. *Sarsia*, Vol. 74, 29-42.

ISAKSEN, G H. 2004. Central North Sea hydrocarbon systems; generation, migration, entrapment, and thermal degradation of oil and gas. *AAPG Bulletin*, Vol. 88, 1545-1572.

JUDD, A G. 2001. Pockmarks in the UK sector of the North Sea. *UK Department of Trade and Industry Strategic Environmental Assessment Technical Report*, TR_002.

JUDD, A G, and FLOODGATE, G D. 1992. The origins of shallow gas. *Continental Shelf Research*, Vol. 12, 1145-1156.

JUDD, A G, and HOVLAND, M. 1992. The evidence of shallow gas in marine sediments. *Continental Shelf Research*, Vol. 12, 1081-1096.

JUDD, A G, LONG, D, and SANKEY, M. 1994. Pockmark formation and activity, UK block 15/25 North Sea. *Bulletin of the Geological Society of Denmark*, Vol. 41, 34-49.

JUDD, A G. 1990. Shallow gas and gas seepages: a dynamic process? *Society for Underwater Technology: Safety in Offshore Drilling*, Vol. 25, 27-50.

KARPEN, V A. 2002. *Fluid discharge at different seep environments; distribution, flow rate, and influence on particle resuspension*.

LEWIS, R W, MAKURAT, A, and PAO, W K S. 2003. Fully coupled modelling of sea bed subsidence and reservoir compaction of North Sea oil fields. Hydrogeol. Journal Vol. 11, 142-161.

MAZZINI, A, DURANTI, D, JONK, R, PARNELL, J, CRONIN, B T, HURST, A, and QUINE, M. 2003. Palaeo-carbonate seep structures above an oil reservoir, Gryphon Field, Tertiary, North Sea.Geo-Marine Letters Vol. 23, 323-339.

PARNELL, J, and SCHWAB, A. 2003. Seismic evidence for the distribution and migration of fluids in sedimentary basins. in *Seismic evidence for fluid distribution and migration.* GARVEN, G, PARNELL, J, and YARDLEY, B (editors). (Blackwell Science. Oxford, United Kingdom. 2003.)

PEGRUM, R M, and SPENCER, A M. 1990. Hydrocarbon plays in the northern North Sea. 441-470 in *Classic Petroleum Provinces*. BROOKS, J (editor). 50. (Geological Society of London.).

APPENDIX A Digital data catalogue

APPENDIX B Commercial site investigation reports

None of the reports are in digital format. They were retrieved in hard copy from the BGS archives. Most rig site surveys contain interpretations of sea bed and sub-sea bed conditions to 1000m below sea bed in a 3 X 3km area surveys generating echosounder, side-scan sonar, single channel high resolution seismic reflection profile and multi-channel 2D high resolution seismic profile data.

ID	OID_	BGS REPTYR	BGS REPTNO	TITLE	AUTHOR	CLIENT	ORIGREF	COMMENTS
1998/1290/A	17589	1998	1290	Cruise report - Challenger deep-tow boomer pock mark survey on Fladen Ground. August	Smith D J and Wallis D G.	BGS	WB/90/49	Used to tie master shotpoints to times
1993/114/A	8187	1993	114	Rig site survey UKCS 15/20b-A		CON	13-503	North margin survey area: high amplitude anomalies associated with Ling Bank Formation indicated by AVO to be associated with low velocity (gas)
1995/57/A	13051	1995	57	Site survey ukcs 15/20b-A		CON	13-502	Report missing
1992/103/A	7213	1992	103	Site survey location UKCS 15/25b-B		CON	1149.1	South margins of project area: no gas
1989/206/A	5519	1989	206	Site survey 15/25b-A		CON	0664 VOLUME I	Gas accumulations, high amplitude anomalies, mapped at approx 300ms twt in Ling Bank Fmn, appear unrelated to overall 'channel sand' topography except that large pockmark is formed over highest elevation of gas acuumulation in the channel sands. Strong acoustic blanking below channels extends down to Crenulate Reflector (which has almost continuous high amplitude anomalies) around 500ms twt
1995/46/A	13007	1995	46	The geochem pockmark ukcs block 15/25		BGS	ETB/323	Scanner pockmark: geochemistry: but no results given

APPENDIX C BGS regional survey lines

The following lines were available for examination:

Cruise 91/03 Lines 1-26
Cruise 1981/04 Line 14

APPENDIX C BGS regional survey lines

The following lines were available for examination:

Cruise 91/03 Lines 1-26
Cruise 1981/04 Line 14

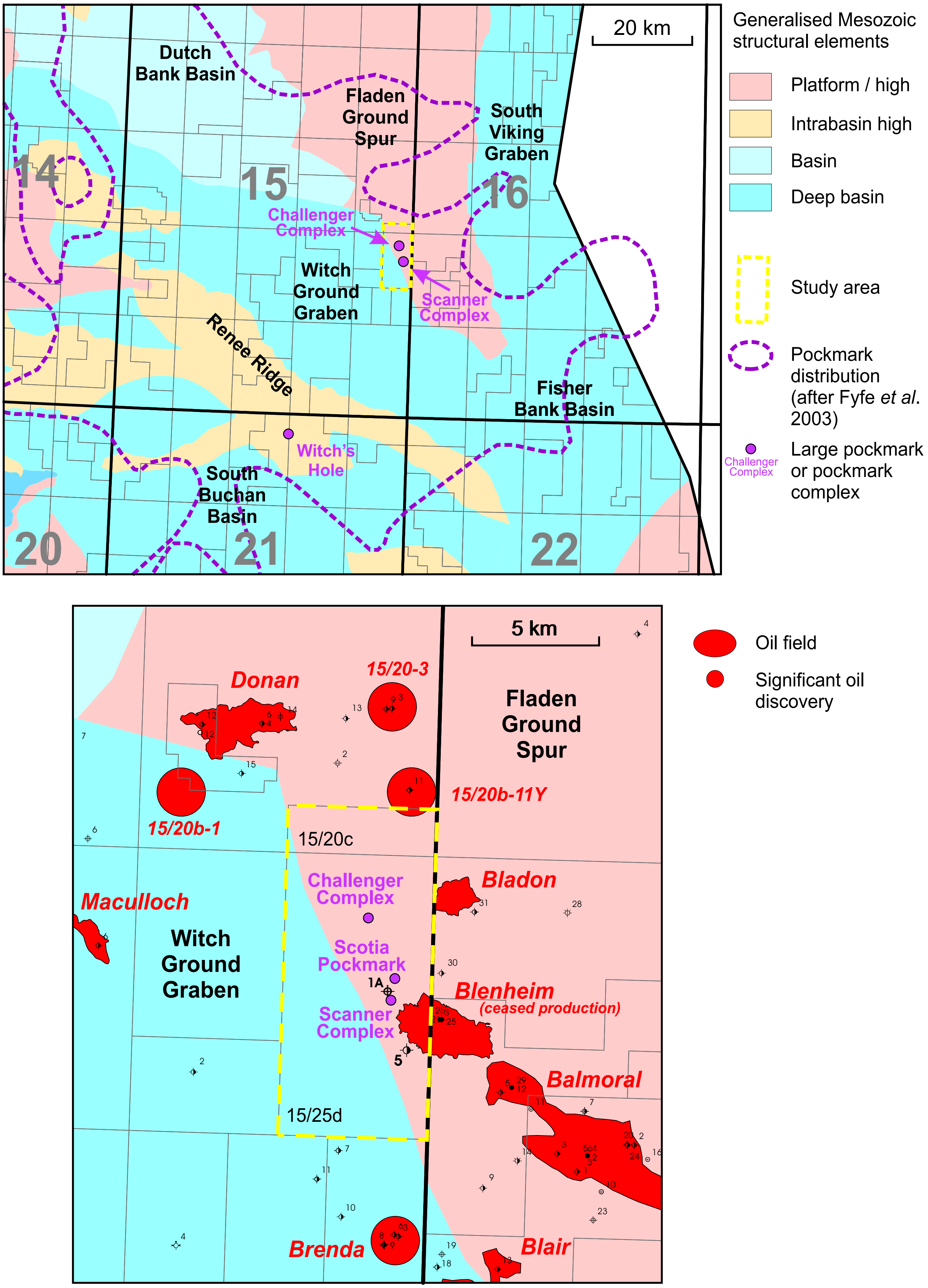


Figure 1 Location of blocks 15/20c and 15/25d, structural elements and pockmarks

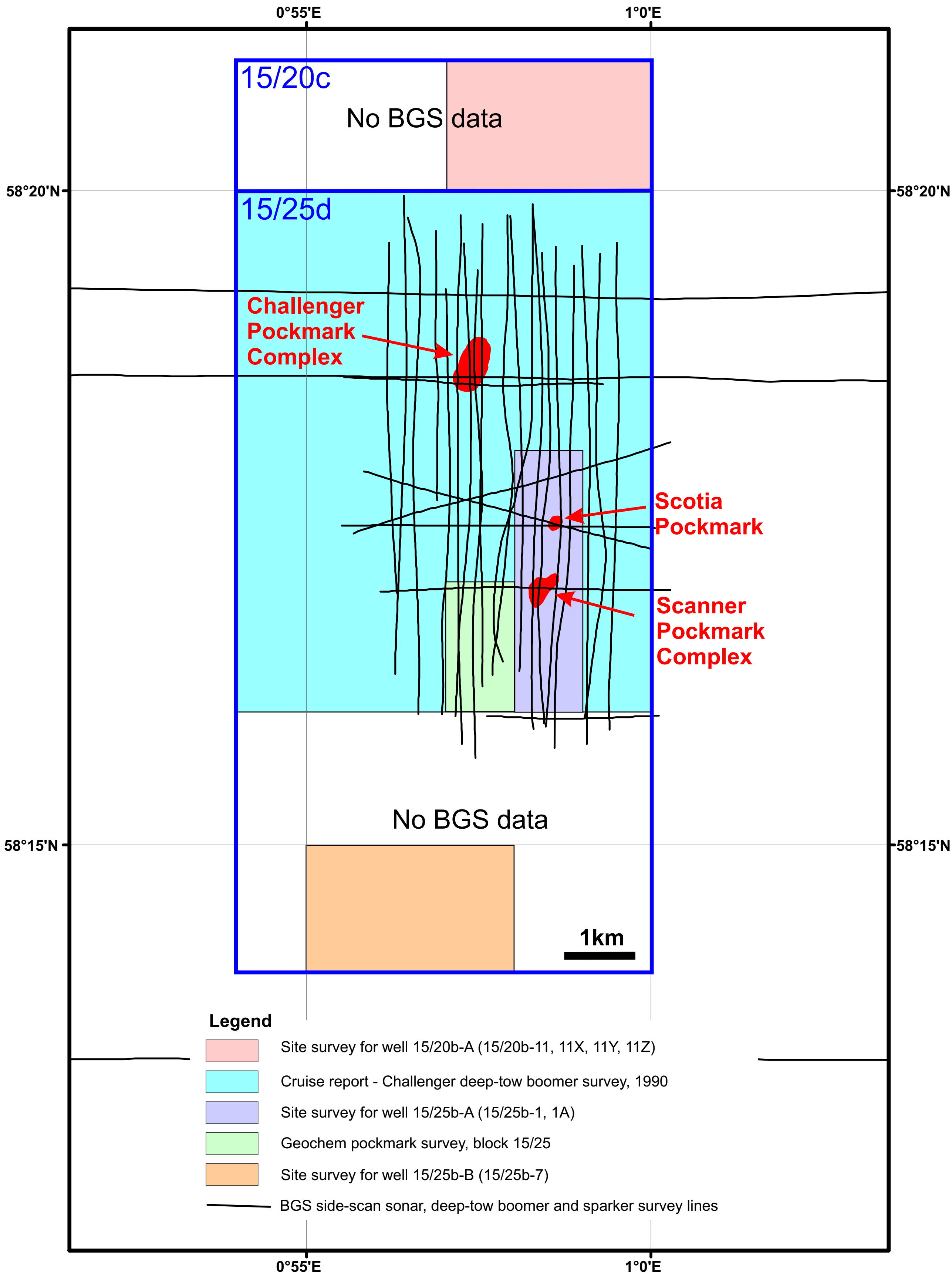


Figure 2 Location of site survey and cruise reports and shallow seismic data held by BGS within study area

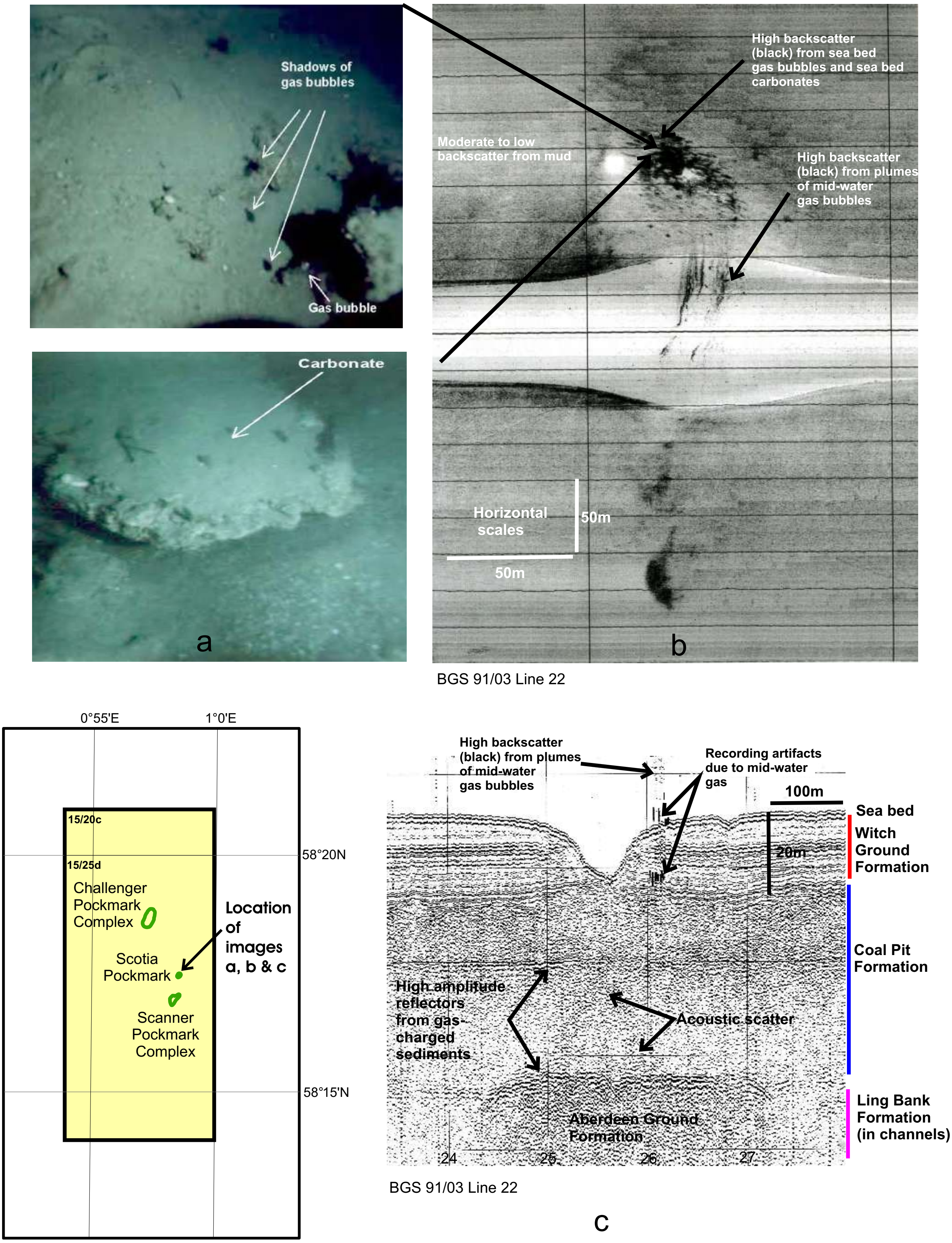
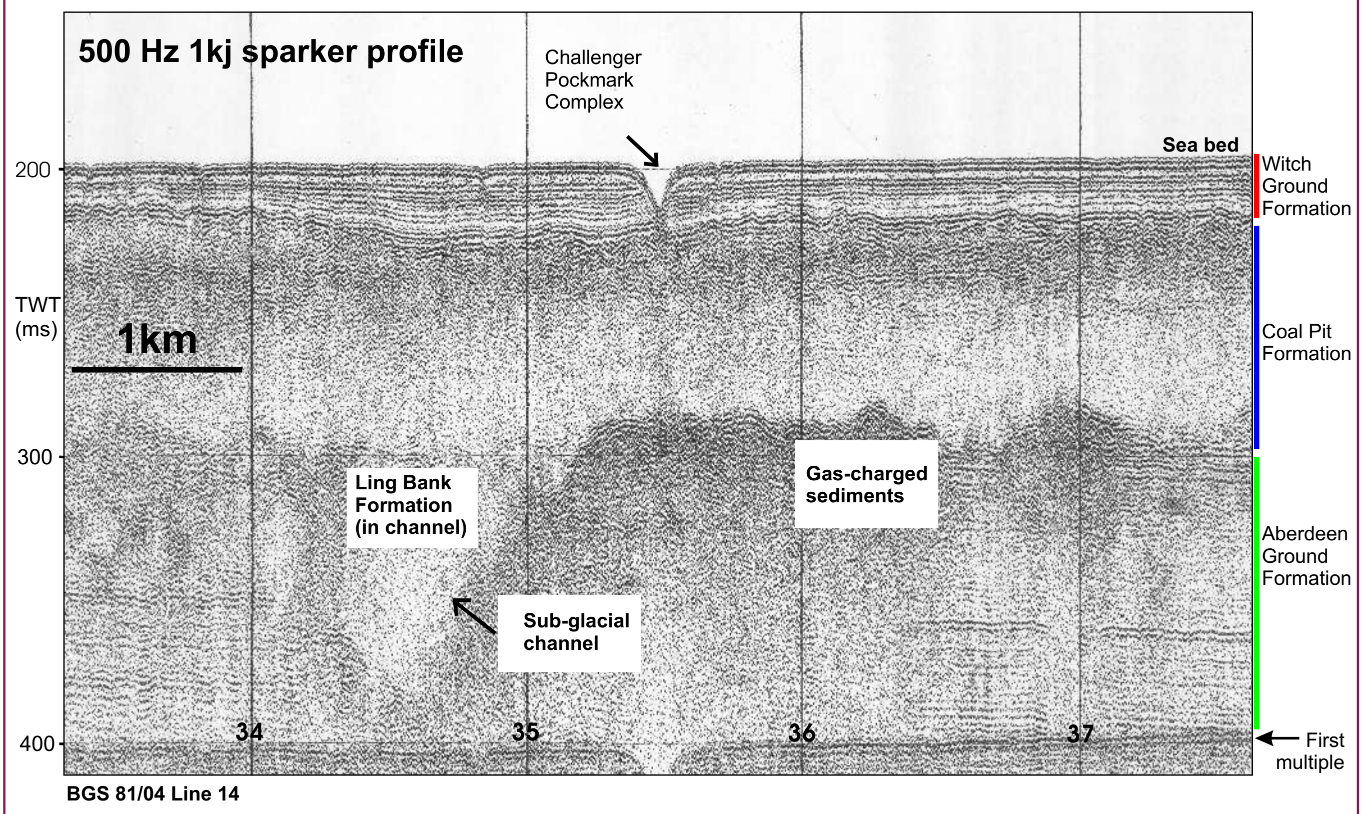


Figure 3 Scotia Pockmark: examples of diagnostic evidence used for interpretations of sub-sea bed gas accumulation, gas ascent and gas expulsion from the sea bed. a) Sea bed photographs (after Judd 2001), b) 1000 kHz side-scan sonar: areas of high sonic backscatter have been recorded with dark tones, c) 1.6 kHz BGS deep-tow boomer



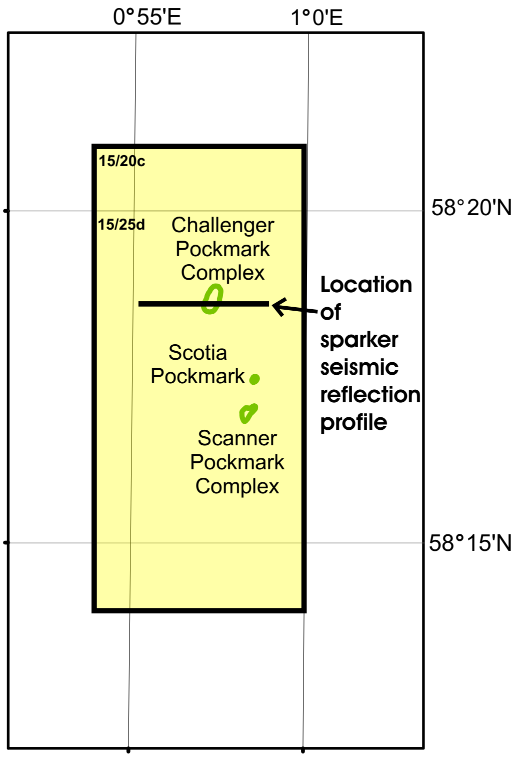


Figure 4 Shallow seismic (sparker) profile across the Challenger Pockmark Complex illustrating the stratigraphy in the study area from sea bed to 400 ms two-way time

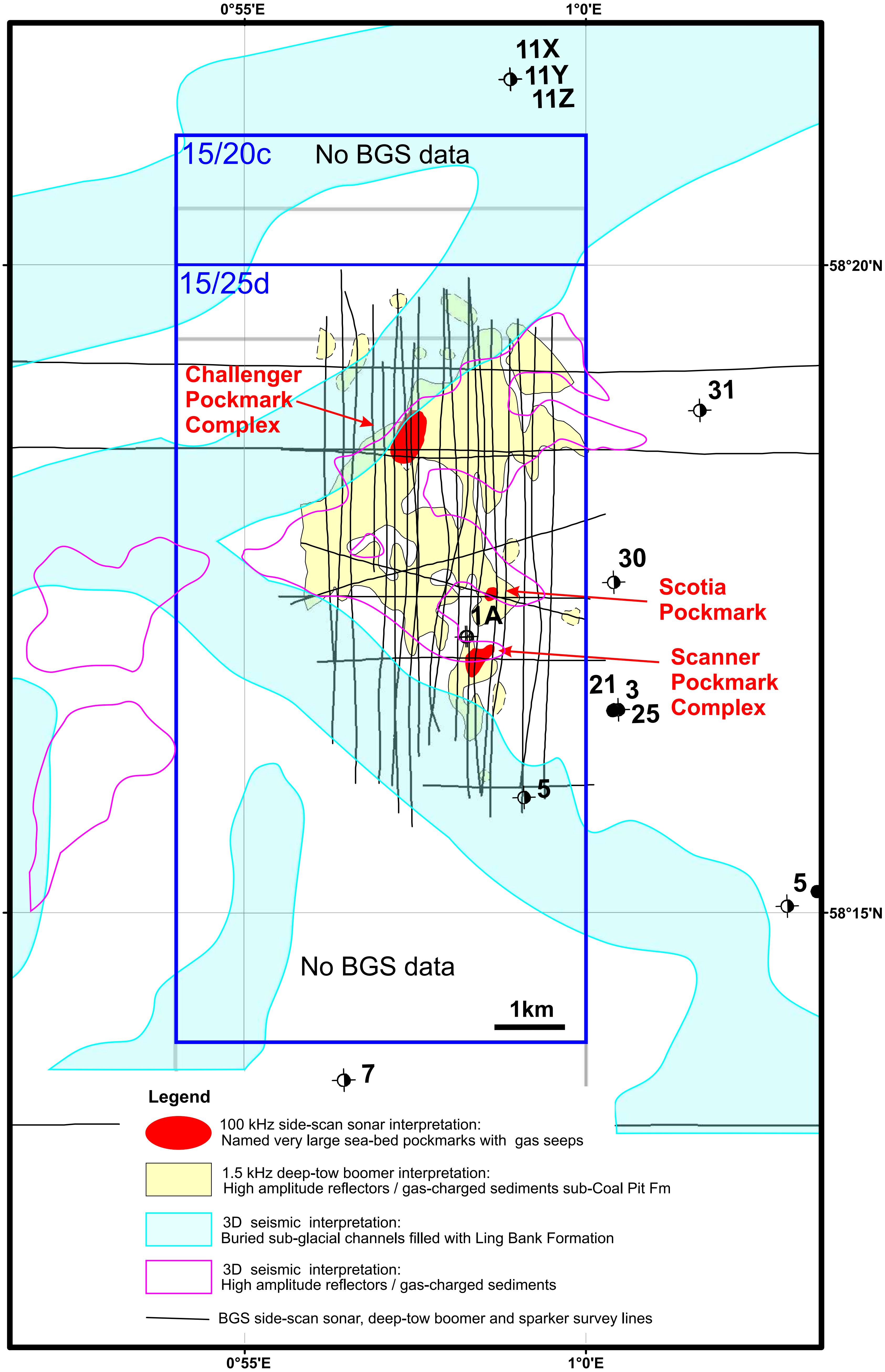


Figure 5 Location of potentially gas-charged sediments interpreted from deep-tow boomer profiles and 3D seismic data, and buried sub-glacial channels interpreted from 3D seismic data

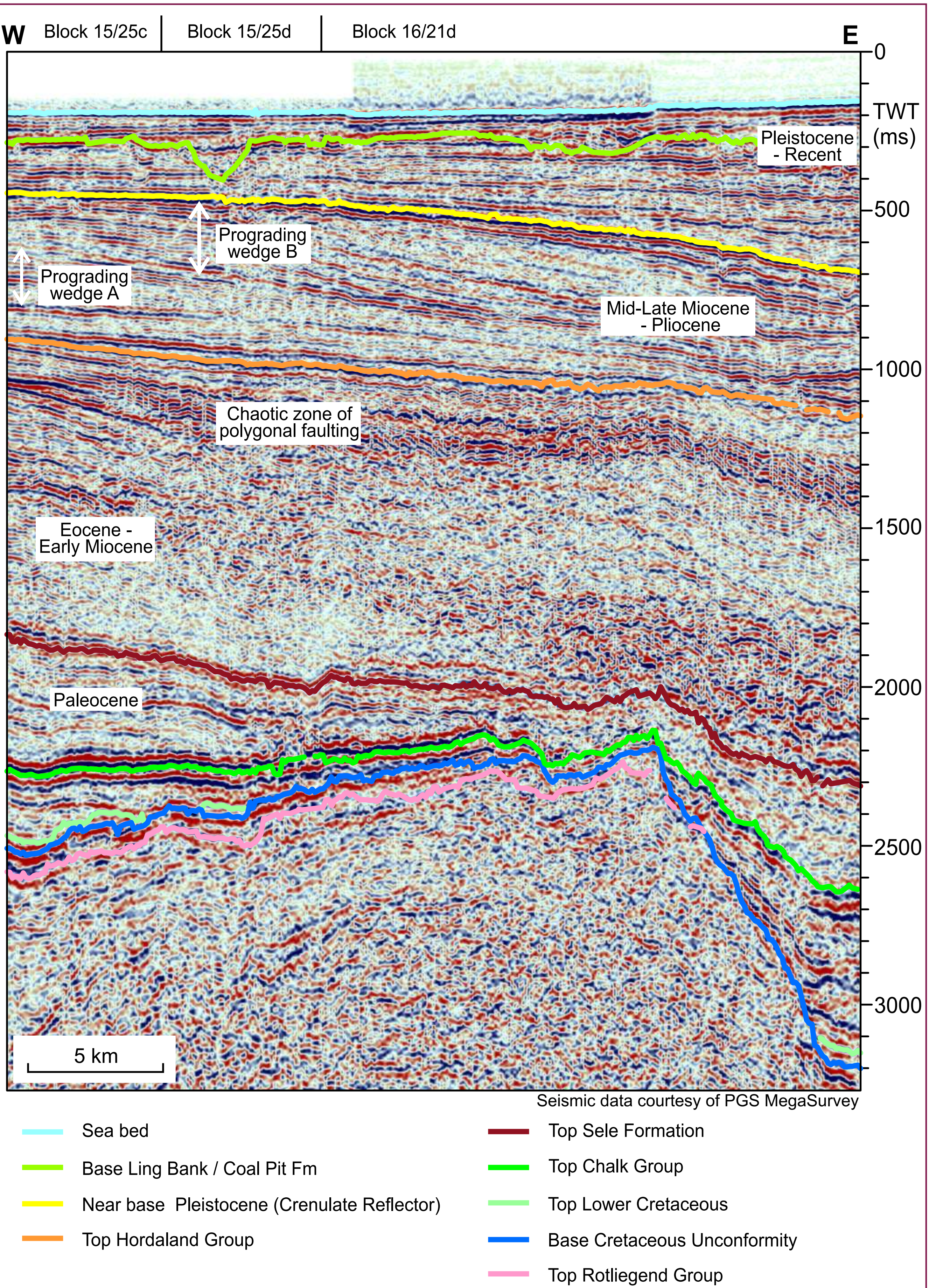


Figure 6 Trace 23504 (*mcns_100*) showing the Mesozoic to Recent section across the study area. See Figs. 8 and 12 for location of section.

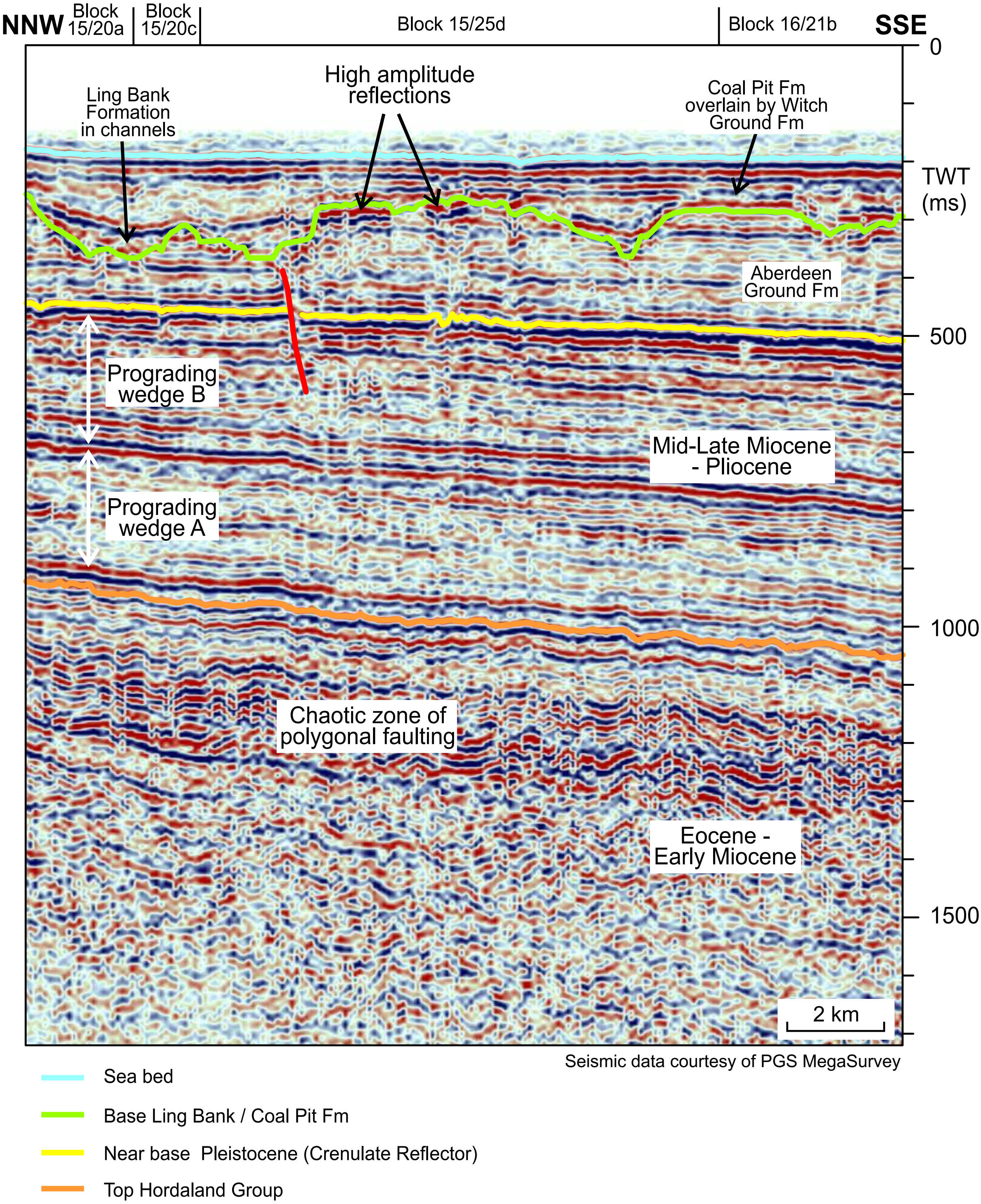


Figure 7 Line 10048 (*mcns_100*) showing sub-glacial channels and minor fault at the near base Pleistocene (Crenulate Reflector). See Fig. 8 for location of section.

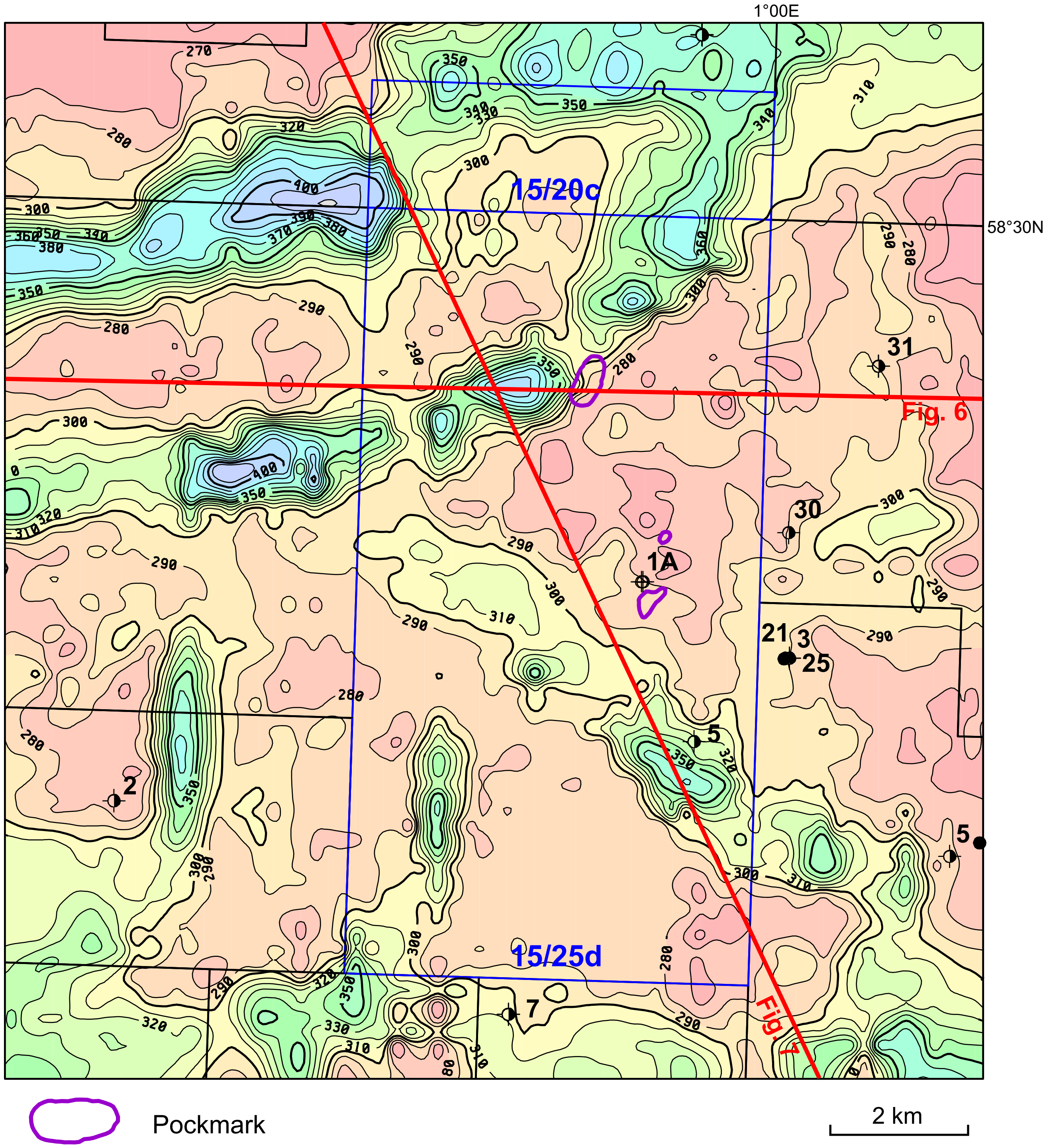


Figure 8 Two-way time contours to base of Ling Bank and Coal Pit formations. Sub-glacial channels filled with Ling Bank Formation are the linear deep areas

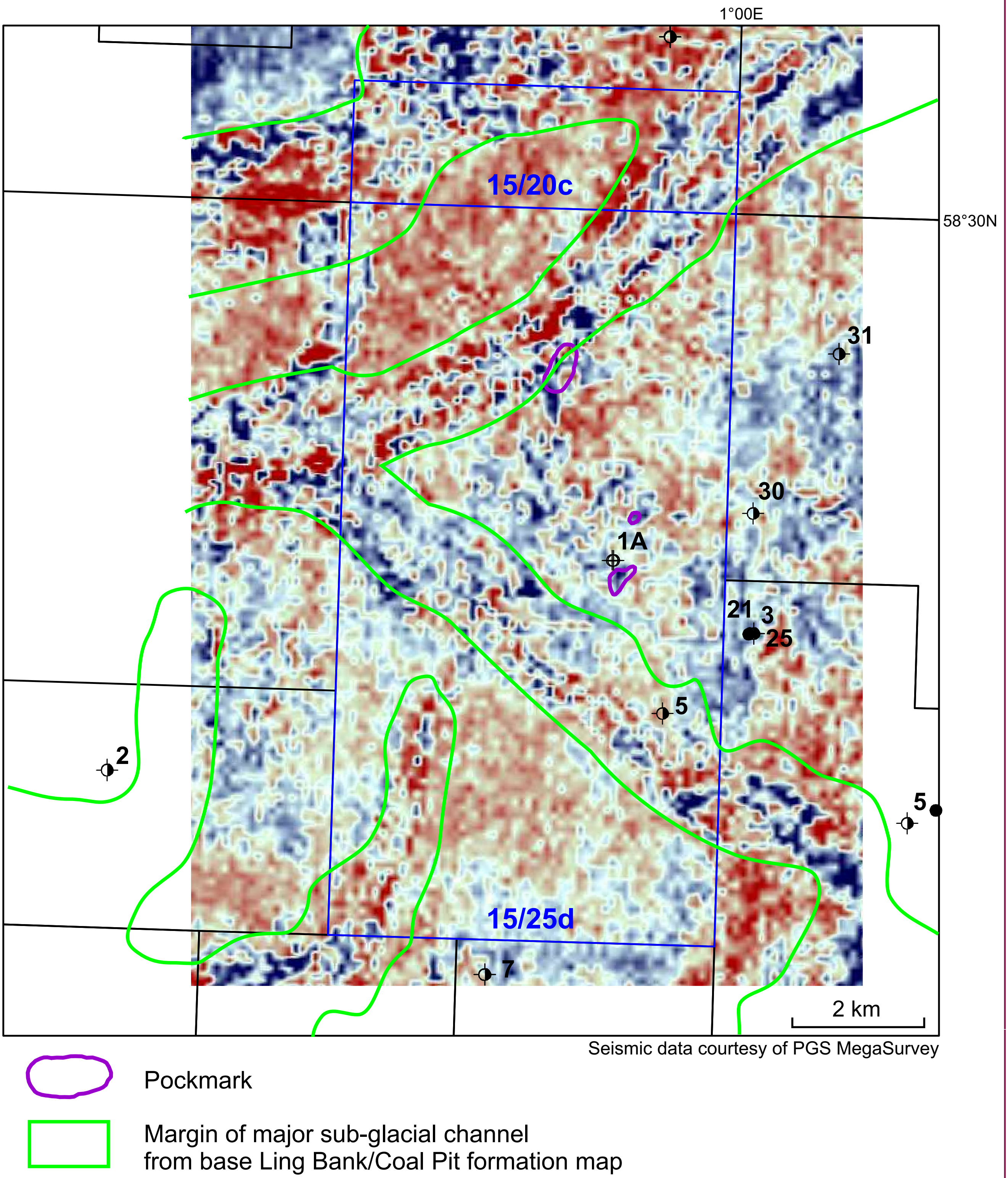


Figure 9   3D seismic time-slice at 352 ms (*mcns_100*) showing sub-glacial channels.

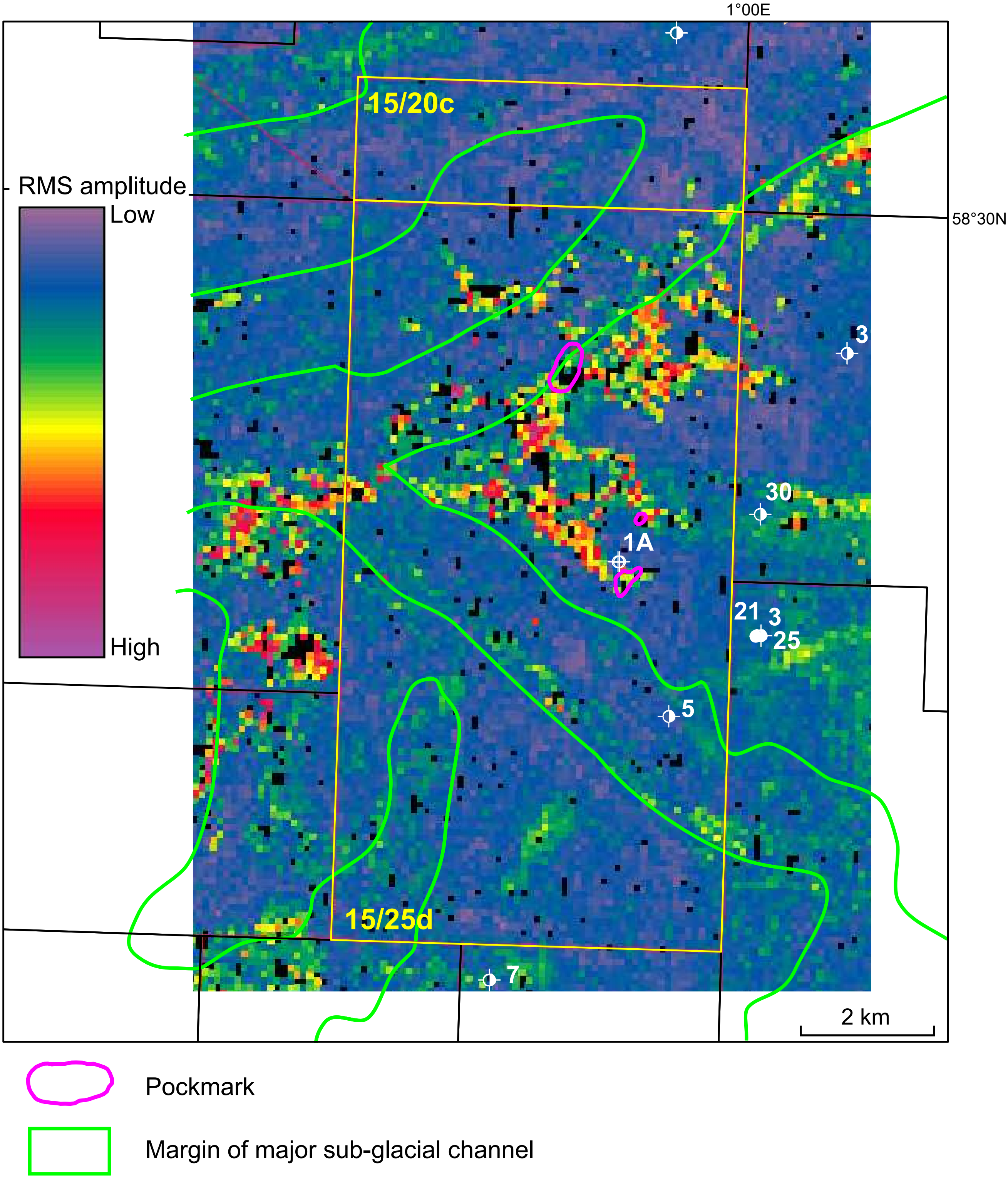


Figure 10 RMS amplitude extraction from the interval 50-150 ms below the sea bed (*mcns_100*) showing area of high amplitudes in inter-channel location.

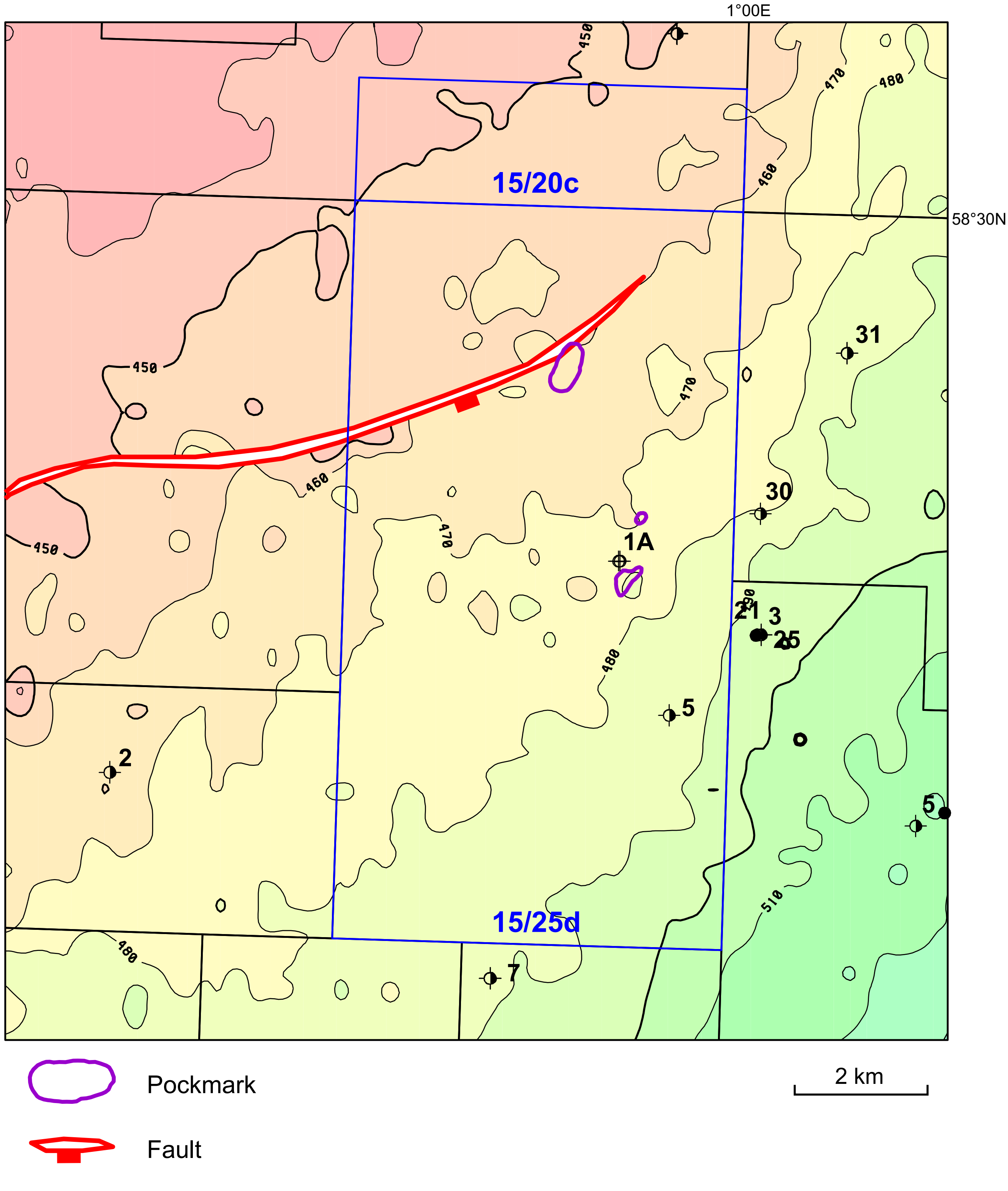


Figure 11 Two-way time to the near base Pleistocene (Crenulate Reflector)

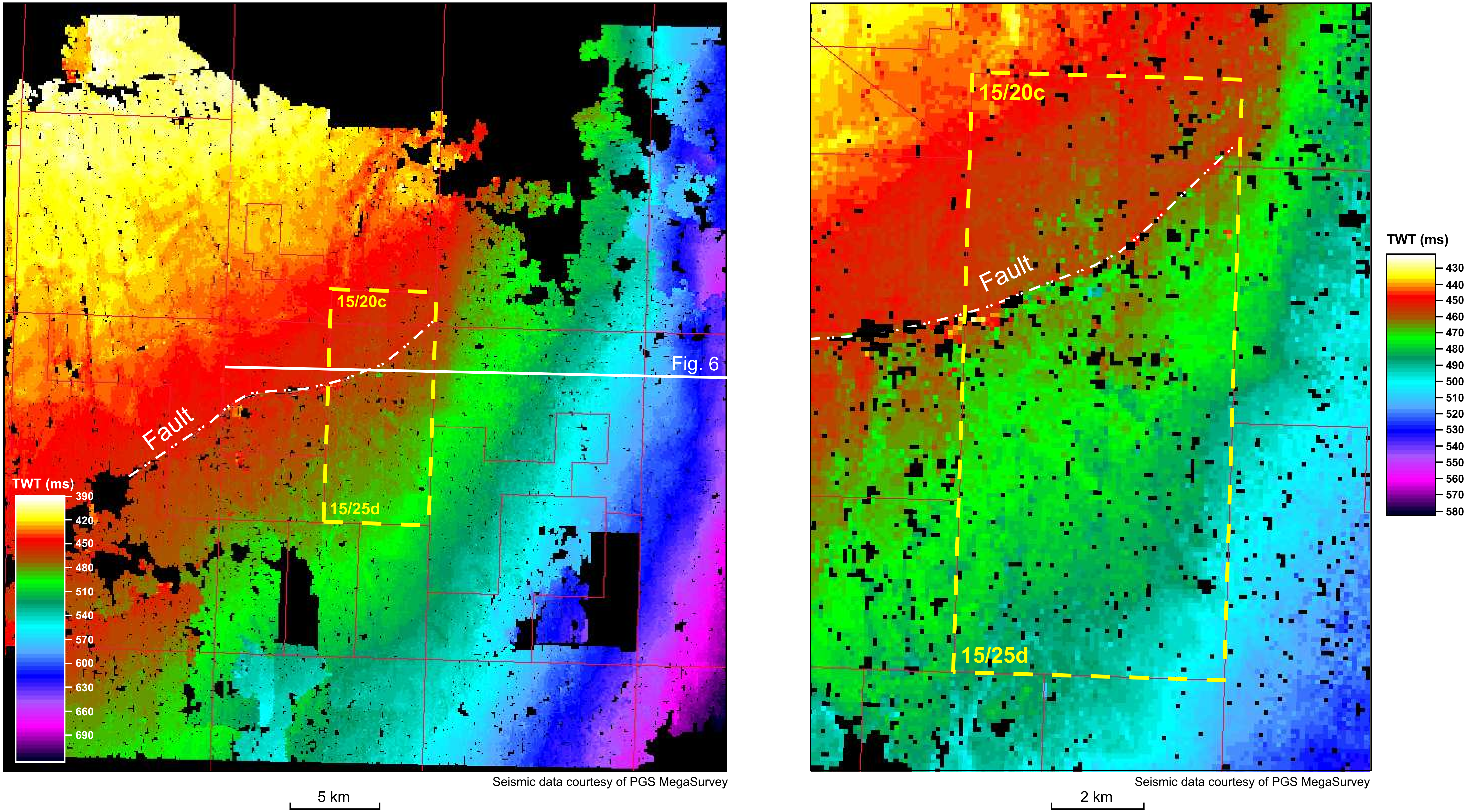
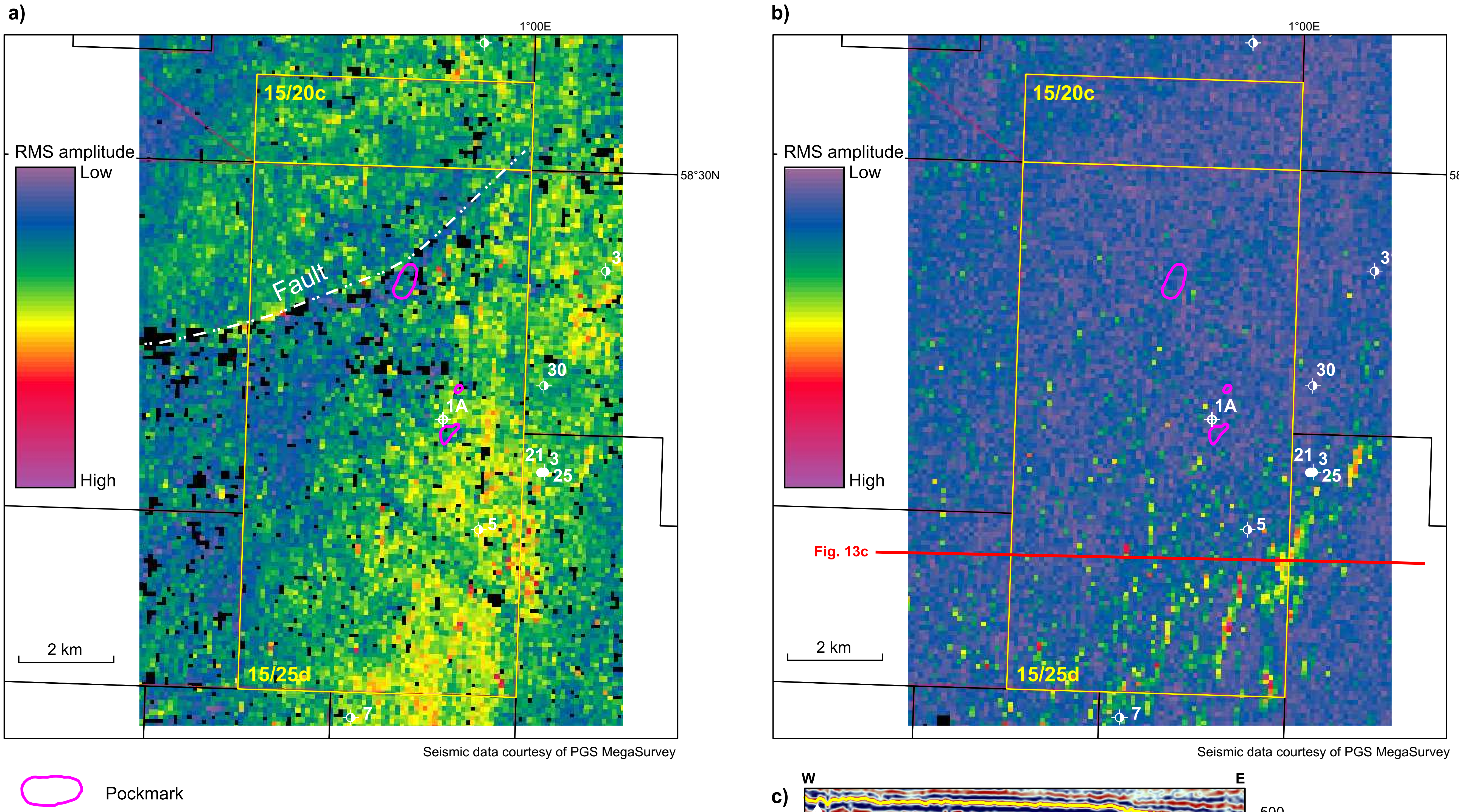


Figure 12 Autotracked ('zapped') near base Pleistocene reflector showing NE-SW oriented fault extending across the north of block 15/25d.



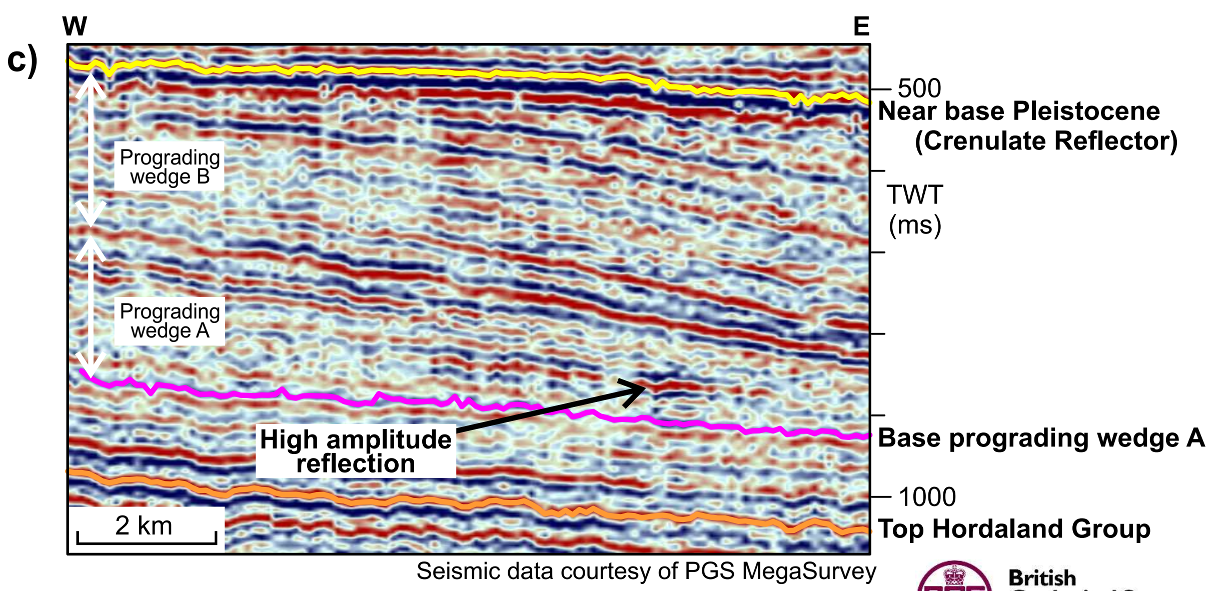


Figure 13 a) RMS amplitude extraction for the Mid-Late Miocene to Pliocene interval, b) RMS amplitude extraction for the basal part of prograding wedge A, c) Trace 23048 (mcns_100) across the amplitude anomaly within prograding wedge A.