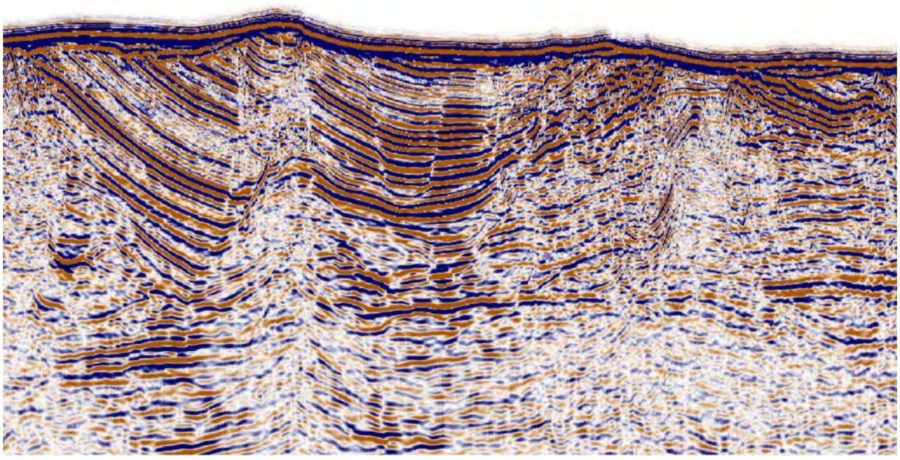
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

A geological interpretation of the nearshore area between Belfast Lough and Cushendun, Northern Ireland, utilising a newly acquired 2D seismic dataset to explore for salt layers for possible gas storage within man-made caverns.

Marine Geoscience Programme

Commissioned Report CR/10/069

Volume 1



Department of Enterprise, Trade and Investment
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Geological Survey of Northern Ireland

BRITISH GEOLOGICAL SURVEY

MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/10/069

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SW corner 999999,999999
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Map

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Front cover

Detail from newly acquired high resolution 2D seismic profile.

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MF Quinn, K Smith and J Bulat

Contributors/editors

H Johnson and D Reay

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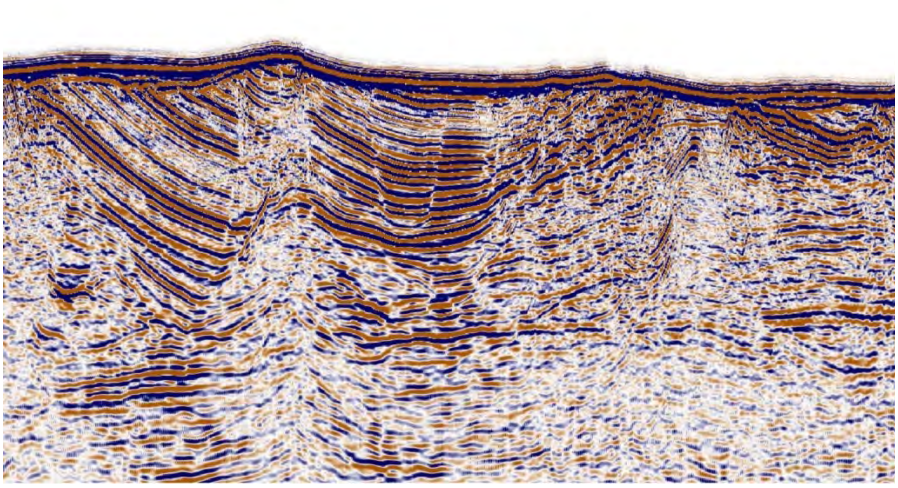

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British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

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Executive Summary

This report describes the geological interpretation of a newly acquired, high resolution, 2D seismic dataset located offshore Northern Ireland. The report represents the final stage of a Department of Enterprise, Trade and Investment (DETI)-sponsored study aimed at gaining a better understanding of the distribution and thickness of subsurface salt layers onshore and offshore Northern Ireland with a view to considering their potential for the construction of gas storage caverns.

Gas storage in salt beds in the Larne area – commercial opportunity and strategic need

Drilling results from the Larne No. 2 borehole completed in 1981, demonstrated the presence of thick salt layers in the Late Permian Belfast Group and Middle Triassic Mercia Mudstone Group successions onshore Northern Ireland. Natural gas storage caverns have been created in similar salt beds around the world and, following the publication of earlier reports (Reay, 2005 and Evans et al., 2006), there has been considerable commercial interest in the gas storage potential of the salt beds around Larne. The Northern Ireland energy market is highly dependent on natural gas, all of which is imported via the Scotland - Northern Ireland Pipeline (SNIP) which makes landfall in Northern Ireland on Islandmagee. Security of supply is, therefore, a major concern and there is a strategic need as well as a commercial opportunity for gas storage facilities in Northern Ireland. The salt beds in the Larne area appear to be unique in Ireland and the juxtaposition of the pipeline and the largest gas-fired power station in Northern Ireland (Ballylumford on Islandmagee) with these salt beds represents a favourable situation. Simultaneously with this study, private sector companies have concentrated on the evaluation of the salt beds in Larne Lough (Infrastrata plc) and onshore southwest of Larne (Bord Gáis and Storengy). These areas may prove to be suitable for the creation of gas storage caverns but, alternatively, geological, planning or environmental factors may preclude this, in which case the offshore area may become more attractive.

Rationale for the offshore seismic survey

There were indications that the salt beds extended offshore into the area off the Antrim coast and an earlier phase of this study mapped their likely extent from an interpretation of existing commercial seismic data in the North Channel. However, there was a significant gap between the existing seismic data coverage and the Antrim coast and it is this nearshore zone (within 10km of the coast) that is of greatest interest with regard to potential gas storage because the salt beds could be drilled from a surface location on land using directional drilling techniques. The construction of gas caverns in salt beds offshore using directional drilling would probably add significantly to the costs relative to an onshore facility but the geology might be more favourable (thicker salt beds, fewer faults or basaltic intrusions) and the increased distance from centres of population might be an advantage. It was, therefore, decided that the acquisition of new seismic reflection data in the nearshore area off the Antrim coast would allow the distribution and thickness of the salt beds to be assessed for their gas storage potential.

Seismic survey – acquisition and results

The seismic survey was designed to acquire high resolution data to image the Permian and Triassic salt bed intervals. Data acquisition parameters were constrained to some degree by the nearshore location with strong tides, shallow water depths and small islets – the safety of the survey vessel and other marine users were of paramount importance. The main effect of this was that the length of the hydrophone streamer was reduced to 1500 metres to increase vessel manoeuvrability and allow data acquisition closer to the coast although this was achieved at some loss of depth penetration. Data coverage would also be dependent on weather conditions and equipment performance so planning was based on a minimum survey layout that was thought achievable within the available budget (which equated to 13 days ship time). In the

event, the survey was carried out in good weather and sea conditions in September 2009, with only a small amount of equipment downtime, resulting in data coverage about 70% above the minimum. Operational constraints dictated that east-west lines were run away from the coast and, as a result, there is a data gap of about 2 km between the survey and the coastline. However, some of the NW-trending lines do come closer to shore. Data quality was generally very good, particularly in the shallower parts of the seismic sections, although the predicted increased density of faulting and basaltic intrusions and more complex geology towards the coast made interpretation difficult in places.

Interpretation of the newly acquired dataset shows that it is very likely that successions of both Permian and Triassic salt are present in the nearshore area offshore Larne, Northern Ireland. Additionally, at certain locations it is possible that the thickness of both Permian and Triassic salt units are greater than that recorded in the Larne No. 2 borehole and consequently have potential for the excavation of salt caverns for gas storage. The following conclusions build on those listed in a previous report (Quinn, 2008), which reported on the initial phase of this study.

Late Permian Belfast Group

- There is indirect evidence, based on the new seismic data, that the Late Permian Belfast Group halite, drilled in the onshore Larne No. 2 borehole, is present offshore in the Larne sub-basin. A seismic horizon, representing the Late Permian halite has been interpreted over much of the area and varies in depth from 300 m to over 2000 m below mean sea level (bmsl).

- A variation in depositional thickness of the Late Permian halite has been mapped over much of the study area. In particular, the halite is interpreted to thicken eastwards into the Larne sub-basin.

- Seismic mapping indicates that the interpreted salt-bearing interval within the Late Permian Belfast Group with potential for excavation of gas storage caverns shows little evidence of rapid thickness variation due to salt mobilisation (halokinesis) in the geological past.

- Two areas within the Larne sub-basin have been highlighted as containing potential sites for the excavation of salt caverns within the Late Permian halite.

    - The first area is defined by a general eastward thickening of the Late Permian halite interval from 300 m to 500 m and at depths of between 1600 and 2000 metres below mean sea level (bmsl).
    - The second area is located at the northern end of the South Maidens Fault where the Late Permian halite interval is interpreted to thicken adjacent to this major north-trending fault.

- North of the Larne sub-basin interpretation of the Late Permian halite is more difficult and although seismic mapping indicates that the halite is expected to attain thicknesses of around 300 m at some locations, these estimates of thickness are made with less confidence.

Middle Triassic Mercia Mudstone Group

- There is good circumstantial evidence, based on the new seismic data, that the Middle Triassic Mercia Mudstone halites, drilled in Larne No. 2 borehole, are present offshore in the Larne sub-basin. The structural style of the Middle Triassic succession is similar to that seen in other basins where salt layers are proven by drilling.

- Within the Middle Triassic Mercia Mudstone Group, the salt with potential for gas storage caverns occurs as salt swells due to post-depositional mobilisation of the salt.

- Two areas within the Larne sub-basin have been identified as containing potential sites for the excavation of salt caverns. Sites are expected to include a combination of Ballyboley and Fylde-equivalent halite and the overlying Carnduff halite.
  - At the first site, depth to top of the younger Carnduff halite is interpreted to vary between 280 to 320 metres bmsl and top Ballyboley halite between 580 to 660 metres bmsl. Thickness of the salt is interpreted to be between 310 to 340 metres.
  - At the second site the Top Carnduff halite lies at a depth of approximately 200 metres bmsl with an interpreted thickness of 225 metres.

- At these depths the Triassic halites are unlikely to be suitable for natural gas storage but may be suitable for Compressed Air Energy Storage (CAES) in caverns.

General conclusions

Following the identification of the potential of the Triassic and Permian salt for construction of salt caverns the next step should be a focussing of effort in the areas highlighted in this report to ultimately identify sites for the drilling of a test well. Several tasks are necessary prior to drilling this well:

- Improve depth-conversion over the area of interest by building a full velocity model covering the whole study area;

- Focussed interpretation and depth-conversion over the area of interest;

- Investigate possibility of shallow drilling at key points in the area of interest to confirm some aspects of the current seismic interpretation.

The final and key recommendation of this study is that in order to move forward in the assessment of the potential of the offshore for excavation of salt caverns a well will ultimately need to be drilled in a specific location to test the potential of the salt interpreted in this report.

However, the most appropriate course of action may be to await the results of the exploration programmes in Larne Lough and the onshore area. Should any of the active private sector gas storage projects progress through to the development stage then the provision of strategic storage within the commercial facility should be a policy priority for the Northern Ireland government. The offshore area should be considered as a lower priority area because of the greater costs and technical complexity associated with the construction of salt cavern storage facilities here. The results of this survey should be made available to the private sector companies currently involved in exploration onshore and in Larne Lough to assist them in their interpretation of their seismic data and modelling of the 3D subsurface geology of the area.

1 Introduction

This report details the geological interpretation of a high resolution 2D seismic dataset located offshore Northern Ireland between Belfast Lough in the south and the town of Cushendun in the north (Figure 1) and acquired on behalf of Department of Enterprise, Trade and Investment (DETI). The study area is defined by the limits of this newly acquired 2D seismic dataset (Figure 1). Onshore the Larne No. 2 borehole, drilled by IGS (now BGS) and the Department of Energy (now DECC) in 1981, proved the presence of 113 metres of Late Permian halite and three thinner Triassic halite units. This evidence provided initial encouragement for the possibility of gas storage in the salt layers if such salts were more thickly developed in the offshore basin. The geological interpretation presented in this report represents the final stage of a DETI-sponsored study aimed at gaining a better understanding of the disposition of subsurface salt layers offshore Northern Ireland; principally comprising the Late Permian halite, but also Middle Triassic halite successions, with a view to considering their potential for the construction of gas storage caverns.

The acquisition and processing of the new high resolution 2D seismic dataset was managed by BGS on behalf of the DETI. The methodologies and results from this survey work are the subject of several reports produced by sub-contractors and these are referenced below. Survey acquisition parameters were chosen to best image the subsurface down to 1.5 seconds Two-Way-Travel-Time (TWTT) taking into account the geological successions expected to be present, the bathymetry and the nearshore location of the survey (Appendix 1). Acquisition of the dataset was sub-contracted to Fugro Survey Limited after a tendering exercise advertised through the European Journal and with contractual procedures overseen by Research Councils UK (RCUK). The new survey was planned to extend as close as possible to the coast, but this aim was constrained by safety, technical and environmental factors (Fugro Survey Ltd, 2009; MSeis, 2009). In the north, the survey is closest to the coast at the headland between the towns of Carnlough and Cushendun where it comes to within 0.8 kilometres of the shore. In the south it lies 1 kilometre from the shore at Islandmagee (Figure 1). Processing of the new dataset was sub-contracted, after a further tendering exercise, to Fugro Seismic Imaging Limited, with all stages of the processing closely managed by BGS personnel (Fugro Seismic Imaging Ltd, 2010). The easy lines of communication between the survey acquisition personnel and the processing team facilitated the processing workflow. The resultant dataset provides a wealth of new information on the nearshore subsurface geology offshore Northern Ireland and this forms the basis for this interpretation report.

Along with the acquisition of the 2D seismic survey, multibeam sonar survey data were acquired along each track line and these data have been reported on separately (Gafeira, 2010). Interpretation of the two datasets also took place concurrently such that each interpretation benefited from reference to the other.

The overall study comprised three broad tasks, as specified within two DETI contracts. These tasks, detailed in section 1.1 below, may be briefly summarised as:

- Task 1, interpretation of pre-existing seismic datasets and report;
- Task 2, acquisition and processing of the new high resolution 2D seismic dataset and data acquisition reports;
- Task 3, interpretation of the new high resolution data and final reports.

This report, and its companion report (Gafeira, 2010), are the main deliverables for Task 3 of this study. This report comprises two volumes, the first volume details methodology and results of the geological interpretation accompanied by explanatory figures. It highlights locations where the salt succession is interpreted to be thicker than that drilled in the Larne No. 2 borehole, and which therefore have potential for further investigation as possible sites for gas storage caverns.

The second volume of this report comprises all the maps generated and summary map/seismic profile montages of the most promising offshore locations for cavern development. In this report, the more specific term ‘halite’ and generic term ‘salt’ are used interchangeably.

1.1 HISTORY OF THE PROJECT

This project commenced in early 2007, when the DETI commissioned a BGS study aimed at obtaining a better understanding of the distribution of subsurface units of salt suitable for the storage of natural gas in excavated caverns. The nearshore area close to the town of Larne and Islandmagee and north towards Carnlough was an area of particular interest. The study was divided into three tasks:

- Task 1 would entail the purchase and rapid interpretation of pre-existing 2D commercial seismic datasets which originally had been acquired for the purpose of oil and gas exploration to understand the regional geology and seek further encouragement for the development of the Permo-Triassic halite units.
- Task 2 would comprise the acquisition and processing of a new high resolution seismic dataset located in the nearshore area, between the existing seismic datasets and the coast of Northern Ireland and whose limits would be informed by results of the Task 1 interpretation;
- Task 3 would comprise the interpretation of the newly acquired high resolution dataset leading to an interpretation of the distribution of possible salt units with the potential for gas storage.

Task 1 was completed and a report presented to DETI in May 2008. Task 2 commenced with the selection of the seismic acquisition contractor and preparations for the survey acquisition. However, delays in the availability of a seismic vessel led to the cruise being postponed due to concerns over potential weather downtime as winter approached. In hindsight, this decision proved to be prudent because the weather conditions during the scheduled survey period were indeed very poor and it is unlikely that much good quality data would have been acquired although the full contract costs would have been incurred (it should be noted that there is relatively little difference between the daily standby and survey rates of a survey vessel).

In early 2009, BGS agreed a new contract with DETI that enabled Tasks 2 and 3 to be completed. The availability of project funds in early 2009 allowed the tender procedure to be carried out earlier in the year which gave a greater probability that the survey could be carried out during the late summer – early autumn better weather window. Task 2 began with the submission of a tender in the European Journal for a contractor who would carry out the acquisition of the new seismic dataset. The tender was written by a small team comprising BGS personnel and a specialist seismic consultant. They specified the survey acquisition parameters (Appendix 1) and limits and assessed the different commercial bids under the guidance of a RCUK contracts specialist. The seismic acquisition took place in September 2009 and is the subject of several reports (e.g. MSeis, 2009; Fugro Survey Ltd, 2009). Concurrent with the seismic survey, a specialist company was contracted to process the newly acquired data and this was completed in early 2010 (Fugro Seismic Imaging Ltd, 2010). Nearly 1000 line kilometres of data was acquired against a target minimum of approximately 580 kilometres. The additional data acquisition inevitably increased the time needed for both processing and the subsequent seismic interpretation.

Task 3 comprised the interpretation of the newly acquired high resolution 2D seismic dataset and companion multibeam survey. These interpretations are now complete and full details of methodologies adopted and results, including sets of maps and recommendations, are presented in this report and within the companion report (Gafeira, 2010).

2 Data and interpretation methodology

The newly acquired high resolution 2D dataset helps to fill the gap in available data between the commercial 2D seismic data acquired for oil and gas exploration and the coast of Northern Ireland. The new seismic survey was specifically located and designed to best image the subsurface at the depth in which the salt layers were considered likely to be developed. The geological interpretation reported on here builds on the earlier Task 1 interpretation (Figure 2; Quinn, 2008). However, production of a unified set of maps incorporating the earlier Task 1 interpretation and this new interpretation is beyond the scope of this project.

2.1 HIGH RESOLUTION 2D SEISMIC DATA

The new survey covers an area of approximately 1000 km^2 with a tighter seismic grid in the south which had been identified as the most prospective area for salt cavern storage. The dataset comprises nearly 1000 km of high resolution 2D seismic comprising 80 profiles of which 10 are divided into part lines (Figure 1; Enclosure 1). Before acquisition, the survey area was divided into a southern high priority area, with a higher density of seismic track lines, and a northern lower priority area, based partly on conclusions drawn from the Task 1 interpretation (Figure 3; Quinn, 2008). The new survey area is subjected to strong north-south tidal currents that could potentially cause distortion (feathering) of the seismic streamer array beyond acceptable limits. Additionally, the nearshore location of the new survey placed constraints on line location and orientation. These factors meant that decisions had to be made during survey operation regarding the sequencing of the line acquisition, depending on the tidal situation and location of vessel in relation to shore and other marine user activity. The prioritisation of the survey area also helped guide such decisions. The orientation of the profiles is generally NW-SE and ENE-WSW but lines were also shot to link the northern area with the southern area and tie with the pre-existing seismic datasets (Enclosure 1; Figure 2; MSeis, 2009). Acquisition of these data and the acquisition parameters are detailed in separate reports (Fugro Survey Ltd, 2009; MSeis, 2009).

The quality of the new seismic data is generally of a high standard, but due to the complexity of the geology, the continuity and resolution of events at different levels varies along and between each line. This complexity is derived from the area having experienced phases of uplift and erosion resulting in sedimentary rocks with abnormally high interval velocities for their present shallow depth of burial. In addition, these sedimentary rocks have dips varying from horizontal to very high angles and are frequently intruded, to varying degrees, by Palaeogene igneous rocks. These factors have contributed to the dissipation and dispersion of the energy generated from the airgun source arrays and have reduced seismic penetration to deeper levels.

2.2 ONSHORE BOREHOLES AND OFFSHORE WELL

Offshore commercial well 111/15-1, located in the far south of the Portpatrick sub-basin, is the only deep borehole within the offshore project area (Figure 2). Interval velocity data from this well were used to carry out the depth conversion for Task 1 (Quinn, 2008). There are no BGS offshore shallow boreholes in the Task 3 study area. Onshore several boreholes, in particular Larne No. 2, provide geological information to this study which is summarised in Figure 4. Larne No. 2 also provided interval velocity information which was used as a starting point for building the velocity model necessary for processing of the new seismic dataset. The stratigraphy at Larne No. 2 is summarised in Figure 5 and described more fully in the Task 1 report (Quinn, 2008).

2.3 INTERPRETATION OF SEISMIC HORIZONS

It is important to emphasize that no well penetrations exist within the new survey area and consequently direct ties between the new seismic lines and a ‘ground-truthed’ geological succession were not possible. The closest tie is provided by onshore borehole Larne No. 2 lying approximately 10 km to the west of the centre of the new survey (Figure 1). Two-Way-Travel-Times (TWTT) between the stratigraphic successions penetrated in this borehole were compared to events imaged on the new seismic data and this, coupled with matching the character of the seismic packages and an understanding of the regional geological relationships, enabled stratigraphic horizons to be identified (Table 1). A total of 7 seismic horizons were picked over the entire survey area - Base Permian Variscan Unconformity, Top Magnesian Limestone Formation, Top White Brae Mudstone halite unit, Top Sherwood Sandstone Group, Top Ballyboley Halite Member, Top Carnduff Halite Member and Top Larne Halite Member. In addition, numerous igneous intrusive sills and dykes were interpreted over the area. The Base Carnduff Halite and other events were picked locally to aid in the interpretation.

Mapped horizon	Depth to top of mapped horizon in metres below KB	Two-Way-Travel-Time in seconds to top of mapped horizon	Two-Way-Travel-Time in milliseconds(msecs) between mapped horizons
Top Larne Halite Member	267.0 m	0.1538 seconds	175.5 msecs
Top Carnduff Halite Member	628.2 m	0.3293 seconds	121.8 msecs
Top Ballyboley Halite Member	871.2 m	0.4511 seconds	46.7 msecs
Top Sherwood Sandstone Group	967.7 m	0.4978 seconds	324.6 msecs
Top White Brae Mudstone halite unit (Near Top Late Permian salt)	1682.2 m	0.85 seconds	52.8 msecs (to top of clean halite)
Top Magnesian Limestone Formation	1801.4 m	0.9028 seconds	>450.4 msecs
Total depth reached within the Lower Permian	2877.3 m	1.3532 seconds	

Table 1. Depths, two-way-travel-times (TWTT) and TWTT intervals at Larne No. 2.

Six depth structure maps and an isopach map of the Late Permian halite, all at a scale of 1:75,000, are presented in this report and are listed below.

2.3.1 Variscan Unconformity (Base Permian) (Figure 6; Enclosure 2)

A Variscan Unconformity horizon, marking the base of the Permian, was interpreted, with varying degrees of confidence, over the new survey area. The horizon defines the maximum depth and structure of the Permo-Triassic basins. The horizon locally exhibits the characteristics of an angular unconformity, with a more steeply dipping pre-Permian succession (Figure 7 and Figure 8). The Lower Permian seismic package, bounded by the Variscan Unconformity horizon below and overlain by a much stronger Top Magnesian Limestone Formation reflector (section 2.3.2), varies in character with some areas containing strong relatively continuous events (Figure 8) and in other areas being relatively transparent (Figure 7). This may reflect a change in lithology or alternatively may be due to the lower penetration of seismic energy in some areas.

2.3.2 Top Magnesian Limestone Formation (Figure 9; Enclosure 3)

The Top Magnesian Limestone horizon is a strong and continuous seismic marker onshore and occurs at a TWTT of 0.903 seconds in the Larne No. 2 borehole. Comparison with nearby onshore seismic data, where the Top Magnesian Limestone Formation horizon is strongly imaged and has been tied to the Larne No. 2 borehole, enabled this horizon to be recognised with some confidence in the new offshore seismic data. In addition, on new offshore survey lines closest to Larne No. 2 borehole, this horizon can be recognised at approximately the TWTT at which the horizon has been logged in this borehole providing further confidence to the interpretation (Figure 7 and Figure 8).

2.3.3 Top White Brae Mudstone Formation halite unit (Figure 10; Enclosure 4)

In Larne No.2 the top of the White Brae Mudstone Formation (named Permian Upper Marls in the borehole) is located 80 millseconds (msecs) TWTT above the Magnesian Limestone (Table 1). The top of the clean halite within the White Brae Mudstone Formation, at 53 msecs TWTT above the Magnesian Limestone, exhibits a sharp increase in velocity and it is this velocity contrast which is likely to be imaged on the seismic data rather than the top of the formation (Table 1). Confidence regarding the position of the Magnesian Limestone horizon (section 2.3.2) enabled the top of the Late Permian halite to be interpreted in some areas (e.g. Figure 7, Figure 8 and Figure 11). However, the seismic package above the Magnesian Limestone Formation seismic horizon was not of a consistent or recognisable character to enable the top of the Late Permian halite horizon to be located and followed with any confidence over the whole of the study area. This is in accord with the situation onshore where the top of the halite unit can only be picked in some places on recent 2D and 3D seismic surveys around Larne and in Larne Lough, respectively. Where possible, a guide horizon has been interpreted and the resulting depth map approximates to the top of the Late Permian halite unit. An area where the seismic data is poorly resolved is immediately SW of the Maidens Igneous Complex, and as a result the Permian salt was not mapped on several seismic lines at this location (Figure 10; Enclosure 4). This area is of interest to this study because of its closeness to the coast near the town of Larne and the Larne No. 2 borehole. Enclosure 5 shows examples of seismic lines across this area, illustrating the difficulties in interpretation at Late Permian halite level, due primarily to the high concentration of igneous sills and associated dykes.

An estimate of the thickness of the Late Permian halite succession **(Figure 12; Enclosure 6)**, has been derived from the product of the One-Way-Travel-Time (OWTT) difference between top Magnesian Limestone Formation and top of the White Brae Mudstone Formation halite unit horizons and the interval velocity of the halite succession as derived from the Larne No. 2 borehole (4515 metres/sec). The thickness will reflect the uncertainty relating to the top Late Permian halite interpretation. This map should be considered to be a guide to thickness trends rather than for absolute halite thickness values.

2.3.4 Top Sherwood Sandstone Group (Figure 13; Enclosure 7)

The top of the Sherwood Sandstone Group marks the base of the Mercia Mudstone Group (MMG) and recognition of the MMG seismic package helps to identify this horizon. The MMG is a distinctive seismic package on the majority of the new seismic profiles (Figure 11 and Figure 14). The Top Sherwood Sandstone Group horizon was picked at the base of this distinctive package and with reference to its TWTT (405 msecs) above the Magnesian Limestone Formation in the Larne No. 2 borehole (Table 1).

2.3.5 Top Ballyboley Halite Member (Figure 15; Enclosure 8)

The Ballyboley Halite Member of the Craiganee Formation (Figure 4) includes the deepest of the three Triassic halite units proved in the Larne No. 2 borehole and occurs 46 msecs above the top of the Top Sherwood Sandstone Group in this borehole (Table 1). A horizon at this approximate position was identified on selected new seismic profiles closest to the Larne No. 2 borehole where sedimentary layers appeared undisturbed (Figure 11). This tie facilitated the interpretation of this horizon over a large part of the Larne sub-basin.

2.3.6 Top Carnduff Halite Member (Figure 16; Enclosure 9)

In the Larne No.2 borehole, the Carnduff Halite Member of the Craiganee Formation (Figure 4 and Figure 5) includes 65 metres of halite with only minor siltstone partings and is the thickest and cleanest of the three Triassic halite members drilled in the borehole. The top of the member occurs 168 msecs TWTT above the Sherwood Sandstone Group (Table 1) and a horizon, at this approximate position was tied on seismic profiles (Figure 11) closest to the Larne No. 2 borehole where sedimentary layers appeared undisturbed and then picked over a large part of the Larne sub-basin. Because of the relatively homogenous nature of the halite succession, a seismic package with no internal reflections may be anticipated where a clean halite bed is present. On some seismic lines, a relatively transparent seismic package, approximately corresponding to expected thickness of the Carnduff Halite and at the expected TWTT location above the Sherwood Sandstone horizon was noted, however this was not a consistent occurrence and although it gave some confidence when interpreting this and other Triassic halite successions it could not be used as an unequivocal indicator of the presence of halite.

2.3.7 Top Larne Halite Member

Although a reflector thought to correspond to the top Larne Halite Member was interpreted where present over the study area, no maps have been produced as the member is expected to have little potential for gas storage, because its shallow depth reduces the likelihood of this halite being exploited for salt caverns. Distribution of the Larne Halite Member is similar to that of the Carnduff Halite Member for which maps have been produced.

2.3.8 Igneous intrusions

The Palaeogene igneous province is well documented onshore Northern Ireland (Cooper and Johnston, 2004). The main focus of igneous activity was located at three central complexes, the Mourne Mountains, Slieve Gullion and Carlingford, which all intrude the Southern Uplands-Down-Longford Terrane, and the Antrim Plateau where fissure eruptions produced a thick pile of basaltic lava flows. In addition, linear dyke swarms are widespread and well imaged on the Tellus dataset (Tellus, 2007) and sills have also been mapped onshore. The Larne No. 2 borehole drilled several dolerite intrusions located within the Late Permian and Middle Triassic succession (Figure 5).

Offshore, the Maidens and North Maidens igneous complexes separate the new survey area into northern and southern sectors and are sea bed manifestations of the high concentrations of igneous dykes and sills. Similar Palaeogene intrusions are interpreted to be present throughout the new survey area and are recognised on seismic data (Arter and Fagin, 1993) by very strong seismic reflections, their masking effect on the horizons underneath and commonly by their cross-cutting relationships with the sedimentary succession (e.g. Figure 7, Figure 11, Figure 14 and Figure 17)

Detailed mapping of all sills and dykes within the new survey area is beyond the scope of this report. However, igneous intrusions were mapped, where necessary, as part of the interpretation of the area in order to explain the often complicated bed relationships seen in the subsurface; once recognised as intrusions, the structure of the remaining horizons could be better understood. The intrusions tend to be most common, or at least best imaged, within the Middle Triassic Mercia Mudstone Group (Figure 17) and their occurrence appears to increase adjacent to the Maidens Igneous complex. Replacement of salt units by igneous intrusions has been observed further south in the East Irish Sea Basin (Arter and Fagin, 1993) and several examples of interpreted igneous intrusions following bedding planes within the Mercia Mudstone Group have been recorded in the new dataset (e.g. Figure 7, Figure 8, Figure 14 and Figure 17).

A prominent NNW-trending linear raised feature imaged on the new multibeam dataset has been mapped at sea bed (Gafeira, 2010, Figure 24) and is also seen in cross-section on several of the new seismic profiles (e.g. Figure 18). This structure was also imaged on commercial seismic profile NC-92-18A interpreted for Task 1 of this project; magnetic modelling interpreted the feature as a steeply dipping igneous dyke (Figure 31 in Quinn, 2008).

2.4 DEPTH CONVERSION

Depth conversion of the two-way-time dataset in the Task 1 interpretation report (Quinn, 2008) was based upon interval velocity data from commercial well 111/15-1 (Figure 2). The newly acquired seismic dataset covers the nearshore part of the Larne sub-basin and the area north of this and velocity data from the relatively distant well 111/15-1 may not be typical of the interval velocities expected in the study area. Onshore, velocity data is available from the Larne No. 2 and Newmill No. 1 boreholes. However, for depth conversion in this study, stacking velocities from the new survey were utilised to derive a time-depth relationship that could be used to depth convert the two-way–time data. BGS was closely involved with the processing of the new dataset and have confidence in the quality of the stacking velocities used. Nevertheless, examination of stacking velocities from the new seismic dataset does show a wide variation of interval velocity for any given two-way time value. These variations are indicative of the complex geology of the area. Only a full velocity model based on all the stacking velocities available, which is beyond the scope of this project, would come close to reflecting this ‘real world’ complexity. A more detailed discussion and details of the depth conversion are given in Appendix 2 of this report.

3 Geological structure of the new survey area

The regional structural framework and the geological structure of the wider project area interpreted in Task 1 of this study is detailed in Quinn, 2008. Consequently, this report concentrates on the structure within the newly acquired survey area. The study area is defined by the limits of the newly acquired 2D seismic dataset (Figure 1) and may be divided in terms of its geological structure into a northern and southern sector, separated by an uplifted fault-bounded block that is characterised at seabed by outcrops of igneous rocks (the Maidens and North Maidens Bank areas) and in the subsurface by a high concentration of igneous sills and dykes (Figure 3). The southern area comprises the nearshore part of the Larne sub-basin whereas the area to the north comprises the Maidens Igneous Complexes and the western extension of the south west Arran sub-basin (Figure 3).

3.1 SOUTHERN AREA: THE LARNE SUB-BASIN

The ENE-trending Larne sub-basin extends westwards onshore Northern Ireland where it is separated from the Lough Neagh sub-basin by an intervening structural high (Shelton, 1997). To the south, the Larne sub-basin is separated from the Portpatrick sub-basin by the Southern Upland Fault Zone. The polarity of these two sub-basins is reversed across this major lineament such that the Portpatrick sub-basin dips eastwards into the NW-trending Portpatrick Fault and the Larne sub-basin dips westwards on to a series of NW-trending faults (Quinn, 2008). To the east, the Larne sub-basin is separated from the Clyde sub-basins by a fault-bounded high.

The style of faulting developed within the Larne sub-basin, in response to Permo-Triassic extensional episodes, has been controlled to a large extent by the presence of halite layers within the Middle Triassic and Late Permian successions. These halite layers have acted as zones of detachment within which the faults tend to sole out. This has resulted in a threefold structural division of the Permo-Triassic succession. The middle component, the Early Triassic Sherwood Sandstone Group, acts as a thick, relatively unfaulted competent slab sandwiched between a thick Late Permian halite beneath and the interbedded halite-mudstone succession of the Middle Triassic Mercia Mudstone Group (MMG) above (see also Chadwick et al., 2001). Within the MMG two main fault trends are apparent. Firstly, an approximately NNW-trending series of faults (Figure 15 and Figure 16; Enclosures 8 and 9) are interpreted to have detached within the Ballyboley or Fylde-equivalent Halite members (Figure 17 and Figure 18). Blocks of undisturbed MMG sediments are observed that appear to have collapsed due to withdrawal of the mobile halite, the latter forming small swells between the undisturbed succession (e.g. Figure 18 Shotpoints 300-560). Penge et al. (1999) describe similar features and mechanisms in other parts of the UKCS including the East Irish Sea Basin. Secondly, a major curved low angle fault within the MMG in the south of the area is interpreted as having been formed by detachment on the Ballyboley or Fylde halite in response to Tertiary uplift to the south of the area in an example of gravity driven tectonics (see Clark et al., 1998) (Figure 15 and Figure 16; Enclosures 8 and 9). However, very few faults pass from the MMG into the underlying Sherwood Sandstone Group.

The interpreted White Brae Mudstone Formation halite unit shows little evidence of mobilisation on the interpreted seismic profiles. Although there is some evidence of faults within the more competent Sherwood Sandstone Group which detach within the Late Permian halite (Figure 19 and Figure 20), the more major faults show displacement of both the Lower Triassic Sandstone Group and Permian successions (Figure 11). The NNW-trending faults mapped in the Middle Triassic Mercia Mudstone Group may have formed to compensate for extension on a major N-trending fault further to the west (Figure 11), that displaces the Magnesian Limestone Formation and Variscan Unconformity horizons by up to 162 and 186 msecs TWTT (500 and 700 metres) respectively (Figure 6 and Figure 9; Enclosures 2 and 3). This fault, located close to the Maidens Igneous Complex, is informally named here the South Maidens Fault (Figure 3). The dominant trend of the major faults that displace the Permian and the older succession varies between NNW and NNE. The longest fault in the Larne sub-basin is approximately 8 kilometres while others are less than 2 kilometres in length (Figure 6; Enclosure 2). The style of faulting described above, whereby widely-spaced major normal faults affect the SSG and Permian interval but extension in the MMG is accommodated by means of smaller closer-spaced faults which sole out along detachment zones within halites, is also seen to the west in Larne Lough and onshore.

3.2 NORTHERN AREA: THE MAIDENS AND WESTERLY EXTENSION OF SW ARRAN SUB-BASIN

The Maidens and North Maidens igneous complexes are hazards to shipping due to the subcrop of igneous intrusions at sea bed and as a result no seismic lines could be acquired over or close to these features. These complexes, situated within a fault-bounded uplifted block, separate the Larne sub-basin to the south and westerly extension of the South West (SW) Arran sub-basin to the north, and their structural relationship with these two areas is described here. Some of the seismic lines acquired adjacent to the Maidens igneous complex are difficult to interpret due to a lack of continuous reflectors and an often chaotic appearance presumed to be due to the large number of cross-cutting igneous intrusions disrupting the sedimentary succession (Figure 21). As a result of these imaging problems, it is difficult to define the relationship this area has with the Larne sub-basin to the south but it is likely, from the mapping carried out here, that the boundary is defined by a generally NE to NNE-trending fault (or faults) (e.g. Figure 6; Enclosure 2). However, the boundary with the SW Arran sub-basin is better defined with seismic horizons gently shallowing to the north before being faulted down by a series of major faults with a dominant NE Caledonoid trend (e.g. Figure 6 and Figure 9; Enclosures 2 and 3). The faults have throws of up to 350 msecs TWTT (approximately 1100 metres) generally throwing down to the north. Faults with this trend are relatively continuous with mapped lengths in excess of 8 kilometres. One of these NE-trending faults is associated with a prominent NE-trending scarp at sea bed along part of its length (Figure 22; Gafeira, 2010). Although this fault appears to throw down to the NW, the positive feature at sea bed sits on its down-thrown side suggesting recent reverse reactivation. Thickness variation in recent sediments show a thinner succession on what would have been the upthrown side of the fault, suggesting footwall erosion prior to reverse reactivation (Figure 22). To the south of these NE-trending faults Middle Triassic MMG formations are either thin or absent. In contrast, MMG formations are preserved in the down-faulted areas which together form a westerly extension to the SW Arran sub-basin (Figure 14).

In the area of the Maidens igneous complexes and the SW Arran sub-basin, there is little evidence of the tripartite subsurface structural divisions caused by detachment of faults within Middle Triassic and Late Permian salt seen in the Larne sub-basin. This may be due to a number of factors including the generally shallower depth of burial, with the result that the Larne and Carnduff halite members are often absent, a less well-developed succession of the Triassic halite (see section 4.4.1), and the different trend of the major faults.

4 Interpreted sedimentary fill in the new survey area

The interpretation of the newly acquired high resolution 2D seismic data has enabled the geological succession in the nearshore area east of Northern Ireland to be mapped in far greater detail than ever before. However, there are no offshore wells within the study area, and consequently the lithological succession must be interpreted on the basis of evidence from nearby onshore boreholes, particularly Larne No. 2 (Figure 5), onshore seismic profiles, outcrop sections and relatively distant offshore well penetrations, such as well 111/15-1, in the Portpatrick sub-basin (Figure 2). The presence of the Late Permian salt succession interpreted offshore in the study area is based on regional palaeogeographical considerations and a very small number of possible salt mobilisation structures seen on the seismic data (Figure 19 and Figure 20). For the Middle Triassic, there is very good structural evidence for the presence of salt layers and this has been described in the preceding structural section (3.1). Further evidence for the presence of salt within the Mercia Mudstone Group (MMG) is seen from mapped depressions in the sea bed, imaged on the new multibeam data and interpreted as being caused by dissolution of salt layers (Figure 23; Gafeira, 2010, Figure 25).

The interpreted succession offshore is summarised in Figure 4 and a detailed description of the preserved sedimentary fill within the entire Larne and Portpatrick sub-basins has been reported elsewhere (Quinn, 2008). The following sections describe the sedimentary fill interpreted within the study area on the basis of evidence from the newly acquired seismic dataset.

4.1 LOWER PERMIAN ENLER GROUP

Maps of the Variscan (Base Permian) Unconformity and Magnesian Limestone Formation (Late Permian) seismic horizons have been produced that approximate to the top and base of the Enler Group respectively (Figure 6 and Figure 9; Enclosures 2 and 3). The interpreted thickness of the Lower Permian in the study area is significantly less than the total thickness of 1056.5 metres (442 msec TWTT) attained in the Larne No. 2 borehole, which did not reach the base of the Lower Permian. However, Larne No. 2 drilled a 554 metre succession comprising basaltic lavas, tuffs and tuffaceous sandstone. The lavas may be areally restricted (they are not present in Newmill No. 1) and may not extend much beyond Larne into the nearshore area. In contrast, the nearshore succession is interpreted to be comprised predominantly of interbedded dune and fluvial sandstones of the Ballytober Sandstone Formation (Figure 4).

In the Larne sub-basin, the depth below mean sea level (bmsl) to the base of the Permian succession varies from approximately 2000 metres on the footwall of the major north-trending South Maidens Fault in the west, to a maximum, in the east of the study area, of over 3300 metres. Although quite variable in detail, the thickness of the Lower Permian succession is interpreted to generally increase eastwards from about 400 metres on the footwall of the South Maidens Fault to nearly 1000 metres on the eastern edge of the study area. Along the southern margins of the sub-basin the Variscan Unconformity horizon lies at about 1000 metres with a minimum depth of 600 metres being attained in the far south-west (Figure 6; Enclosure 2). The Lower Permian succession is thinner towards the south, but no onlap on to the Variscan Unconformity is observed, and the succession maintains a thickness of between 200 and 300 metres to the southern boundary of the study area.

North of the Larne sub-basin the Lower Permian succession is present in an uplifted fault-bounded block (horst) where a high concentration of igneous sills and dykes associated with the Maidens Igneous Complex tends to obscure seismic events and results in a less certain interpretation of the deeper geology (Figure 21). Here, the Variscan Unconformity lies at depths of approximately 1600 metres. Northwards, it shallows to 800 metres against the NE-trending fault that lies north and west of the Maidens and North Maidens Igneous complexes respectively. On the fault-bounded block, the Lower Permian succession thins markedly towards the east and may be very thin or absent on the eastern edge of the study area with the Late Permian Magnesian Limestone horizon overstepping the pre-Permian topography (Figure 24). To the north of the Maidens horst, the Lower Permian succession is faulted down on a series of NE-trending faults with the Variscan Unconformity horizon reaching a maximum depth of 2500 metres before gradually shallowing northwards towards the Highland Border Ridge (located outside the study area). The Lower Permian succession is interpreted to be absent in the north of the area (Figure 6; Enclosure 2) where the Variscan Unconformity is onlapped by the Magnesian Limestone Formation horizon (Figure 25).

4.2 LATE PERMIAN BELFAST GROUP

In the Larne No. 2 borehole, the Late Permian Belfast Group (Top ~1600, Base ~1800 metres bmsl) is represented by the White Brae Mudstone Formation, consisting of 113 metres of pure halite overlain by 72 metres of Late Permian siltstone and mudstone, resting directly on 22 metres of the Magnesian Limestone Formation comprising a dolomitic unit, here intruded by doleritic intrusions, overlain by anhydrite (Figure 4 and Figure 5). In the nearshore Larne sub-basin, the Magnesian Limestone Formation reaches a maximum depth of 2600 metres below mean sea level (bmsl) while on the footwall of the South Maidens Fault it lies at a depth of around 1600 metres (bmsl) shallowing to approximately 500 metres (bmsl) along the southern margins of the sub-basin (Figure 9; Enclosure 3). Based on the two-way-travel-time (TWTT) information from the Larne No. 2 borehole and the position of the Magnesian Limestone Formation horizon (Section 2.3.3), the top of the Late Permian halite has been mapped over most of the Larne sub-basin where it reaches a maximum depth of approximately 2100 m.

The isopach map of the Late Permian halite interval (section 2.3.3) generally shows little thickness variation, the succession being between 100 and 200 metres over much of the area, and there is little evidence on the seismic data for post-depositional mobilisation of the Late Permian salt. Two possible examples of mobilisation within the Late Permian salt are shown in Figure 19 and Figure 20. However, there does appear to be a slight eastward, primary depositional, thickening of this Late Permian succession to more than 300 metres, reaching a maximum of nearly 600 metres at one location. At this location, the Top Late Permian halite horizon has been interpreted as thickening across a major N-trending fault (Figure 26). The top of the Late Permian halite horizon shallows towards the southern edge of the Larne sub-basin to depths of 1000 metres or less, and here, on some seismic lines, the Late Permian salt has been interpreted to thin and pinch-out onto the Late Permian Magnesian Limestone horizon (Figure 20). This may be similar to the situation onshore where the Newmill No. 1 well, to the south of Larne, where no Late Permian salt was present (although there is a possibility that it is cut out by a fault here). Elsewhere the event could not be discerned and the relationship of the Late Permian salt with the underlying reflectors could not be ascertained.

North of the Larne sub-basin, the Magnesian Limestone Formation shallows northwards from approximately 1300 metres (bmsl) to 600 metres (bmsl) over the Maidens Igneous Complexes fault block. In the westerly extension of the SW Arran sub-basin it reaches a maximum depth of 2200 metres (bmsl) in the hanging wall of a major NE-trending fault (Figure 9; Enclosure 3). The Late Permian halite horizon could not be interpreted adjacent to the Maidens Igneous Complex due to the poor quality of the seismic data, but north of this, it shallows from approximately 1000 metres (bmsl) on the footwall of the fault bounding the Larne sub-basin to approximately 500 metres adjacent to the northerly bounding fault (Figure 10; Enclosure 4). The thickness of the Late Permian halite on this block is expected to be less than 200 metres. In the westerly extension of the SW Arran sub-basin thicknesses may vary between 100 to 300 metres at depths ranging from between 1000 to 2000 metres (Figure 12; Enclosure 6 and Figure 10; Enclosure 4).

4.3 EARLY TO MIDDLE TRIASSIC SHERWOOD SANDSTONE GROUP

In the Larne No.2 borehole, the Sherwood Sandstone Group (SSG) comprises 648 metres of predominantly sandstone with interbeds of siltstone and mudstone that become less common in the upper part of the succession. In the Larne sub-basin the top of the Sherwood Sandstone Group reaches a maximum depth of about 1000 metres just east of the major north-trending South Maidens Fault, which is slightly deeper than in Larne No. 2. The Group subcrops at sea bed along the south-eastern margins of the Larne sub-basin (Figure 13; Enclosure 7). On the Maidens horst block, the top Sherwood Sandstone Group horizon gently shallows and subcrops at sea bed to the east of the study area; it varies in depth from about 500 metres in the south rising to depths of around 150 metres in the north. In the Northern area, where sediments are faulted down by a series of major NE-trending faults the top of the SSG reaches a maximum depth of 950 m before shallowing and eventually subcropping at sea bed in the northwest extremities of the new survey (Figure 13; Enclosure 7).

4.4 MIDDLE TRIASSIC MERCIA MUDSTONE GROUP

The Larne No.2 borehole proved a 951 metre Mercia Mudstone Group succession including the basal Lagavarra Formation composed of 55 m of sandstone, siltstone and mudstone. The Lagavarra Formation is overlain by the Craiganee and Glenstaghey formations 431 m and 337 m thick respectively. The Craiganee Formation includes two halite dominated successions, the Ballyboley and Carnduff members (Figure 4 and Figure 5). The succeeding Glenstaghey Formation contains the uppermost Middle Triassic halite unit, the Larne Halite Member, and is overlain by a 127 m succession of mudstone with minor sandstone, assigned to the Knocksoghey Formation that subcrops recent sediments.

Identification of Middle Triassic halite seismic horizons has been described in sections 2.3.5, 2.3.6 and 2.3.7. Identification is largely based upon comparison of TWTT between the different horizons in the Larne No. 2 borehole and nearshore new seismic profiles. Mapped depressions in the sea bed (Figure 23; Gafeira, 2010, Figure 26) coupled with salt mobilisation related to faults soling out in the Ballyboley salt succession (Figure 18) provide good evidence for the presence of Triassic salt. It was not possible to follow these horizons confidently from the Larne sub-basin northwards over the Maidens igneous complexes and into the westerly extension of the SW Arran sub-basin due to major faults and variable quality of the seismic data. Thus, although seismic horizons interpreted to represent all three Middle Triassic halite members were mapped in the study area, maps were only produced for the Ballyboley and Carnduff halite members and only the latter has been mapped north of the Larne sub-basin (Figure 15 and Figure 16; Enclosures 8, 9).

Rapid lateral thickness variations in the Triassic salt units are also evident onshore. Larne No. 1 and Larne No. 2 were drilled approximately 600 metres apart but the Larne Halite increased in thickness from 188 metres to 481 metres and the Carnduff Halite decreased from 182 metres to 41 metres between the No. 1 and No. 2 wells. The 2007 Larne Lough 3D seismic survey also shows evidence of salt mobilisation in the Triassic succession.

4.4.1 The Ballyboley/Fylde Halite members

In the Larne No. 2 borehole, the Ballyboley Halite Member comprises a 40.8 m succession of halite containing frequent beds of siltstone and mudstone, the thickest being approximately 3 m (Figure 5). It is possible that the Ballyboley Halite may be supplemented in the nearshore Larne sub-basin by the older Fylde Halite (Figure 4; Chadwick et al., 2001). The Fylde Halite Member of the Lagavarra Formation is largely a topography filling, syn-rift fault deposit with a more limited distribution than the other Triassic halite members and is absent from the Larne No. 2 borehole. However, the Fylde Halite Member is present in the East Irish Sea Basin and has been interpreted in well 111/15-1 in southern part of the Portpatrick sub-basin (Figure 2; Chadwick et al., 2001; Quinn, 2008). North of the Larne sub-basin it was not possible to interpret the

Ballyboley and associated Fylde halite members with any confidence. In some areas, a thinner seismic package between the Carnduff Halite Member and underlying Sherwood Sandstone Group suggests that the Ballyboley and more locally-developed Fylde halite members were either not deposited or are poorly developed (Figure 15; Enclosure 8).

4.4.2 The Carnduff Halite Member

In Larne No. 2 the Carnduff Halite comprises a 182 metre thick succession of which approximately 65 metres comprises relatively clean halite. The Carnduff Halite Member has been mapped over much of the Larne sub-basin and in part of the westerly extension of the SW Arran sub-basin in the Northern area (Figure 16; Enclosure 9). In the Larne sub-basin it reaches a maximum depth of approximately 550 metres where a succession of Mercia Mudstone Group sediments has subsided along faults detaching in the underlying Ballyboley/Fylde halite layers (Section 3.1; Figure 18). It subcrops the sea bed along parts of the southern boundary of the Larne sub-basin and adjacent to the Maidens Igneous Complex (Figure 16; Enclosure 9). The member appears to vary in thickness, interpreted here to be due to the mobilisation of the salt layers and activated as a result of extensional movement on faults within the MMG and gravity sliding from the southern boundary of the sub-basin northwards into the deeper parts of the sub-basin (Figure 17).

4.4.3 The Larne Halite Member

In the Larne No. 2 borehole, the Larne Halite Member of the Glenstaghy Formation (Figure 3) is 188 metres thick and comprises a succession of silty mudstone, siltstone and minor sandstone with the uppermost part containing an increasing number of halite units. The thickest continuous halite unit is approximately 22 metres thick with the majority of the halite within this member separated by siltstone and mudstone beds. The drilled Larne Halite succession also included several igneous intrusions (Figure 5). In the Larne No. 1 borehole the Larne Halite Member is 481 metres thick, with approximately 331 metres of this being halite and the thickest salt bed reaching 38 metres. The Larne Halite Member, where present in the new offshore survey area, is too shallow to be considered for either natural gas storage or CAES. Onshore it may be deep enough in places to have potential for CAES (e.g. at Larne No. 1 ~360 – 840 metres bmsl).

5 Preliminary evaluation of the new survey area for future gas storage within salt caverns

Gas storage in excavated salt caverns may take place in salt domes or swells formed by mobilised salt, or in bedded salt deposits. Volumes of salt caverns can be maximised by excavating different shapes depending on the dimensions of the original salt body (Platt, 2009). A vertical cylinder shaped cavern in a salt dome may have a diameter of 50-80 m and be several hundred metres high. In France, Canada, and parts of USA, storage caverns have been constructed in bedded halite deposits. Halite beds may vary between 100 to 300 m in thickness. A balance is required between the need to keep cavern convergence (collapse of the cavern wall due to salt creep) within acceptable limits and the need to maximise the amount of gas stored and its deliverability (under pressure from the subsurface). Consideration of these requirements means that salt caverns for gas storage are most commonly developed at depths of less than 1700 metres, with an optimal range between 1000 – 1500 metres (Platt, 2009). Lux, 2009, provides examples of caverns in bedded salt at a shallower depth range of between 500 – 650 metres, although these depths would be more suitable for Compressed Air Energy Storage (CAES), which is also being investigated in the Larne area.

Four areas have been identified offshore Northern Ireland as having potential for further consideration for the excavation of salt to form natural gas storage caverns. These locations have been selected on the basis of the interpretation of the DETI high resolution seismic survey and on the following criteria:

- Evidence for the presence of salt layers, either as undeformed beds or mobilised salt swells, which may be thicker than their equivalents drilled in the Larne No. 2 borehole
- Although not necessarily lying in the optimal depth range as defined by Platt (2009), the depth of the salt layer is still acceptable for construction of salt caverns (Lux, 2009)
- Given the uncertainties relating to identification of these seismic horizons, the salt layers are as robust and well constrained as possible.

However, it should be noted that seismic interpretation can derive an estimate of the depth to and possible thicknesses of buried salt, but can only give a very slight indication as to the purity of the thickened salt body.

5.1 LOCATION 1: LATE PERMIAN HALITE (FIGURE 27; ENCLOSURE 10)

Location 1 has been selected where seismic interpretation of the Late Permian Belfast Group in the Larne sub-basin shows a slight eastward thickening from between 100 and 200 metres in the west to more than 300 metres and reaching a possible maximum thickness of over 500 metres at one location (section 4.2; Figure 12; Enclosure 6). The greater thicknesses are considered to be depositional, as there are no unequivocal or widespread indications on seismic profiles of significant mobilisation of the salt. The thickening of the Late Permian succession may be the result of the filling of depressions in existing topography and may in part be fault controlled (Figure 26; Enclosure 10 seismic examples). The area is situated approximately 15 kilometres from the port of Larne in a water depth of approximately 150 metres (Figure 27; Enclosure 10). Depth below mean sea level of top of the Late Permian salt at this location varies between 1600 metres and 2000 metres (Figure 10; Enclosure 4) and is therefore generally greater than depths in which storage caverns are commonly developed (Platt, 2009). This location would, therefore, require drilling from an offshore platform and, although the increased thickness of the salt interval is attractive the distance from land reduces the viability of this location for natural gas storage for the foreseeable future.

Three more isolated areas of interpreted thickened salt, shown on seismic profiles in Figure 19, Figure 20 and Figure 28 and possibly due in part to post-depositional movement, are also highlighted on Enclosure 10. Here, salt occurs at depths of approximately 1500 metres (bmsl) and with estimated thicknesses of between 150 metres and 200 metres.

5.2 LOCATION 2: LATE PERMIAN HALITE ASSOCIATED WITH SOUTH MAIDENS FAULT (FIGURE 29; ENCLOSURE 11)

The isopach map of the White Brae Mudstone halite (Figure 12; Enclosure 6) shows an area of thickened Late Permian halite straddling the northern end of the major north-trending South Maidens Fault. The salt may be up to 250 metres thick and is interpreted to occur at a depth of 1400 metres below mean sea level. The hanging wall of the northern part of this fault is associated with an interpreted igneous dyke and associated relatively flat lying sills within the Mercia Mudstone Group which tend to reduce the seismic signal penetration to deeper levels (See seismic example in Enclosure 11). The poor resolution of the seismic data at this location increases the uncertainty regarding the interpretation of salt thickening. Conversely, thickening of salt adjacent to faults is seen in other offshore basins where salt layers occur.

This area of potential thickening of Late Permian salt occurs 10 kilometres from the Port of Larne, and about 5 kilometres east of Islandmagee, in a water depth of 115 metres. Its proximity to Islandmagee, the SNIP gas pipeline and Ballylumford power station make this a more attractive location but there is an increased potential for igneous intrusions to cause difficulties for cavern construction.

5.3 LOCATION 3: MIDDLE TRIASSIC HALITE (FIGURE 30; ENCLOSURE 12)

Within the Mercia Mudstone Group (MMG), the NNW-trending series of faults mapped within the Larne sub-basin (Figure 16; Enclosure 9) appear to detach within the Ballyboley/Fylde Halite Member (Figure 11). Blocks of relatively undisturbed MMG sediments are observed that seem to have moved down these detachment faults possibly facilitated by mobilised salt that has created space into which the blocks have subsided (Figure 18).

Location 3 is a NNW-trending structural high between two NNW-trending down-faulted blocks situated 12.5 kilometres from the port of Larne in a water depth of approximately 115 metres (Figure 30; Enclosure 12). This horst exhibits updoming within the deeper part of the section that could indicate mobilisation and migration of salt away from the adjacent faulted-down section and into the central high. Depth to top of thickened salt varies from 270 to 320 metres and base from between 580 to 660 metres bmsl. The north-trending high is approximately 4 kilometres in length and about 1 kilometre wide. Several possible igneous intrusions have been interpreted within the nearby area but it remains unclear whether these occur within the salt high. However, as noted in section 2.3.8 above, replacement of salt units by igneous intrusions has been recorded further south in the East Irish Sea Basin (Arter and Fagin, 1993) and in the study area possible examples of this have been observed on the interpreted seismic data (e.g. Figure 7, Figure 8, Figure 14 and Figure 17). This location may have some potential for CAES but its distance from land and the potential presence of igneous intrusions severely downgrades it.

5.4 LOCATION 4: MIDDLE TRIASSIC HALITE ON SOUTHERN EDGE OF LARNE SUB-BASIN (FIGURE 31; ENCLOSURE 13)

Location 4 lies close to the southern margin of the Larne sub-basin. A possible area of salt thickening has been interpreted on the basis of seismic character and is best imaged on line DETI09-31 (Figure 17; Enclosure 13, seismic example). The thickened salt is located on the hanging wall of a low-angle fault that has a central NE-trending segment but which veers NW at each end, giving it a curvilinear shape. The fault detaches in the lowermost Ballyboley halite and the overlying Triassic succession has slumped down the fault plane. The halite layers within this succession are interpreted to have been mobilised resulting in localised thickening.

Depth ranges between approximately 200 metres (bmsl) at Top Carnduff Halite Member level down to about 400 metres (bmsl) at top Ballyboley Halite Member level giving a possible thickness of thickened salt of around 200 metres but at shallower levels than that described by Lux (2009). The area is situated 15.5 kilometres from the port of Larne in a water depth of approximately 115 metres. As a consequence of its distance from Larne and shallow depths this location is unlikely to be suitable for gas storage and is only marginal for CAES in the lower salt interval.

6 Conclusions

This report represents the culmination of a 3-year project aimed at gaining a better understanding of the distribution of subsurface salt layers lying offshore Northern Ireland with a view to facilitating future assessment of their potential for the construction of gas storage caverns. The report is primarily based upon a geological interpretation of a specifically commissioned DETI high resolution 2D seismic dataset located offshore NE Ireland.

This study shows that there is potential for gas storage in salt of Permian and Triassic age, as drilled in the Larne No. 2 borehole. Whereas the Late Permian salt appears relatively undisturbed in the nearshore Larne sub-basin with no strong seismic evidence for salt mobilisation, the Triassic salts do appear to have been mobilised and as a result, their original depositional thicknesses have been re-distributed into salt swells and areas where salt is thin due to withdrawal. However, the seismic interpretation suggests that both Late Permian and the Middle Triassic salts may have potential for construction of salt caverns in 4 areas, subject to further more detailed technical assessments. However, the increased complexity of the geology near the coast and the high concentration of igneous intrusions in this zone means that these areas of apparent thicker salt beds are a considerable distance from land. This significantly reduces their potential for the construction of gas storage caverns because directional drilling from an onshore location becomes more expensive and difficult with increased horizontal displacement. Location 2, near the South Maidens Fault, appears to have the greatest potential, being close to Islandmagee and the Northern Ireland gas infrastructure.

In addition to these locations, where the mapped thicknesses of the salt intervals are seen to increase significantly with respect to those proved in the Larne No. 2 borehole, there are also broader areas where the salt is likely to be similar in thickness to Larne No. 2. These areas cannot be ruled out for gas storage and may warrant further investigation where they come closest to the coast of Islandmagee.

As with the previous Task 1 interpretation report (Quinn, 2008) it is important to stress that uncertainties remain with respect to the seismic interpretation of the subsurface geology. In the new survey area, all horizons picked were identified with reference ties to nearby onshore boreholes, comparison of onshore seismic data and with a more distant offshore well. There is no direct evidence that salt layers are present in the nearshore area as this area has not been tested by deep drilling and if present how suitable they would be for cavern construction. However, indirect evidence in the form of structural swells imaged by the new seismic data, especially for the presence of Triassic salt, is strong. For the Late Permian salt, a seismic package and event lying above the strong and continuous Magnesian Limestone has been interpreted where possible as representing an offshore extension of the succession proved in the onshore Larne No. 2 borehole. The presence of Late Permian salt offshore is based on regional palaeogeographical considerations and a small number of possible salt mobilisation structures seen on the seismic data. For the Triassic salt, there is strong seismic evidence that suggests that salt layers are present and that the salt has mobilised to produce areas of enhanced thickness. However, the seismic data can provide only a very slight indication, for instance frequency of internal reflections within the interpreted salt succession, on how clean the salt is and whether it is heavily intruded by dykes and sills. Confirmation that a seismic package comprises a salt unit will remain equivocal unless the seismic data can be directly tied to a new offshore borehole.

As noted above, onshore Northern Ireland, salt layers occur at two different stratigraphic levels. Firstly, within the Late Permian Belfast Group, 113 m of clean salt has been drilled in the Larne No. 2 borehole. This salt layer is interpreted to be present in the offshore extension of the Larne sub-basin within a succession that thickens eastwards into the deeper parts of the sub-basin. This report has highlighted this depocentre as a potential location for further investigation with regard to future salt cavern development. The thickness of the Late Permian salt interval may vary from

300 metres to 600 metres in this part of the Larne sub-basin, however, here depths of between 1600 to 2000 metres are generally greater than the optimal criteria (1000 – 1500 metres) stated by Platt, 2009 although not dissimilar to the depth range (1678 - 1791 metres) in Larne No. 2. Secondly, several onshore boreholes record the occurrence of salt layers within the Middle Triassic Mercia Mudstone Group. The Larne No. 2 borehole drilled three separate halite members within the MMG, the Ballyboley, Carnduff and Larne Halite Members that contain halite layers of varying thickness interbedded with siltstone, mudstone and occasional sandstone. The thickest continuous halite layer within each member is 7 m, 65 m and 22 m in the Ballyboley, Carnduff and Larne halite members respectively. It has been suggested in this report that the Fylde Halite Member, the oldest of the Triassic halite members, best developed within the East Irish Sea Basin (Jackson and Johnson, 1996; Chadwick et al., 2001) may also be present within parts of the Larne sub-basin. For the Triassic halites, two locations within the Larne sub-basin have been identified, on the basis of apparent thickening of salt layers, as having potential for further investigation with regard to future salt cavern development.

The new seismic data has highlighted the presence of numerous igneous intrusions, dykes and sills, that occur in all parts of the new survey area but appear to be most frequent in the Middle Triassic Mercia Mudstone Group sediments. Igneous intrusions appear less frequent in the older strata. Possible examples of replacement of salt units within the Mercia Mudstone Group by igneous intrusions have been observed.

The interval velocity of the rock units has been shown to vary markedly over the report area and although velocity data, sourced from Larne No. 2 borehole has been used to build a velocity model for the processing of the new data and this data used in part in depth converting the new interpretation, the depth conversion remains a source of error.

A companion report, describing the interpretation of a multibeam dataset acquired in conjunction with the high resolution seismic data has also been produced. The report aims to map all sea bed features imaged by the new multibeam dataset and discuss their possible mode of formation. The report also identifies features that are due to structure and stratigraphy in the subsurface helping in the interpretation of the latter (Gafeira, 2010).

6.1 FUTURE WORK RECOMMENDATIONS

This project has generated a new seismic dataset, multibeam data and interpretations of this new data as well as interpretation of the existing seismic information (Quinn, 2008). Despite the advances made in our understanding of the disposition of Permian and Triassic halite along the NE coast of Northern Ireland, there are still uncertainties related to the thickness, location and purity of the salt. Many of these uncertainties cannot be fully resolved without exploratory drilling; however carrying out some of the following recommendations may help identify with greater certainty possible drill sites.

6.1.1 Improve depth conversion

By using all stacking velocities used to process the new seismic dataset it is possible to build a full velocity model covering the whole study area. This approach would enable depth conversion of the TWTT data taking into account the wide variation in interval velocities expected in the area and result in a more precise depth conversion of the interpreted dataset. This would be an important task prior to drilling a borehole in the offshore area.

6.1.2 Focused interpretation of prime location sites

This would be done in conjunction with construction of a complete velocity model and prior to drilling of a test well. The interpretation effort would focus on horizons that define the sites identified as having most potential for exploitation of the salt layers for salt cavern construction. It may be possible to build a 3D model of the structures within the Middle Triassic salts which would enhance our understanding of their formation though still with uncertainties related to lack of direct borehole information.

6.1.3 Integrate new interpretation with earlier Task 1 interpretation

Although this new interpretation utilised information from the earlier Task 1 interpretation report no attempt was made to fully rationalise the horizon picks and the fault linkages. Integration of the two interpretations would refine the geological model.

6.1.4 Additional multibeam acquisition

Understanding of sea bed features in the nearshore area, Northern Ireland, benefits many of the activities taking place in this region as well as informing interpretation of the deeper subsurface geology (Gafeira, 2010). This knowledge, and benefits, would increase if gaps in the original newly acquired multibeam data and existing nearshore surveys could be filled by a selective acquisition program.

6.1.5 Shallow borehole sampling

There is an opportunity to collect rock samples from a small number of selected borehole sites over the newly mapped area. Sites will be selected with the aim of constraining the Triassic stratigraphy and collecting more information on Triassic lithologies close to sea bed. Shallow boreholes are limited to tens of metres depth (maximum 40 metres). Cost of collection will come from the science budget, however, description and dating of any samples recovered would have to be met by other funds.

6.1.6 Specialist re-processing of the new high resolution dataset

The potential for further specialist processing of the newly acquired seismic dataset could be assessed in the light of the initial and more focussed interpretations of seismic profiles and possible collection of shallow borehole samples that may help in identifying the shallow seismic events.

6.1.7 Exploration borehole

In order to 'ground truth' the new interpretation presented in this report and enable it to be constrained and improved upon it is recommended that a well be drilled to test one or more of the sites identified in this study as having potential for salt cavern construction. Such a proposition should only be considered if the Larne Lough and onshore areas prove to be unsuitable for the construction of gas storage caverns. The cost of an onshore facility would be substantially less than one offshore that required an extended-reach deviated borehole drilled from an onshore surface location. However, it is possible that an onshore facility will be ruled out, for geological, environmental or public safety reasons, and then further assessment of offshore sites by drilling might be considered. Besides gas storage, the Permo-Triassic contains aquifer sandstones (Sherwood Sandstone, Ballytober Sandstone) that may have some potential for carbon capture and storage which might merit further investigation in the future.

Appendix 1 – New acquisition parameters

DETI09 survey

Navigation parameters

Primary:
Differential GPS, using Fugro Skyfix HP system port antenna, utilising a dual frequency Novatel OEMV GPS card and receiving differential corrections from a selection of reference stations in the Starfix network. Corrections are received via the AOREH satellite through the port antenna and internal demodulator and via AF-Sat through an independent antenna and external demodulator. GPS data is received via the GPS card within the Starpack unit and combined with corrections to produce a multiple reference station, weighted mean solution position which is then sent to the Starfix Seis survey software.

Secondary:
This is derived from Fugro's Starfix.HP system starboard antenna. All other corrections applied as per the primary.

Tertiary:
This is derived from Fugro's Skyfix.XP system port antenna. All other corrections applied as per the primary.

Quaternary:
This is derived from Fugro's Skyfix.XP system starboard antenna. All other corrections applied as per the primary.

Recording parameters

Streamer parameters

Type:	NTRS2
Active Streamer Length:	1500 m
Number of Groups:	168
Group Interval:	6.25 m (1-96) 12.5 m (97-168)
Tow Depth:	4.0 m ± 1.0 m
Fold Coverage:	60 / 120
Hydrophone sensitivity	20000 mV/bar

Source parameters

Type:	Sleeve Guns
Array Volume:	140 / 500 cu in
Array Configuration:	2 X 40 cu in, 2 X 20 cu in, 2 X 10 cu in
	2 X 250 cu in
Energy:	2000 psi
Tow Depth:	4.0 m ± 1 m
Shot Interval:	6.25 m / 12.5 m

Recording system

Type:	NTRS2
Recording Medium:	Hard drive
Format:	S1
Sample Rate:	1.0 msec
Record Length:	2.0 seconds
Filters:	Low Cut 4.6 Hz, High Cut 412 Hz
Auxiliary Channels:	Trace type 6, channels 1-24
Record Delay Time:	69 msec
Camera Record Plotter:	OYO

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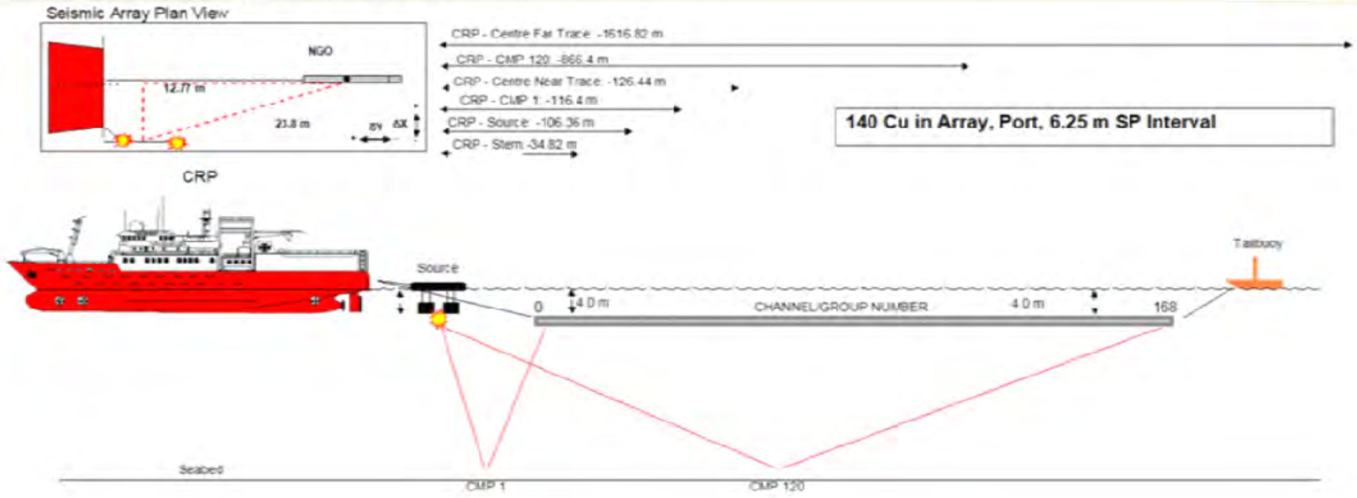
2D SEISMIC SURVEY
NORTH CHANNEL BASIN, OFFSHORE NE IRELAND



OFFSET MEASUREMENTS (From CRP)				
CRP - Stern	δX	0.00 m	δY	-34.82 m
CRP - Source	δX	-12.69 m	δY	- 106.36 m
CRP - Centre Near Channel	δX	0.08 m	δY	-126.44 m
CRP - Centre Far Channel	δX	+0.08 m	δY	-1616.82 m
CRP - CMP 1	δX	-6.31 m	δY	-116.4 m
CRP - CMP 120	δX	-6.31 m	δY	-866.4 m
Towpoint Streamer	δX	+ 0.08 m	δY	-34.82 m
Towpoint Source	δX	-12.69 m	δY	-34.44 m

ACQUISITION PARAMETERS	
Streamer Length	1500 m
No. of Channels	168
Group Interval	6.25 m (1-96) 12.50 m (97-168)
Shot Point Interval	6.25 m
Fold	120

SOURCE-TO-STREAMER OFFSETS	
Required Direct Offset	< ½ Water Depth
Predicted Direct Offset	23.8
Lateral Offset (X)	12.77
Longitudinal Offset (Y)	20.1 m
True Direct Offset (Z)	25 m

2DHR Multi-channel Survey Towing Configuration – M/V Fugro Meridian

Job No. 29-00050

Page 1

Diagram showing source and streamer configuration used in survey.

Appendix 2 – Depth conversion

All horizons on seismic data are picked as two-way times. These need to be converted to depths. However, our knowledge of the velocity structure in the offshore area is limited to seismic stacking velocities and extrapolation from boreholes. The nearest onshore borehole to the study area is Larne No.2; the nearest offshore well is 111/15-1 in the Portpatrick sub-basin approximately 65 km distant (Figure 2). For the Task 1 interpretation, depth conversion was performed using well 111/15-1 (Quinn, 2008). This choice was appropriate because of the uncertainties in using stacking velocities from relatively old commercial speculative surveys upon which that study was based.

The difficulty with using well velocity data alone is that it assumes that the well is representative of the whole study area. In this study, we have far greater confidence in the quality of the stacking velocities having been involved with the processing of the data and the fact that the DETI09 survey itself was designed to provide high spatial and temporal resolution which required a large number of detailed velocity analyses to image reflectors during processing. Thus we feel it is more appropriate to use the stacking velocities in preference to the boreholes. However, time constraints have prevented us from building a full velocity model based on all the stacking velocities available. Instead, we have examined the data on a few example lines and have performed regression analyses to generate time, RMS velocity functions that have been input into Landmark's TDQ (Time, Depth, Quick) depth conversion module. TDQ converts time horizons into their equivalent depth horizons that can then be contoured within SeisWorks and Zmap.

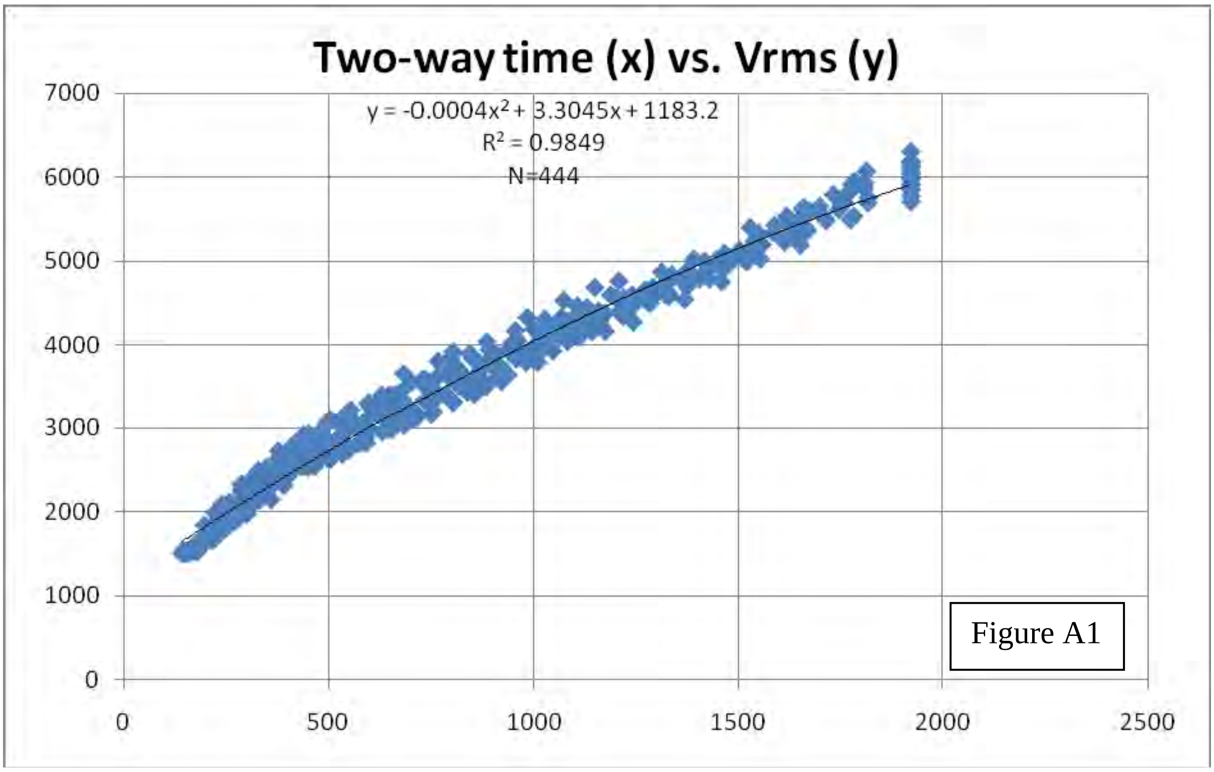


Figure A1

After some deliberation, we selected the stacking velocity data on line DETI09-50 to use in generating a time vs. RMS velocity relationship, as the line traverses the middle of the Larne sub-basin within the principle area of interest and so was deemed to be the most representative line for the area. Figure A1 shows a graph of RMS velocity against two-way time. A polynomial regression curve was derived as this gave a good fit to the data and was in a convenient form to input into TDQ (Figure A1). The data distribution is quite tight with errors of approximately plus or minus 250m/s in RMS velocity for any one-way time. The same data can be used to calculate depth by assuming RMS velocity to be identical to Average velocity. The resultant time, depth relationship is presented in Figure A2. Closer examination of this curve, gives some measure as the expected errors in depth conversion based on the scatter of the data points. At 1 second two-way time there is a spread of depth values ranging from 1909m to 2127m representing an error of approximately plus or minus 100m. This error may in practice be larger given that this represents data from just one line.

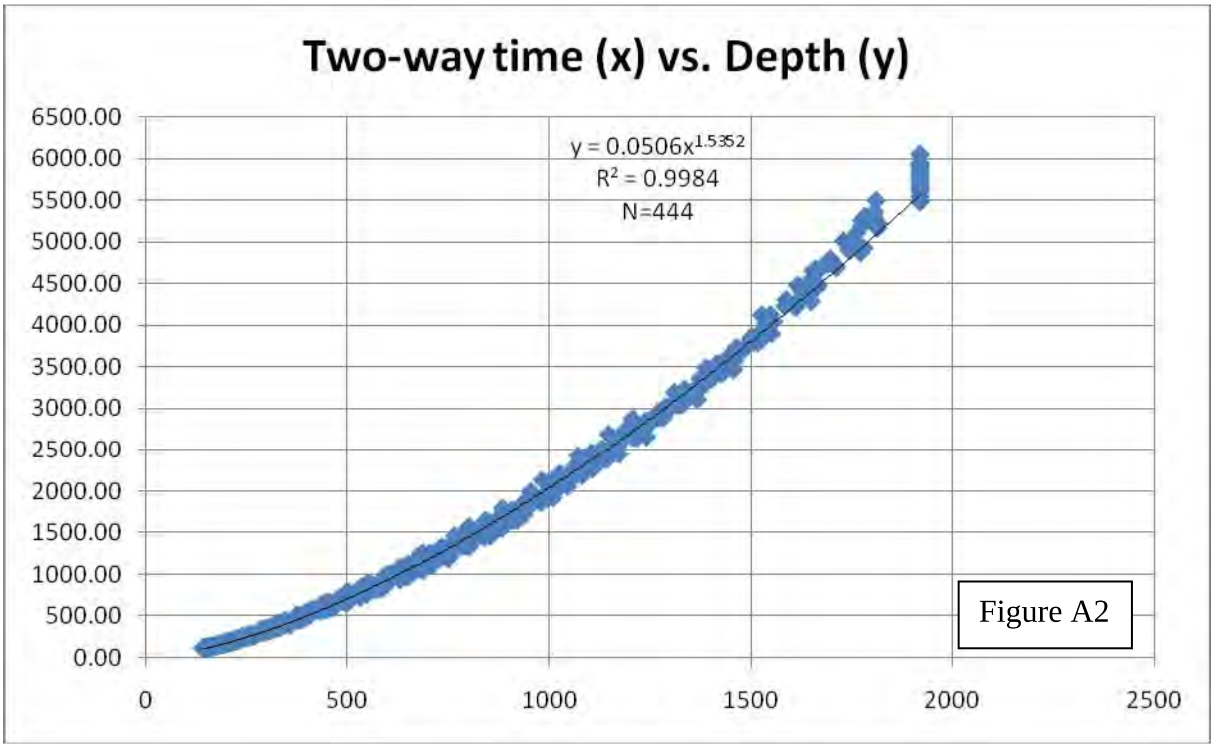


Figure A2

With the exception of the area just to the east of the Maidens Bank water depths vary gently over most of the survey area. Thus there are no major pull-down effects due to the low velocity water layer variation to consider.

Appendix 3 – Data storage

Digital Data

Seismic data

The British Geological Survey holds the digital data, in SEG-Y format. The final pre-stack time migration (PSTM) seismic profiles are stored in:

S:\offshore\surveys\Pending\DETI2009_Restricted\Geophysical\Airgun\ProcessedData\final_pstm_stack

Raw pre-stack time migration seismic profiles are stored in:

S:\offshore\surveys\Pending\DETI2009_Restricted\Geophysical\Airgun\ProcessedData\raw_pstm_stack

Raw CDP gathers in SEG-Y format are stored in:

S:\offshore\surveys\Pending\DETI2009_Restricted\Geophysical\Airgun\RawData\raw_cdp_gathers

Field data have been received on 3 IBM3592 data cartridges (two SEG-Ds and one SEG-Y) and are stored as encap (a BGS encapsulation variant of Tape Image Format) files in:

S:\offshore\surveys\Pending\DETI2009_Restricted\Geophysical\Airgun\RawData\FIeldTapeImages

All observers' logs, acquisition reports, multibeam records, navigation files, brute stacks and signature files are to be found under:

S:\offshore\surveys\Pending\DETI2009_Restricted

Seismic acquisition report is located in:

S:\offshore\surveys\Pending\DETI2009_Restricted\DVD1 - Bathy Logs Report UKOOA\Report

Seismic processing report and testing power point files are located in:

S:\offshore\surveys\Pending\DETI2009_Restricted\ReportAndDeliverables\Final Processing Report FSI

SeisWorks 2D project

Project name : deti

Master project: irish_mst

Oracle project : IRISHSEA

The final PSTM profiles have been loaded into Landmarks SeisWorks proprietary internal format as an interpretation project. All horizon interpretations are stored within this project. All navigation data are stored within the Oracle project.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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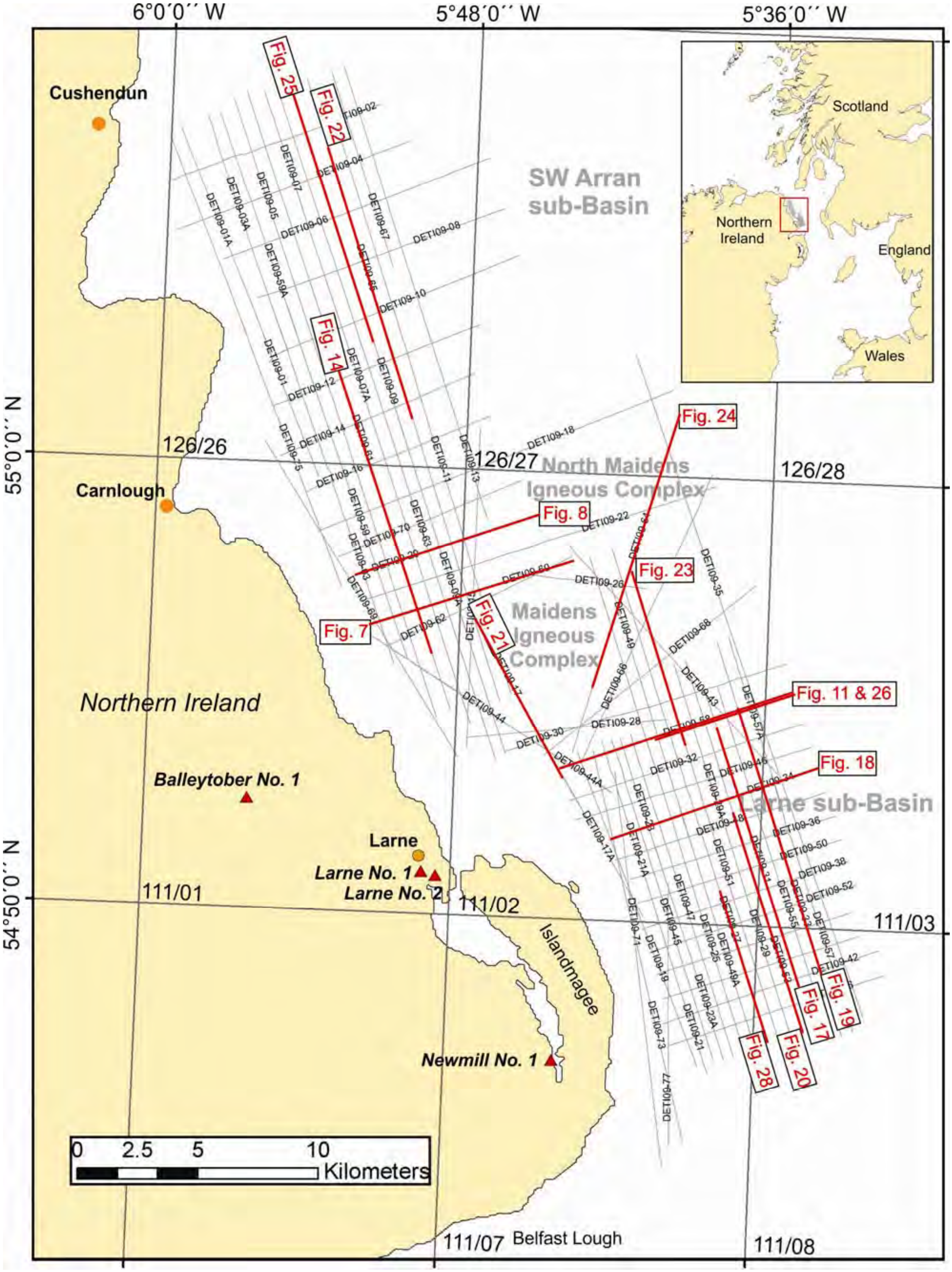

Figure 1. Location of study area showing new 2D seismic dataset. Onshore boreholes are shown as red triangles. Location of seismic lines that are referred to in Figures are shown as red lines.

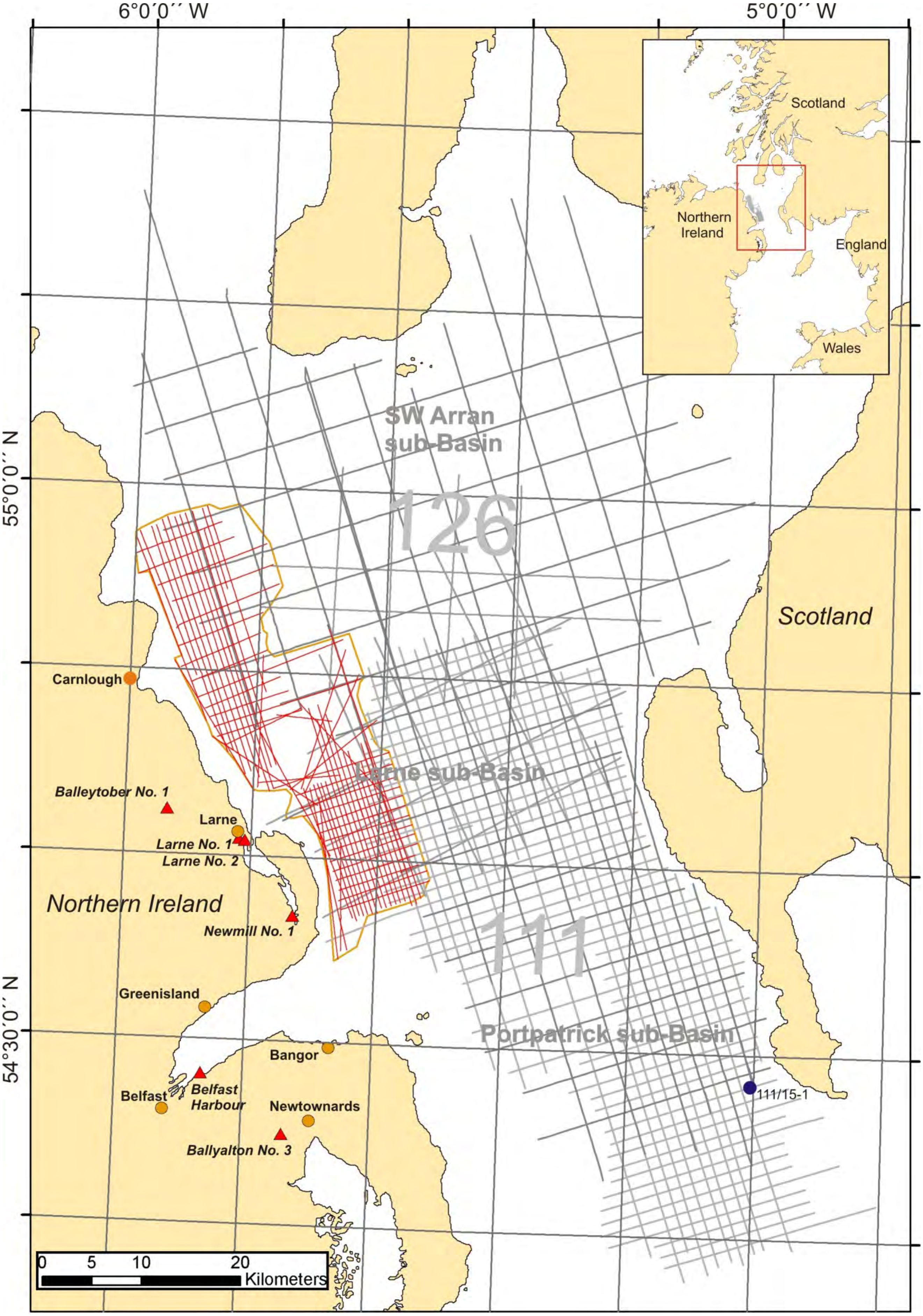

Figure 2. Location of wider project area showing seismic dataset (grey) interpreted for Task 1 (Quinn, 2008). Offshore commercial well 111/15-1 is shown.

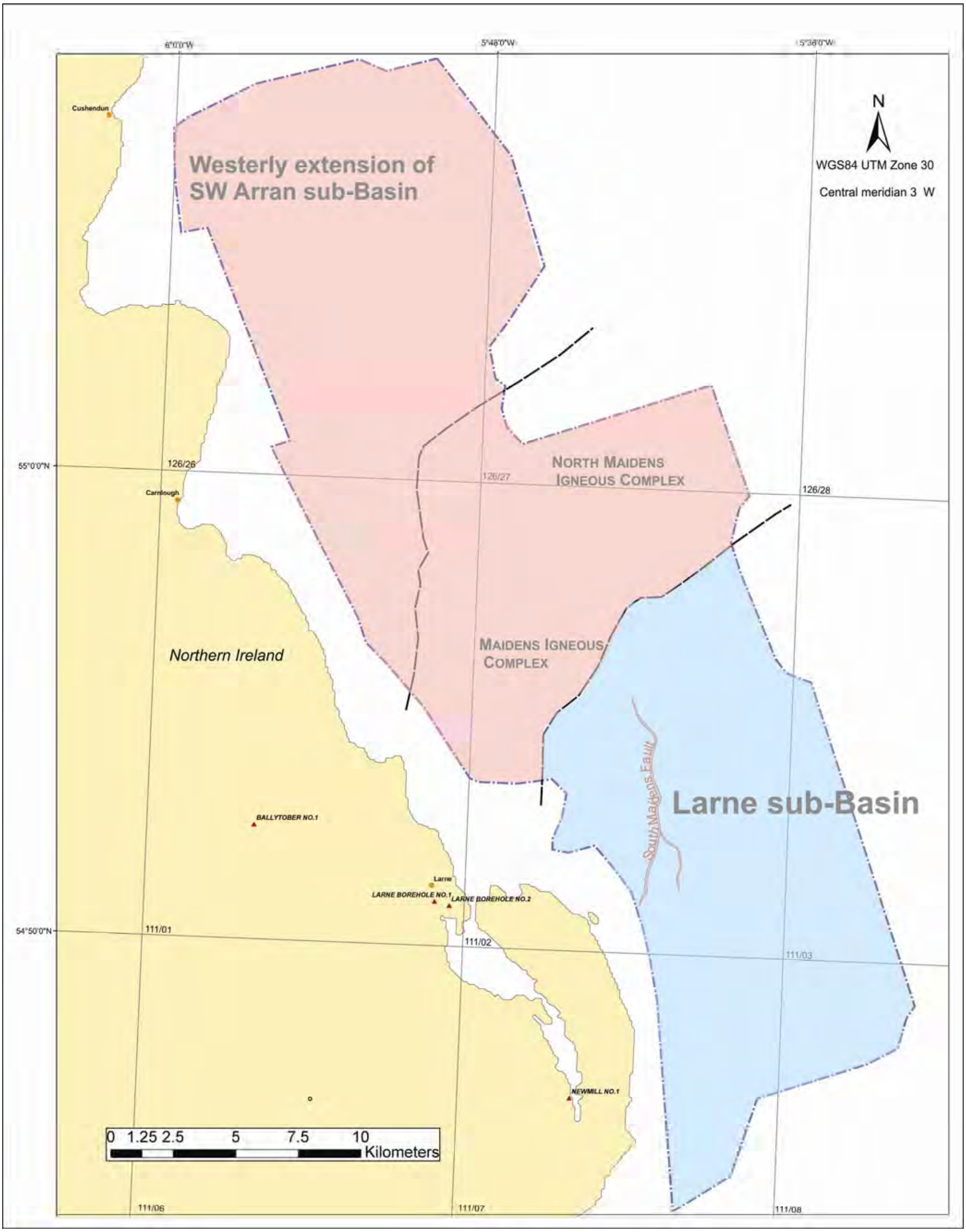

Figure 3. Map summarising main structural subdivisions of the study area. The two offshore coloured areas show limits of high priority SOUTHERN (blue) and lower priority NORTHERN (pink) areas referred to in the text.

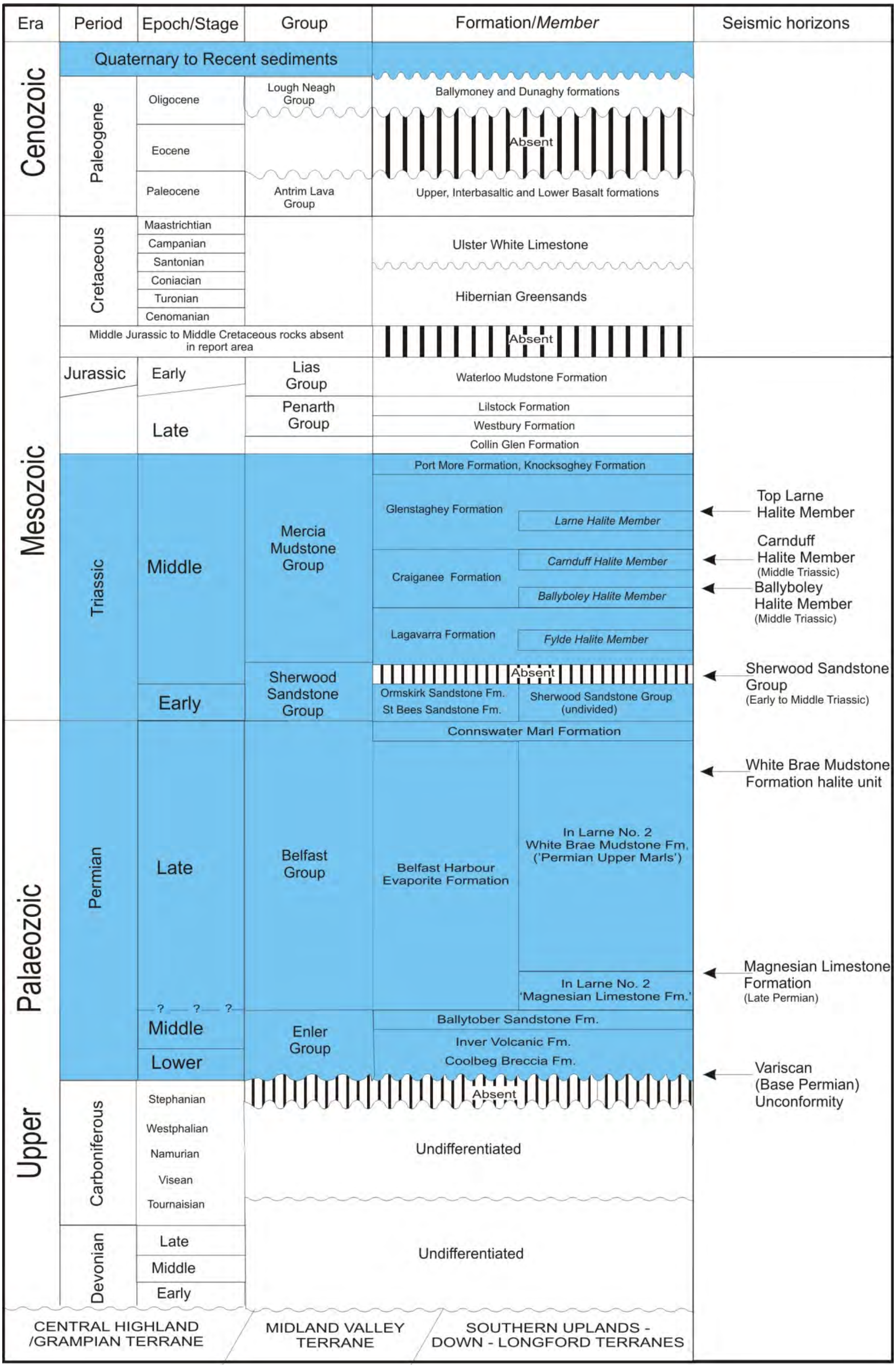

Figure 4. Summary of stratigraphic nomenclature used in this report. Blue fill represents the Permo-Triassic succession expected offshore. Interpreted seismic events are also shown (Modified after Quinn, 2008; Mitchell (ed). 2004; Chadwick et al., 2001).

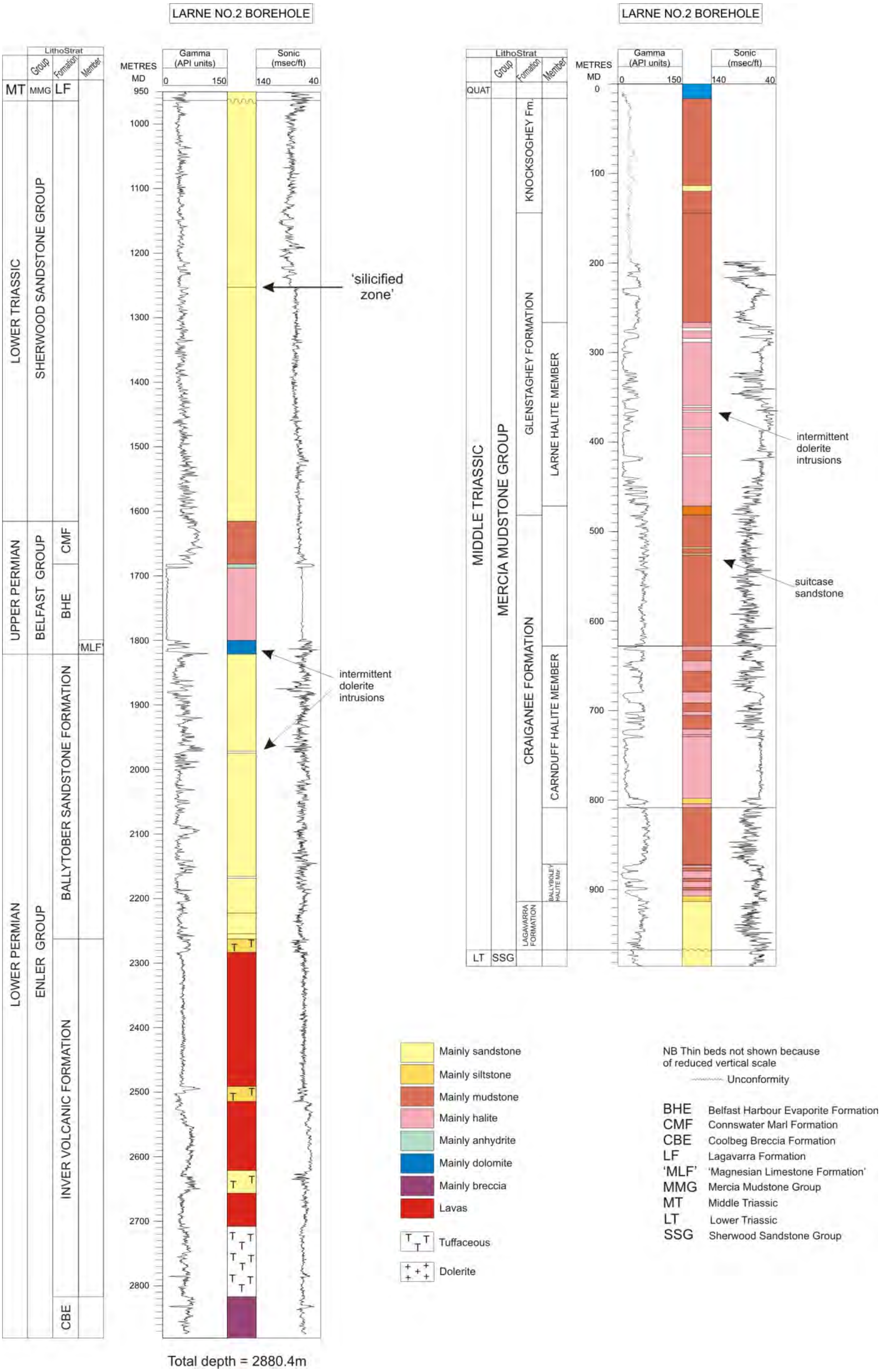

Figure 5. Stratigraphy from the Larne No. 2 borehole.

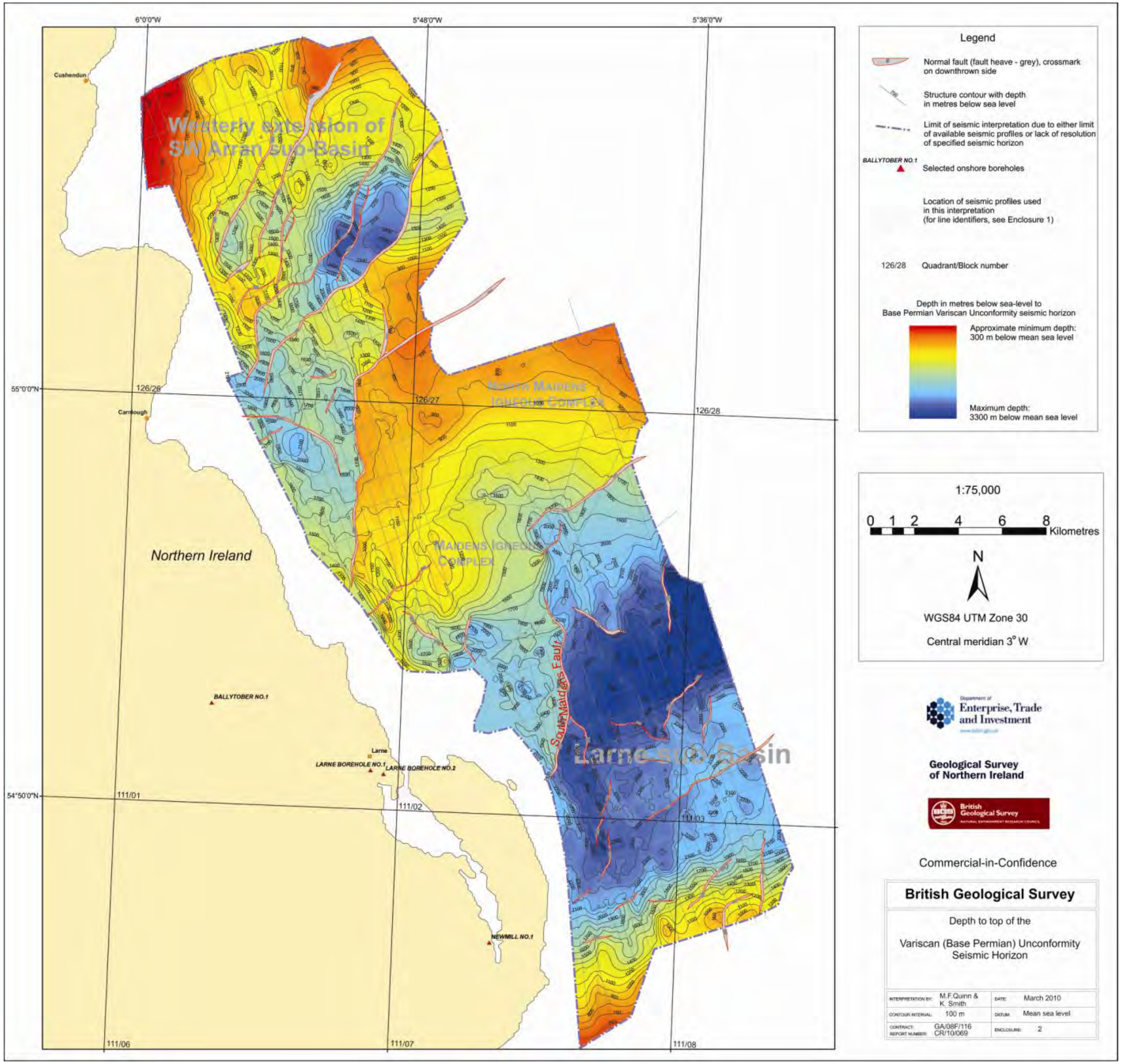

Figure 6. Depth to Base Permian Variscan Unconformity in metres below mean sea level (For full scale map, refer to Enclosure 2 in Volume 2 of this report).

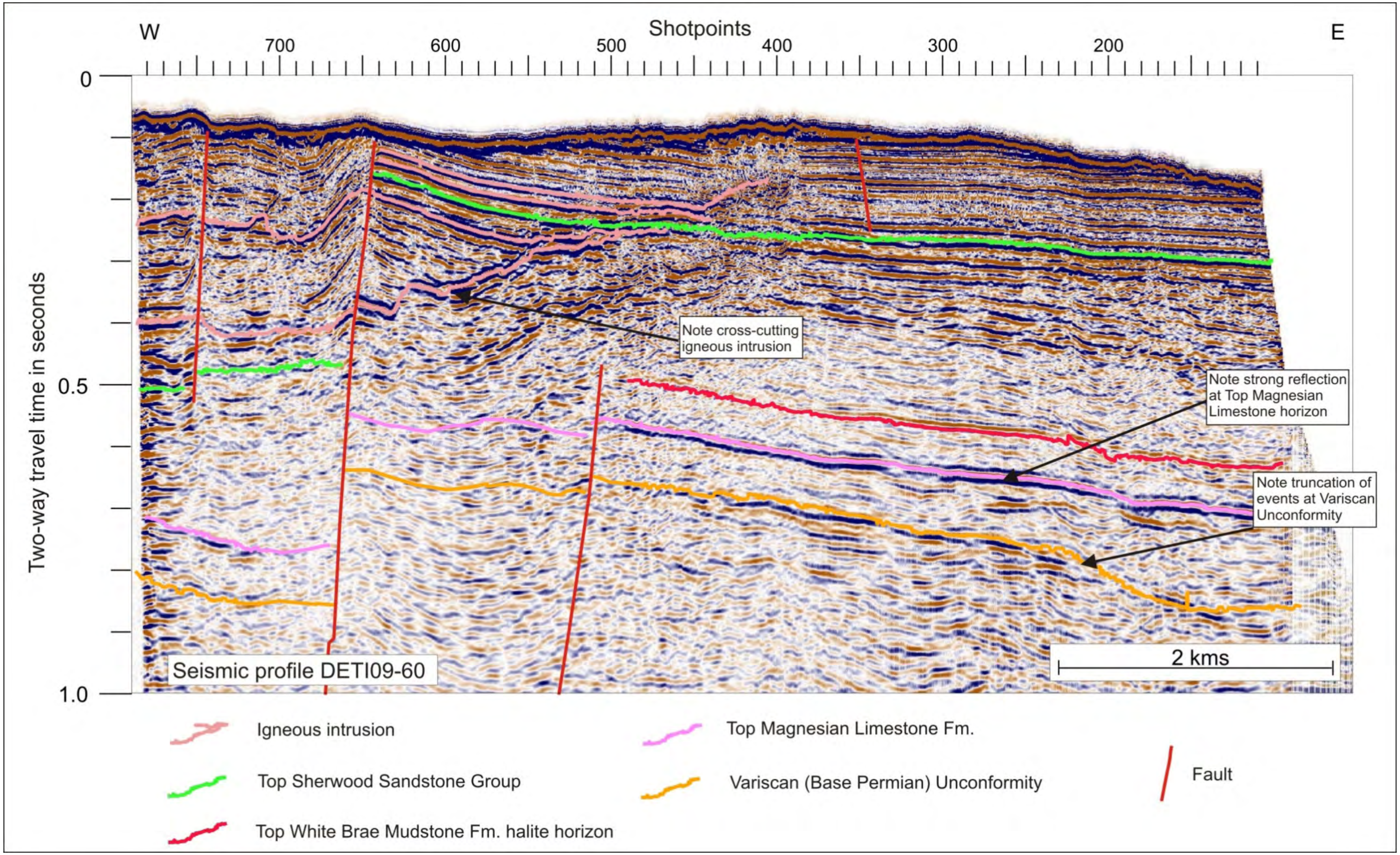

Figure 7. Seismic profile DETI09-60, located just to north of Maidens Complex, showing angular relationship of seismic horizons at near Base Permian Variscan Unconformity level. Also note cross-cutting igneous intrusion (Profile location shown in Figure 1).

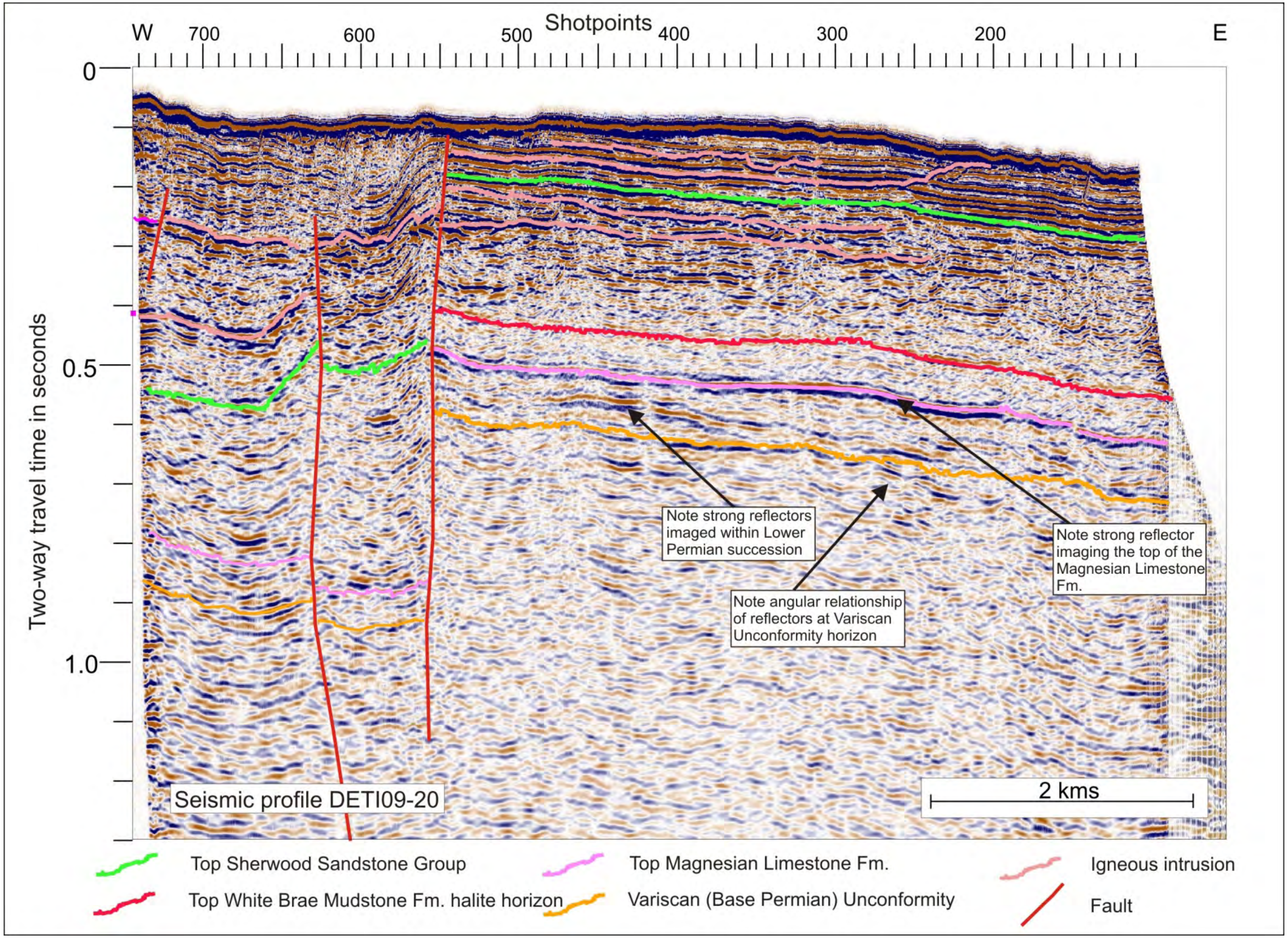

Figure 8. Seismic profile DETI09-20, located just north of the Maidens Complex, showing strong continuous reflector at Magnesian Limestone horizon level and good reflector imaged within the Lower Permian succession (Profile location shown in Figure 1)

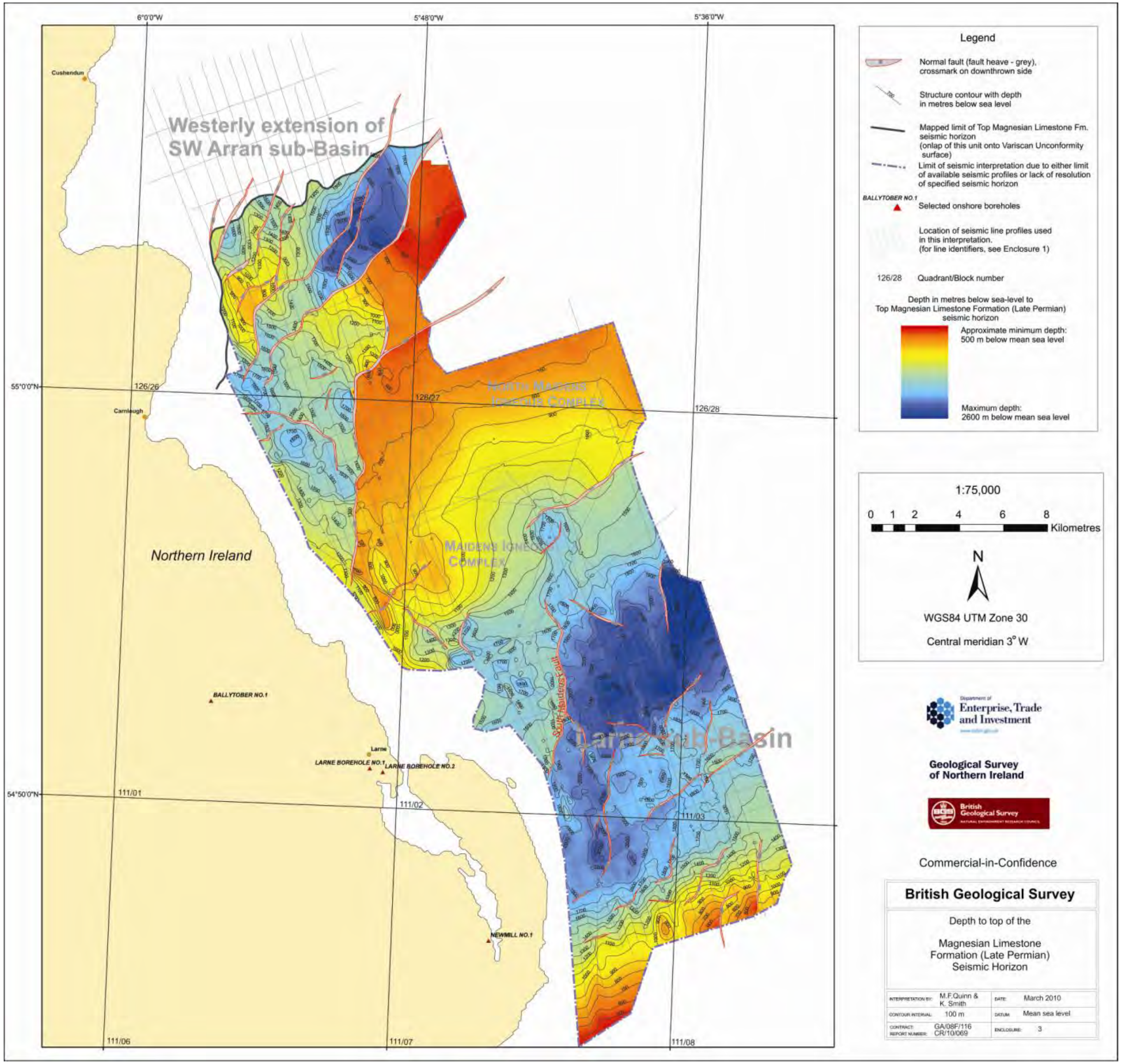

Figure 9. Depth to Top Magnesian Limestone Formation in metres below mean sea level (For full scale map, refer to Enclosure 3 in Volume 2 of this report).

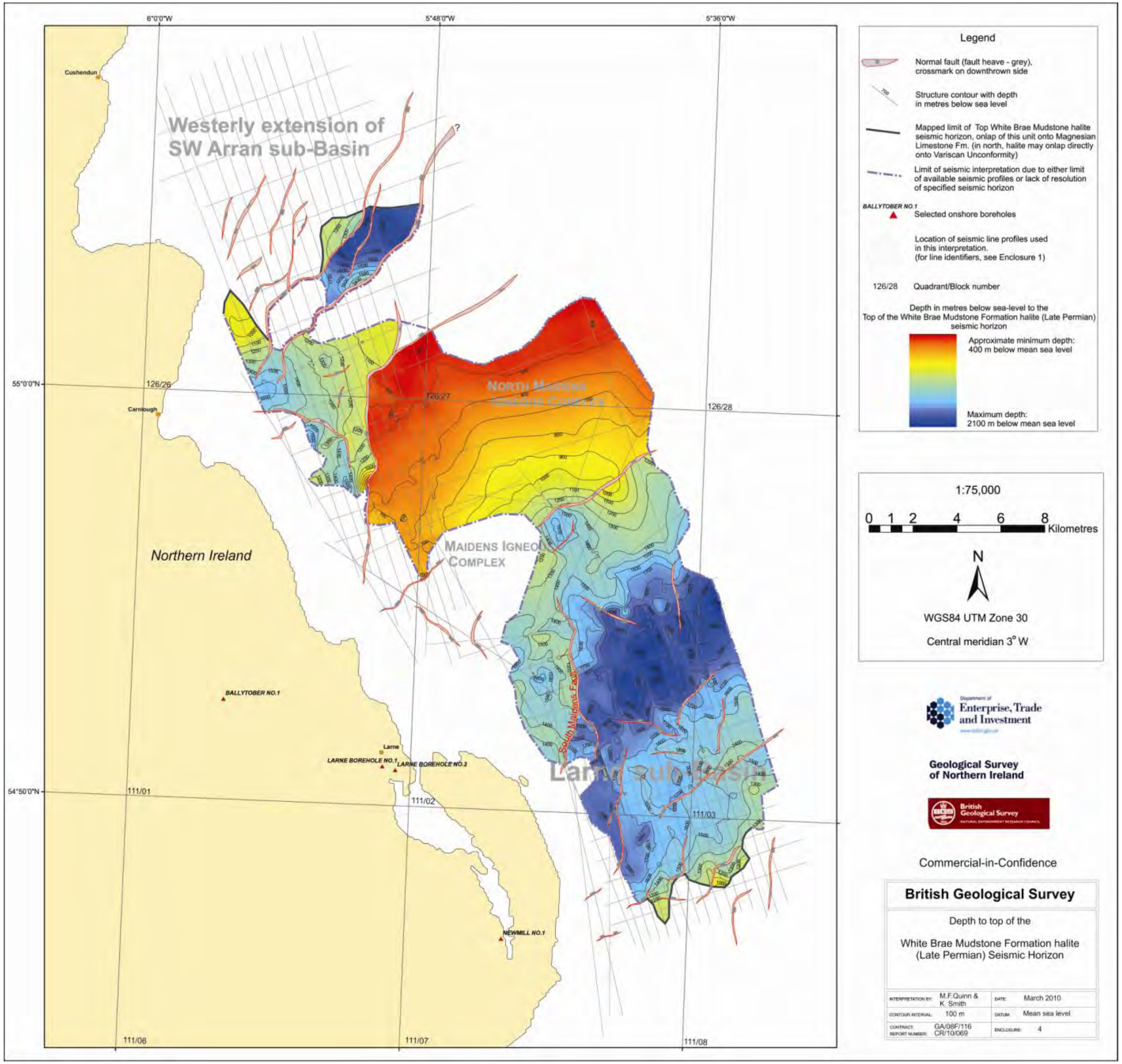

Figure 10. Depth to White Brae Mudstone Formation halite in metres below mean sea level (For full scale map, refer to Enclosure 4 in Volume 2 of this report).

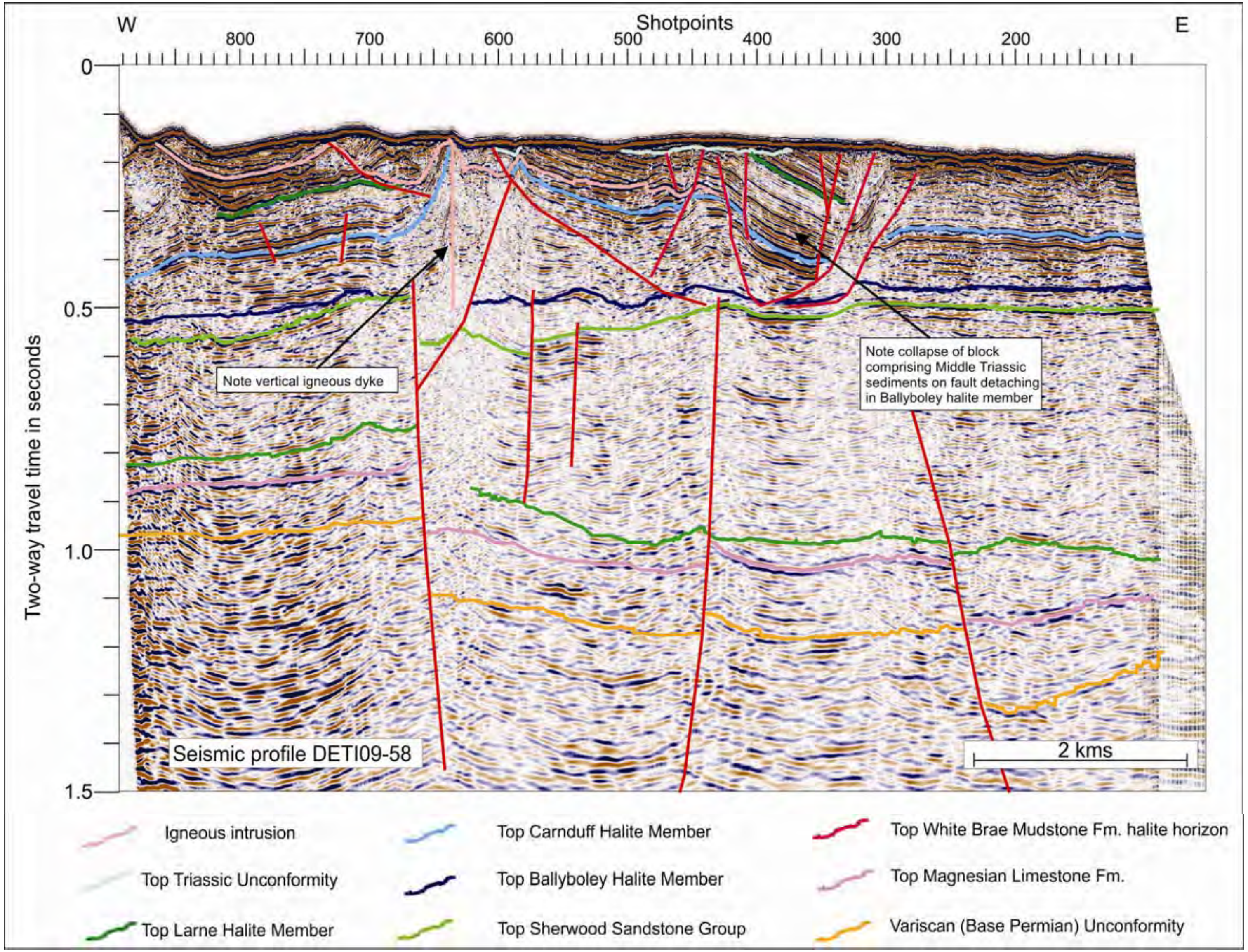

Figure 11. Seismic profile DETI09-58, located just south of Maidens Complex, showing Magnesian Limestone, Sherwood Sst., Ballyboley and Carnduff halite horizons at depths similar to those recorded in the Larne No. borehole. (Profile location shown in Figure 1).

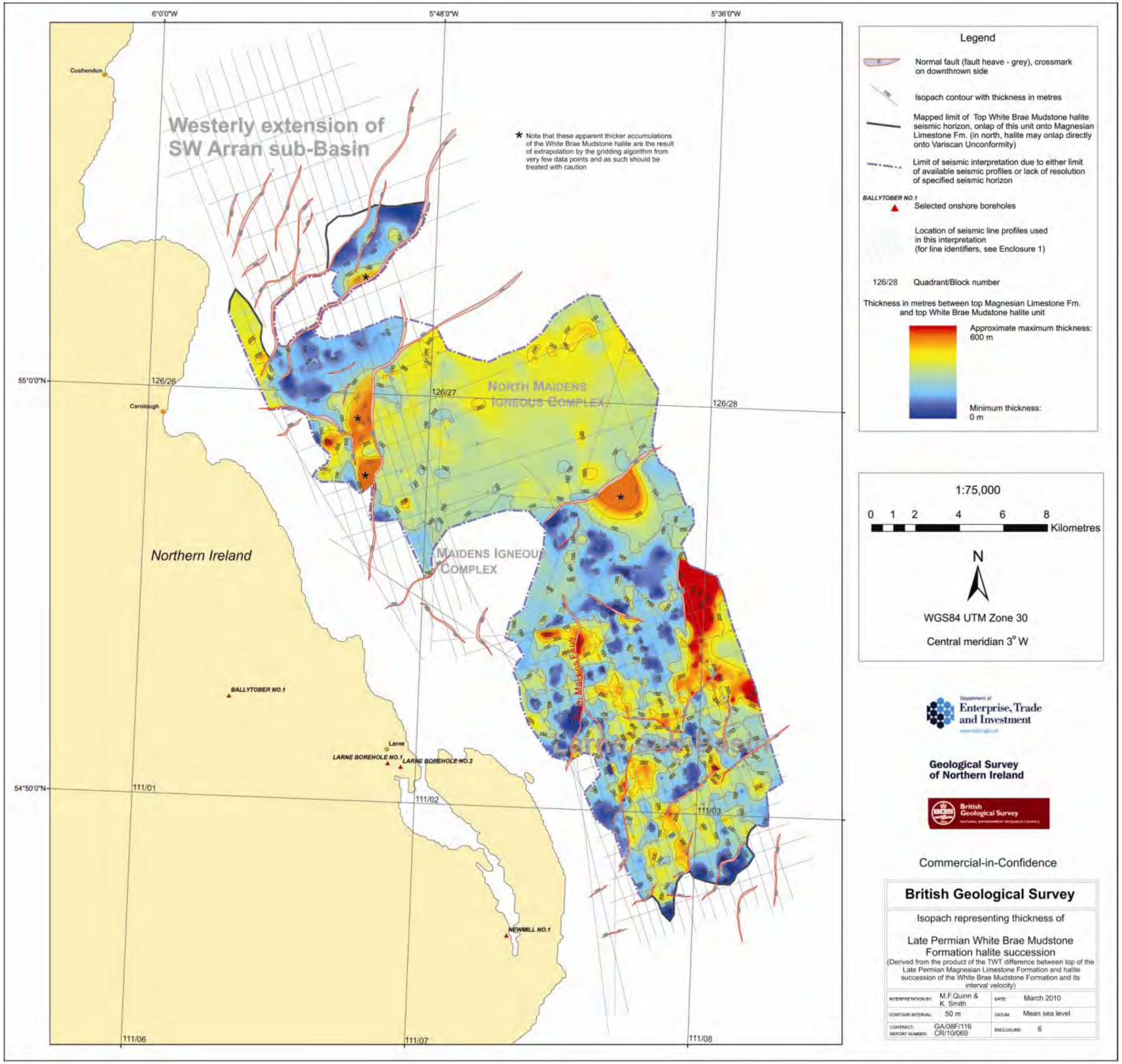

Figure 12. Thickness of White Brae Mudstone halite unit in metres (For full scale map, refer to Enclosure 6 in Volume 2 of this report).

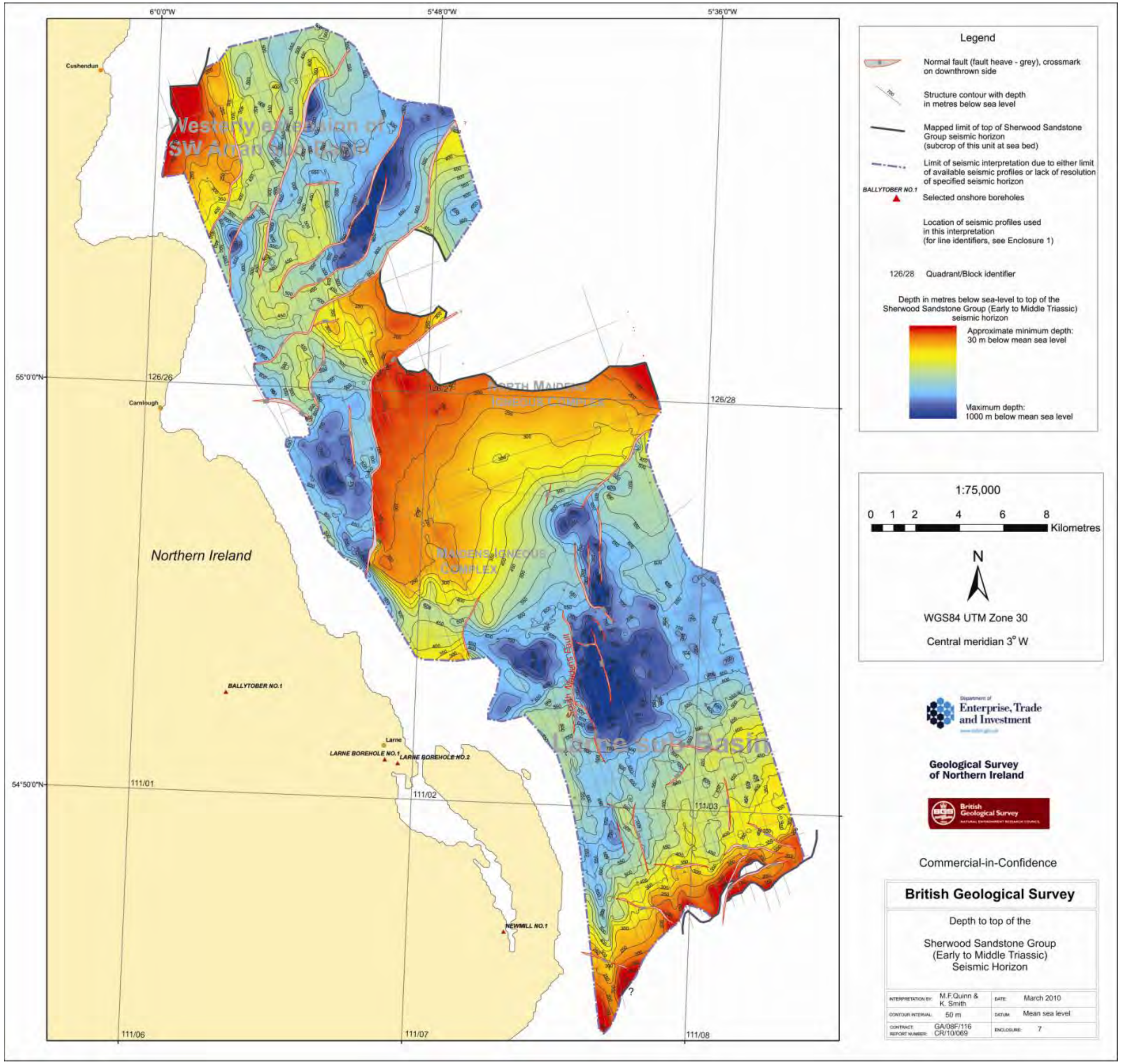

Figure 13. Depth to top Sherwood Sandstone Group in metres below mean sea level (For full scale map, refer to Enclosure 7 in Volume 2 of this report).

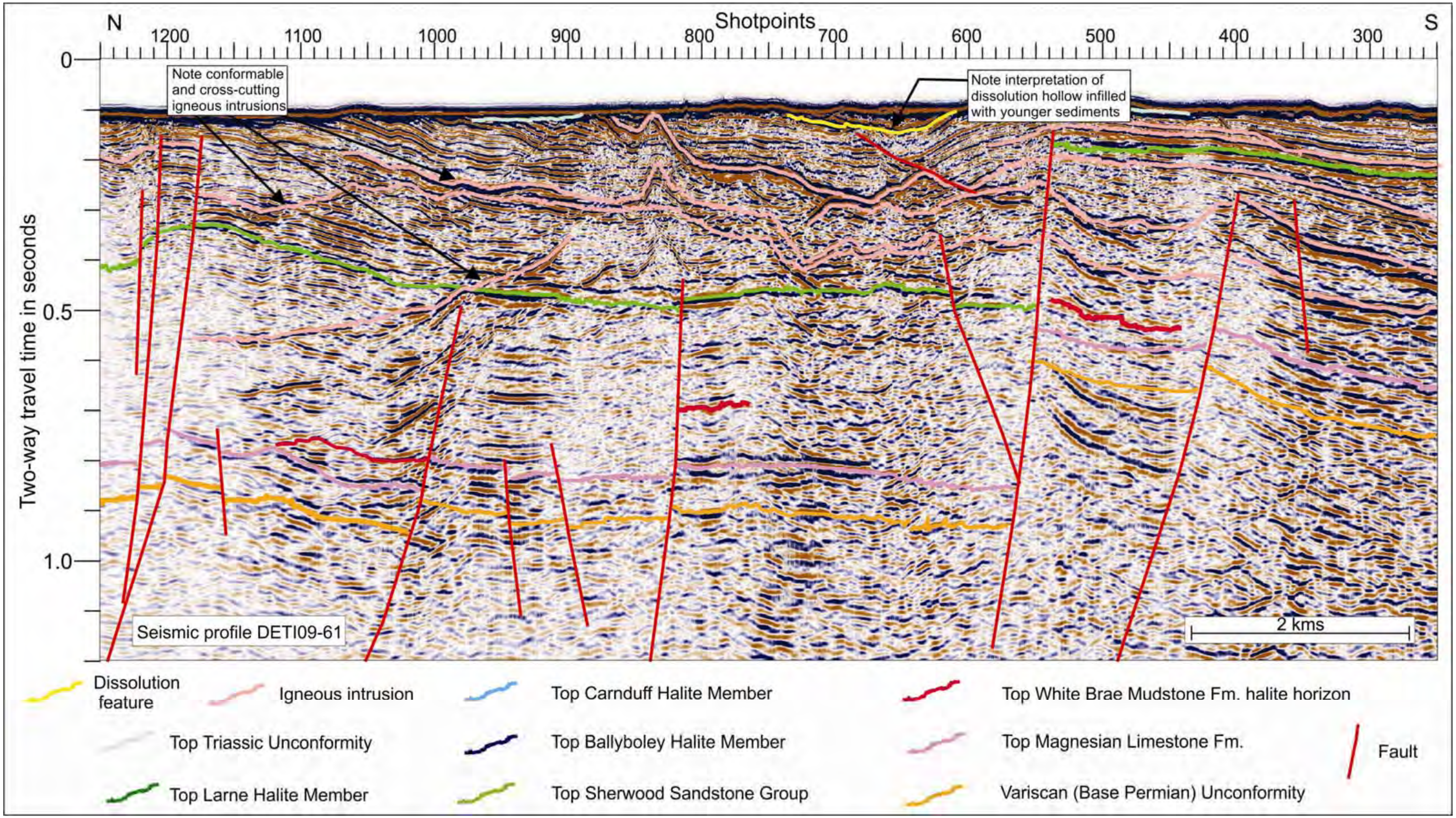

Figure 14. Seismic profile DETI09-61, located in the Northern area, showing several cross-cutting and conformable igneous intrusions (dykes and sills) mainly within the Mercia Mudstone Group succession (Profile location shown in Figure 1).

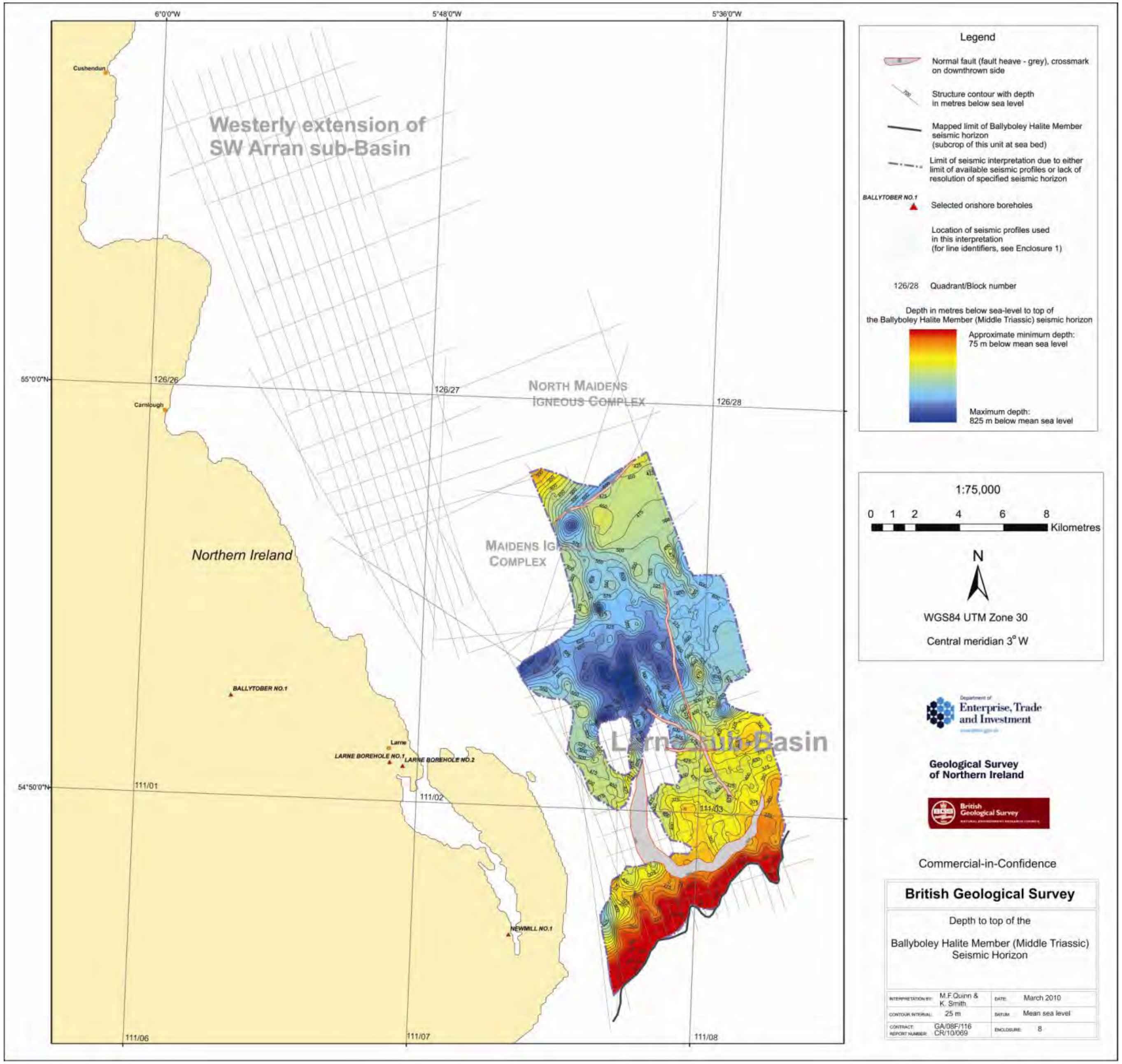

Figure 15. Depth to top Ballyboley Halite Member in metres below mean sea level (For full scale map see Enclosure 8 in Volume 2 of this report).

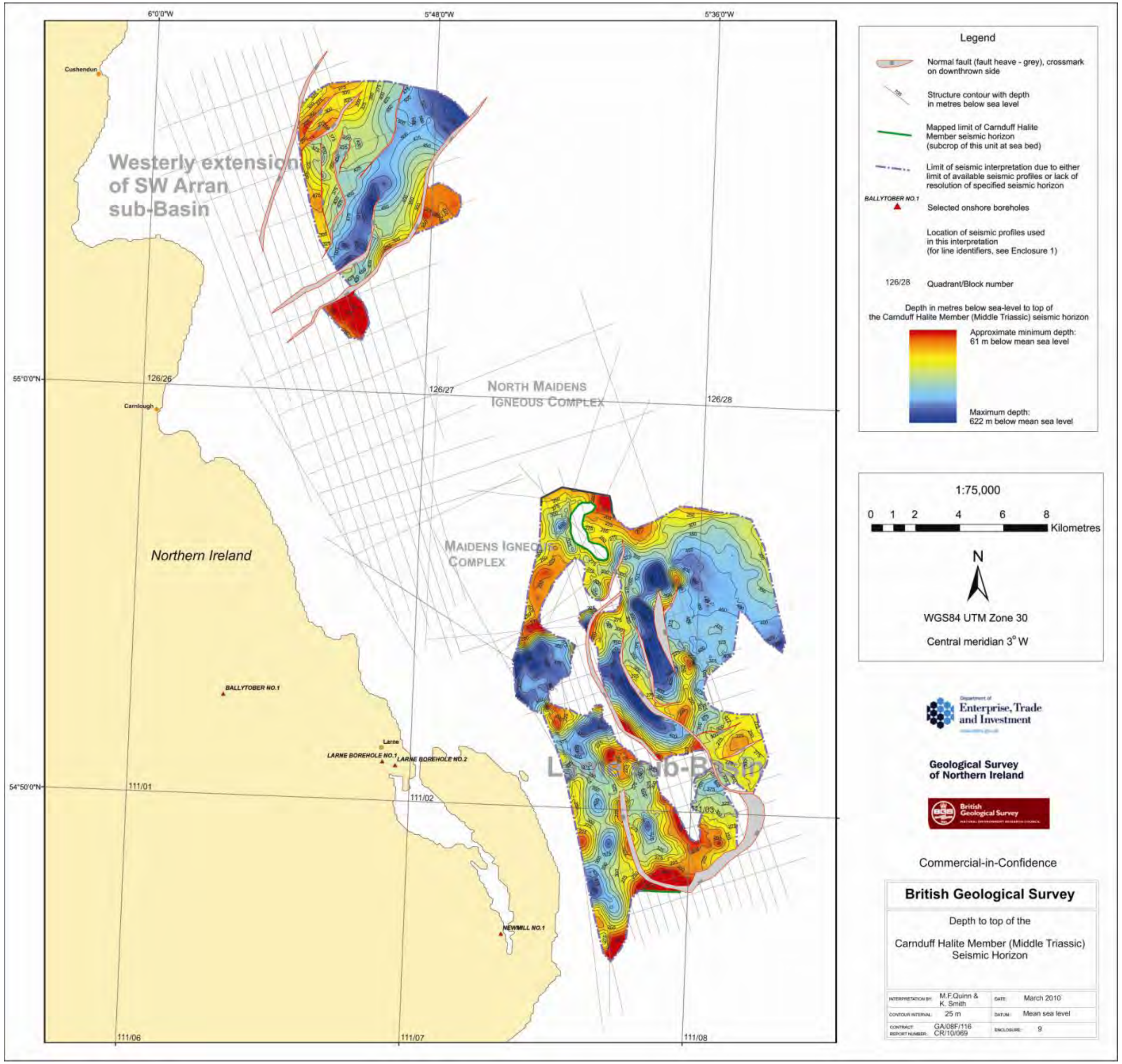

Figure 16. Depth to Carnduff Halite Member in metres below mean sea level (For full scale map, refer to Enclosure 9 in Volume 2 of this report).

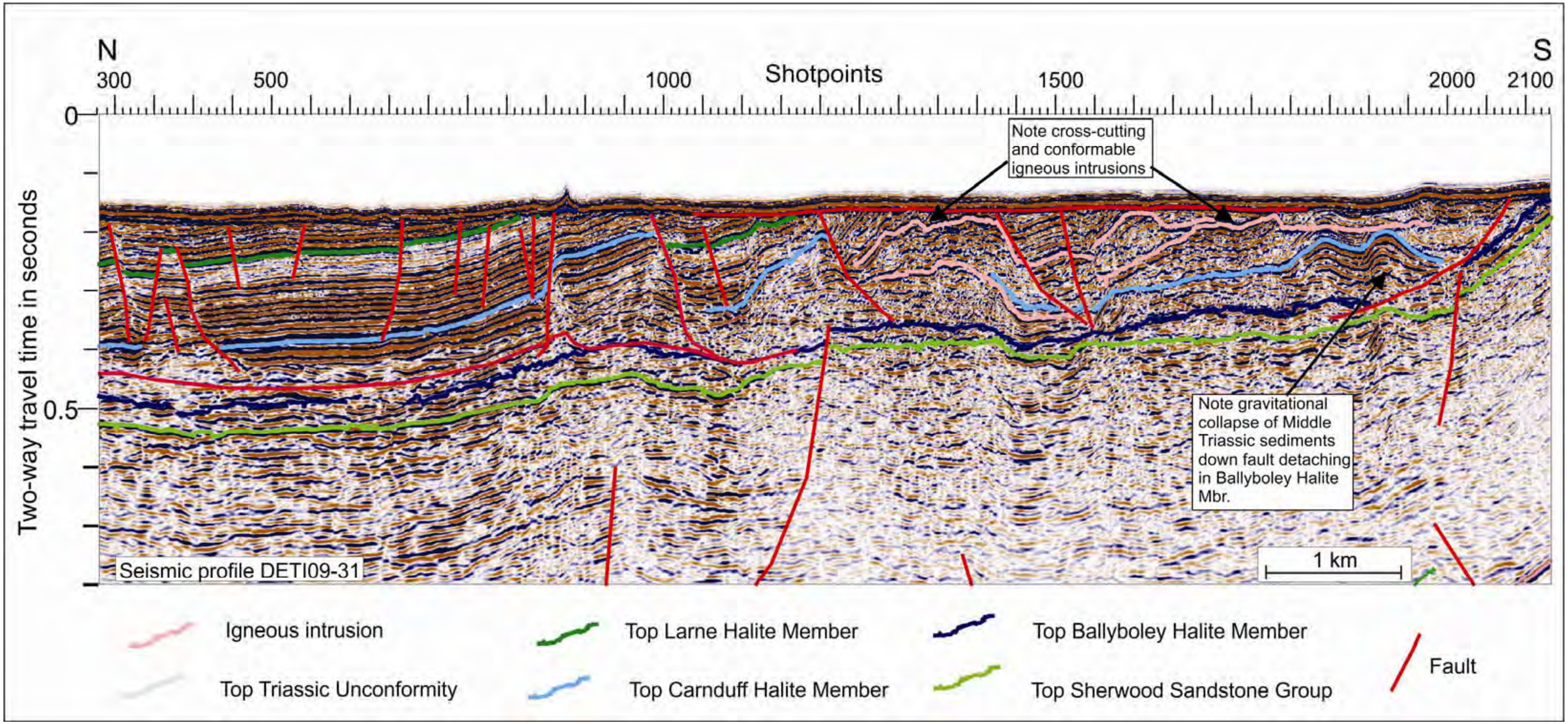

Figure 17. Seismic profile DETI09-31, located across the Southern area, showing regional structural style within the Mercia Mudstone Group, the base of which is marked by the Top Sherwood Sst Gp. horizon (Profile location shown in Figure 1).

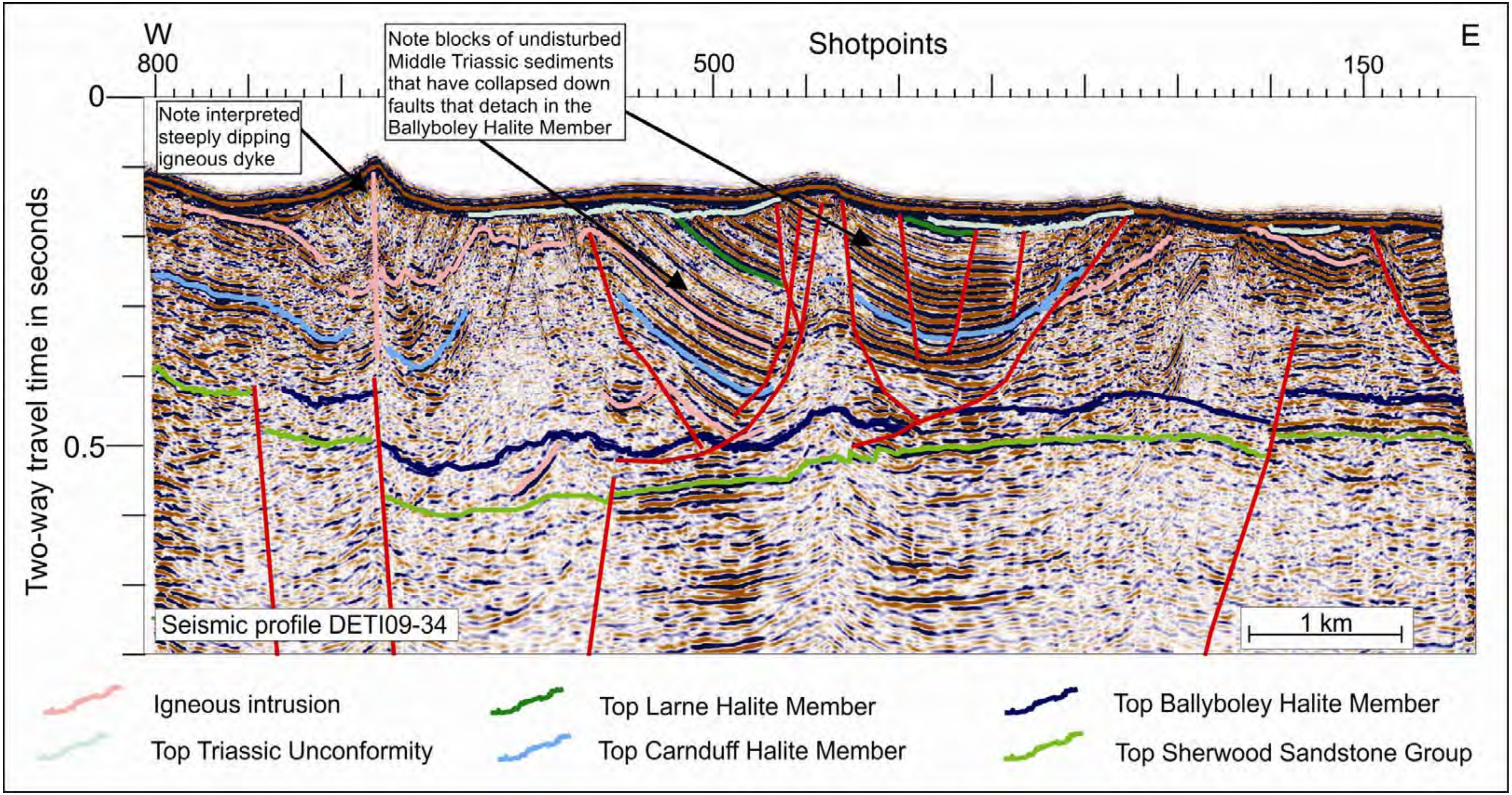

Figure 18. Seismic profile DETI09-34, located across Southern area, showing regional structural style of the Mercia Mudstone Group, the base of which is marked by the Top Sherwood Sst Gp. horizon (Profile location shown in Figure 1).

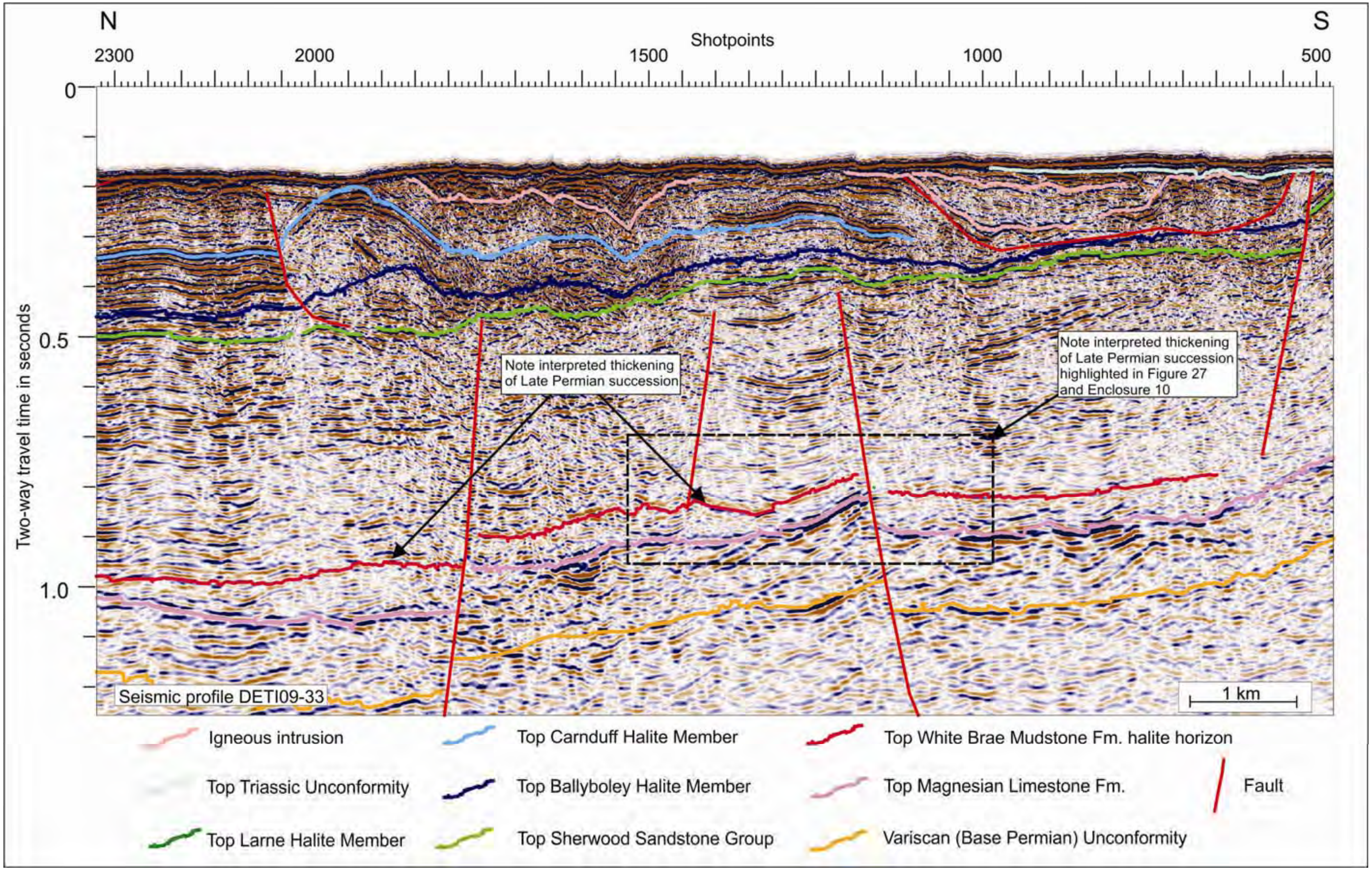

Figure 19. Seismic profile DETI09-33, located in the Southern area, showing Top Late Permian salt interpretation (Profile location shown in Figure 1).

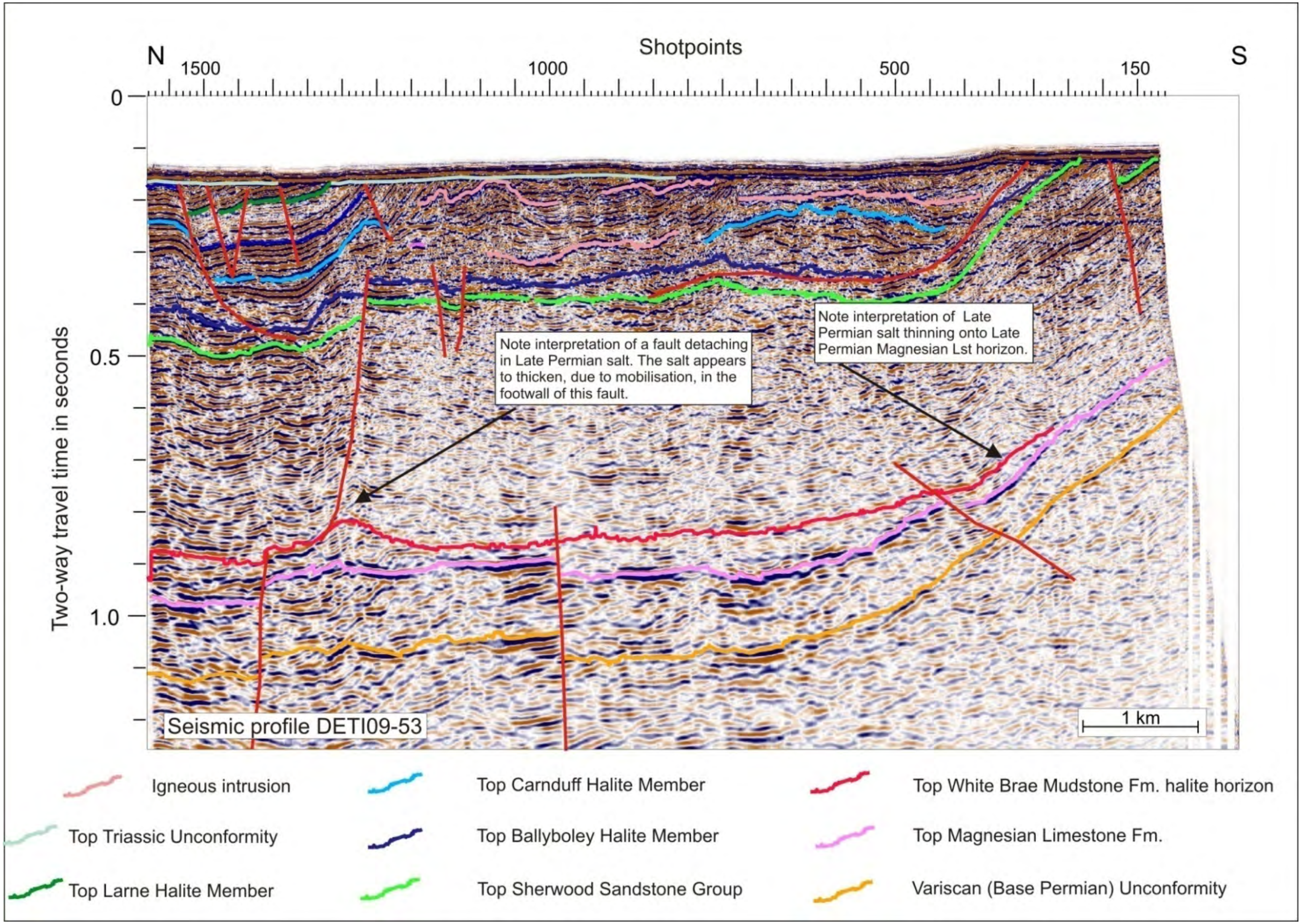

Figure 20. Seismic profile DETI09-53, located in Southern area, showing possible mobilisation of Late Permian salt and thinning onto Magnesian Limestone Fm. Detachment of fault within Late Permian salt is also illustrated (Profile location shown in Figure 1).

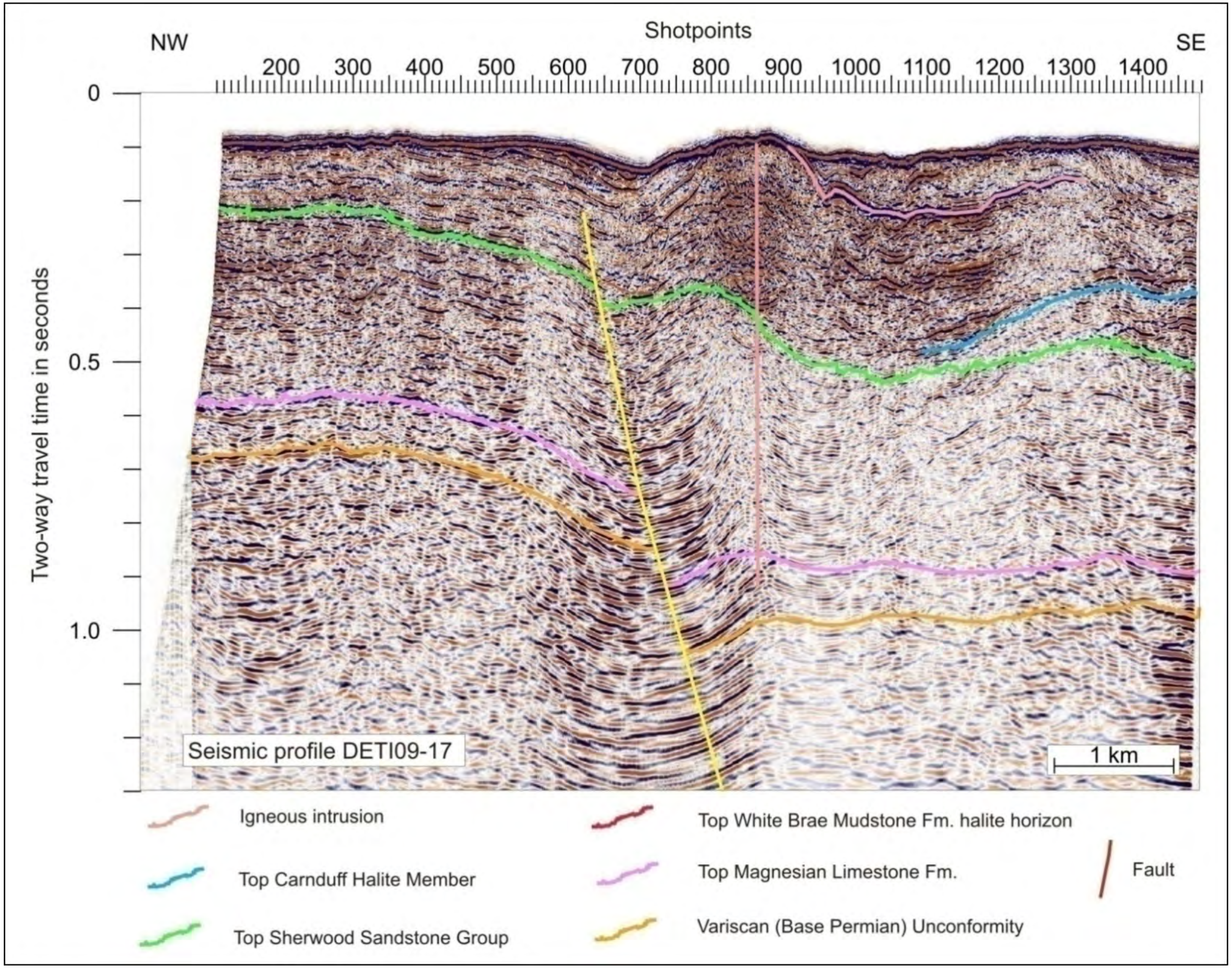

Figure 21. Seismic profile DETI09-17, located immediately west of the Maidens Igneous Complex, showing quality of seismic data in this area (Profile location shown in Figure 1).

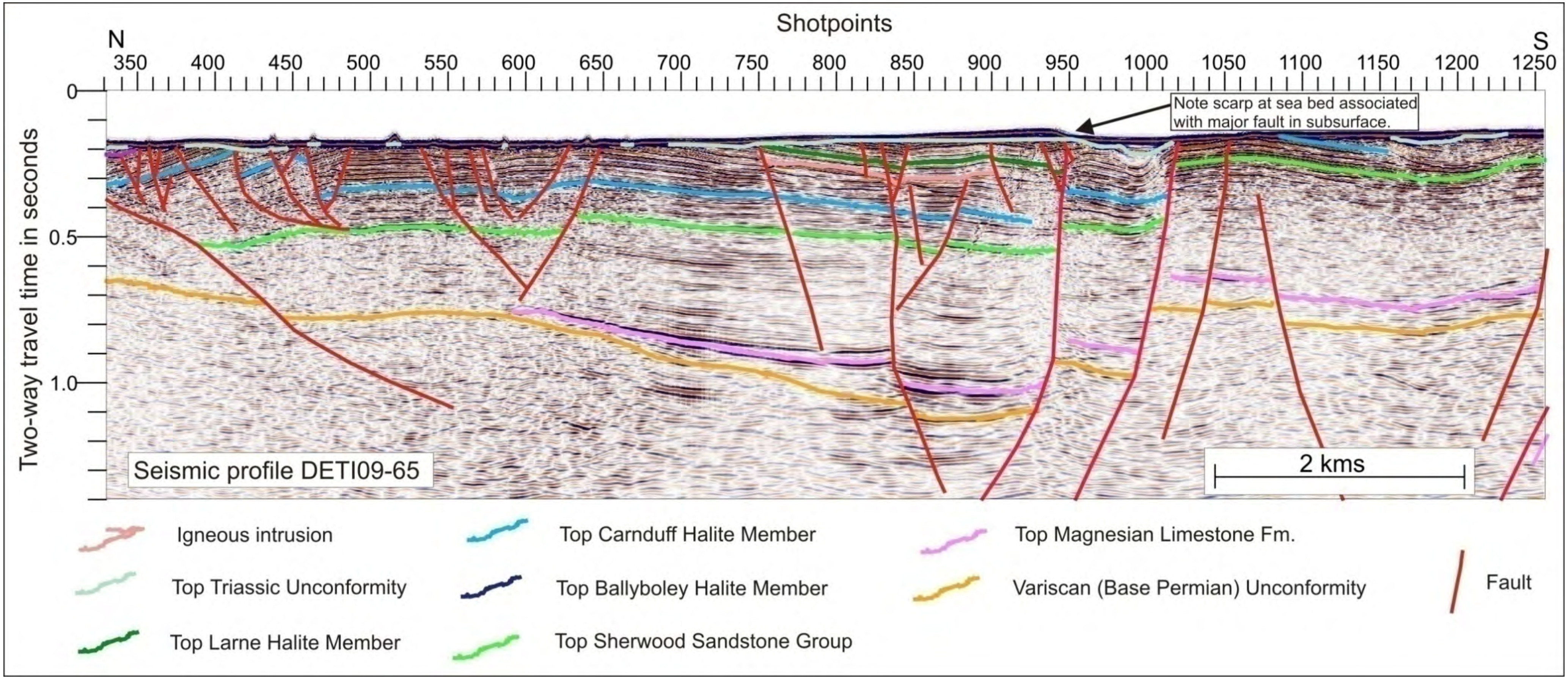

Figure 22. Seismic profile DETI09-65, located in northern area, showing major subsurface fault associated with sea bed topography (Profile location shown in Figure 1).

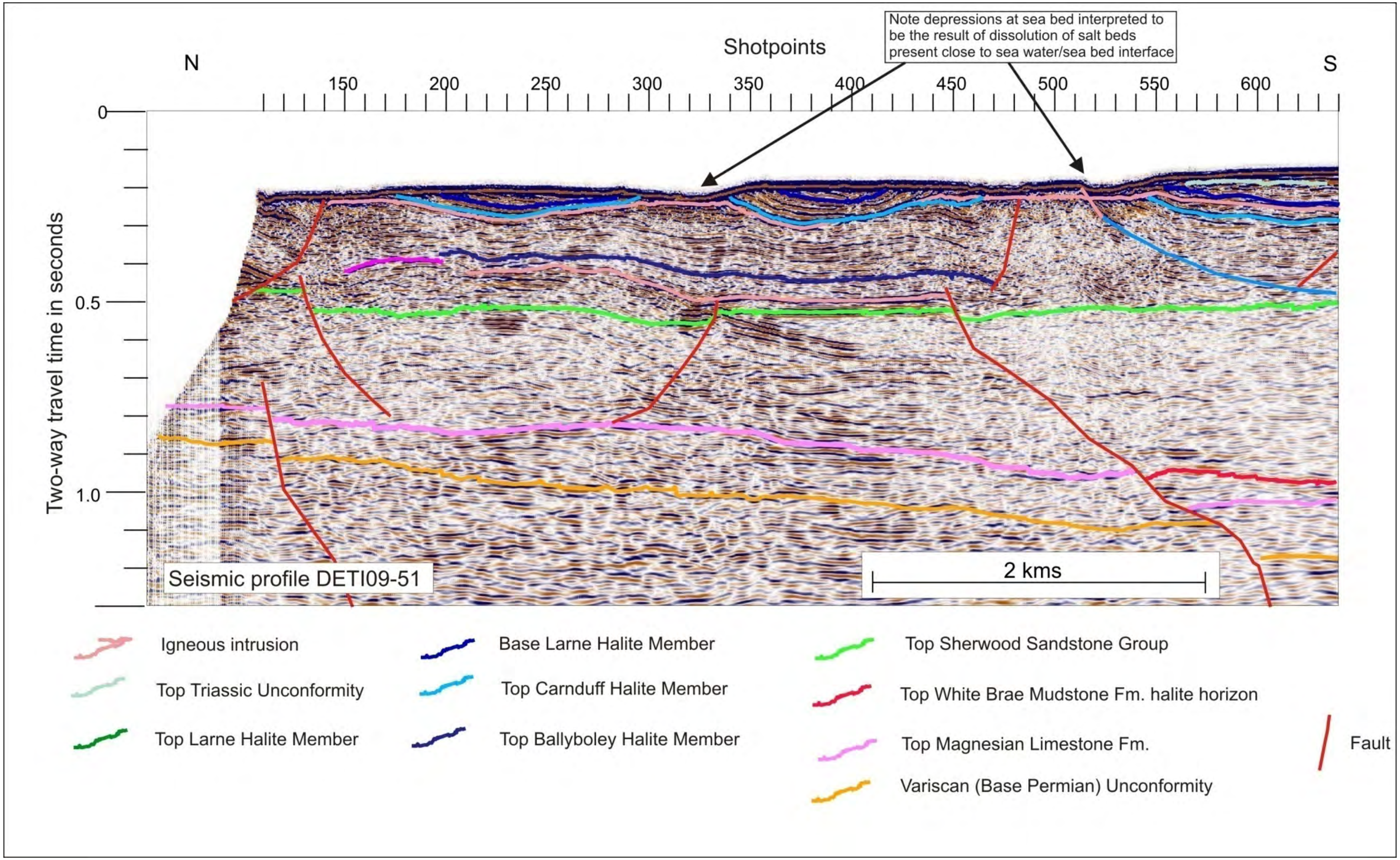

Figure 23. Seismic profile DETI09-51, located just east of Maidens Igneous Complex, showing examples of sea bed features related to dissolution of salt layers (Profile location shown in Figure.

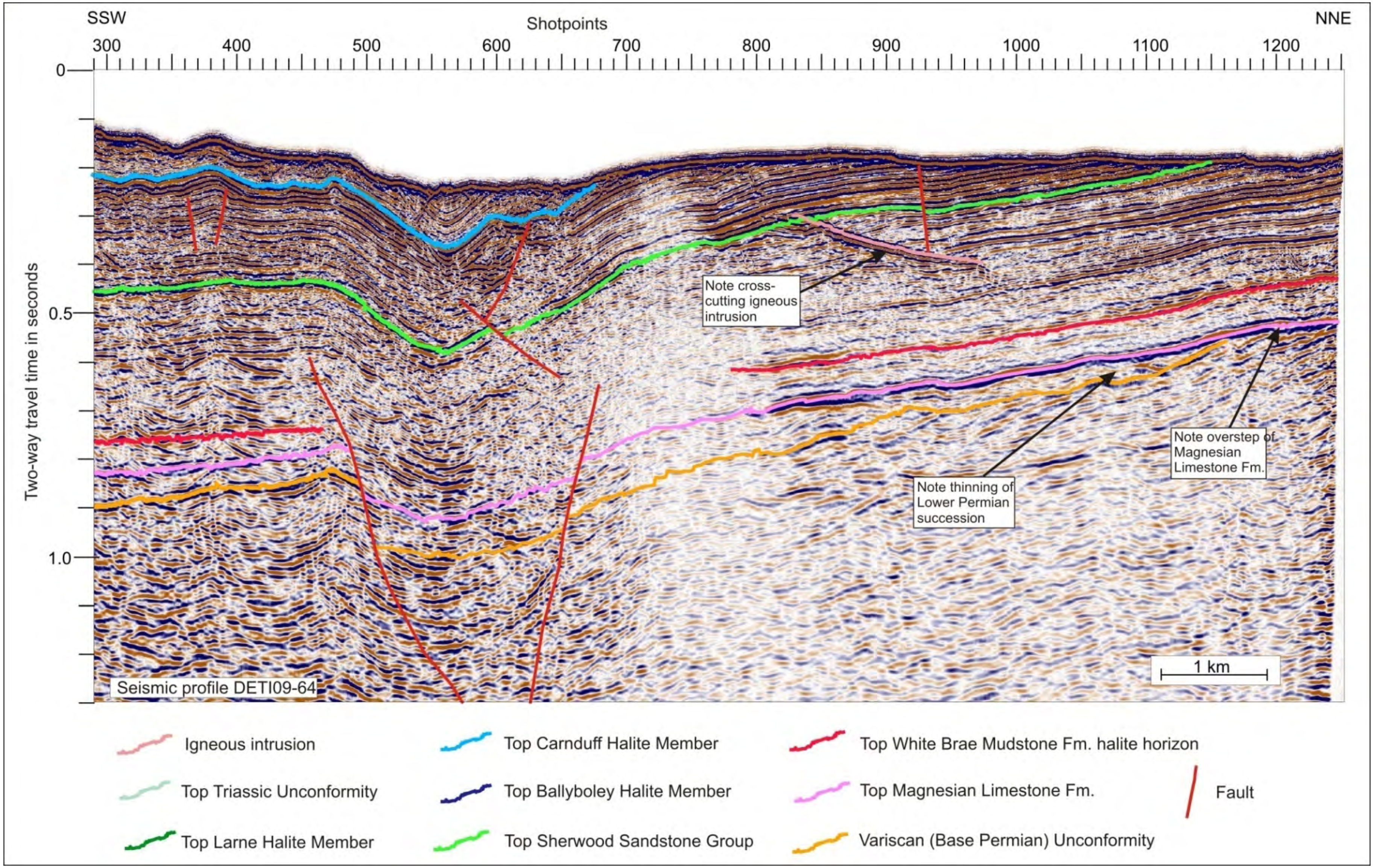

Figure 24. Seismic profile DETI09-64, located just to SE of Maidens igneous complexes, showing thinning of Lower Permian succession and overstep of Magnesian Limestone horizon to NE. Also note cross-cutting sill (Profile location shown in Figure 1).

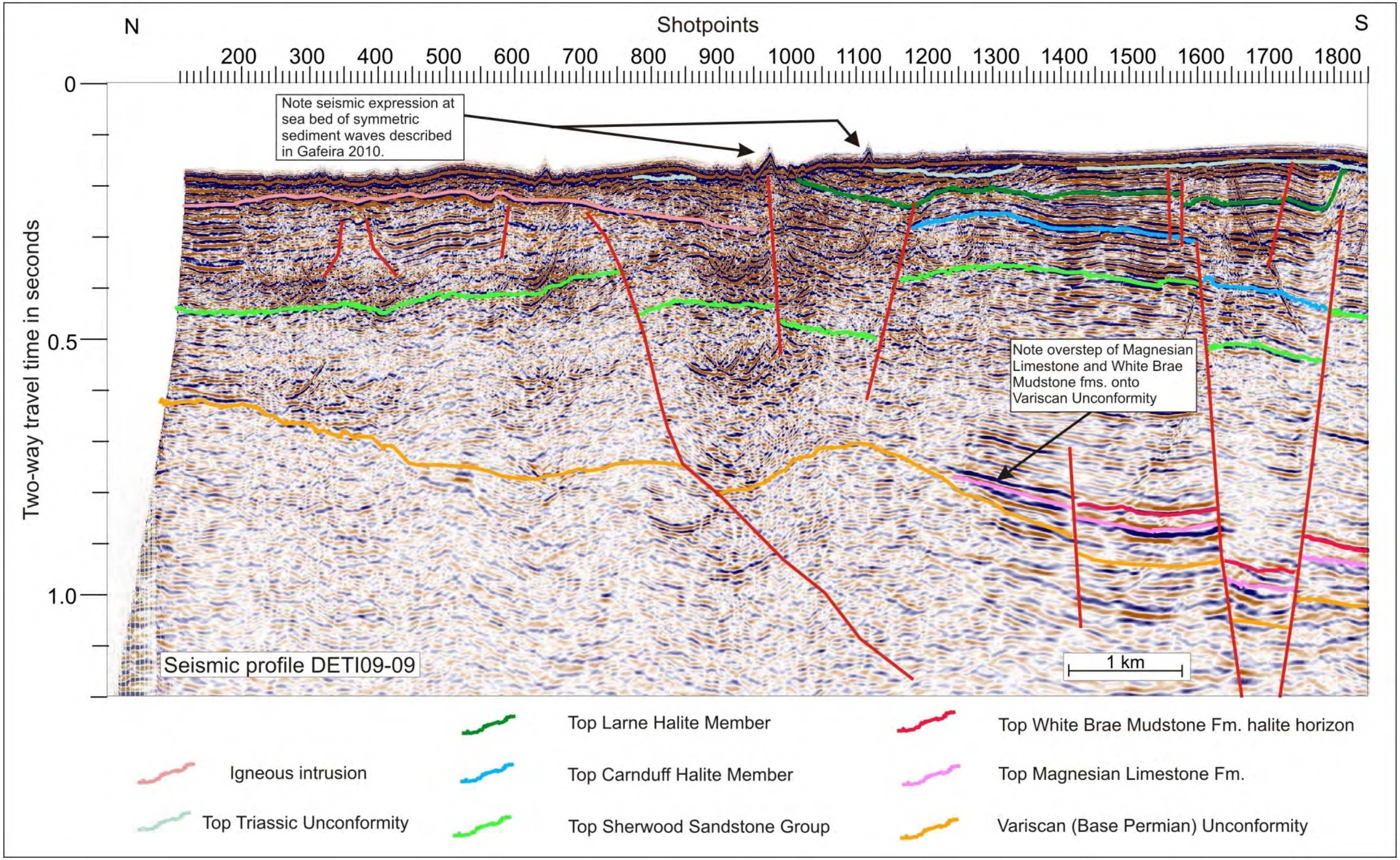

Figure 25. Seismic profile DETI09-09, located in northern area, showing onlap of top Magnesian Limestone and White Brae Mudstone horizons onto Variscan Unconformity (Profile location shown in Figure 1).

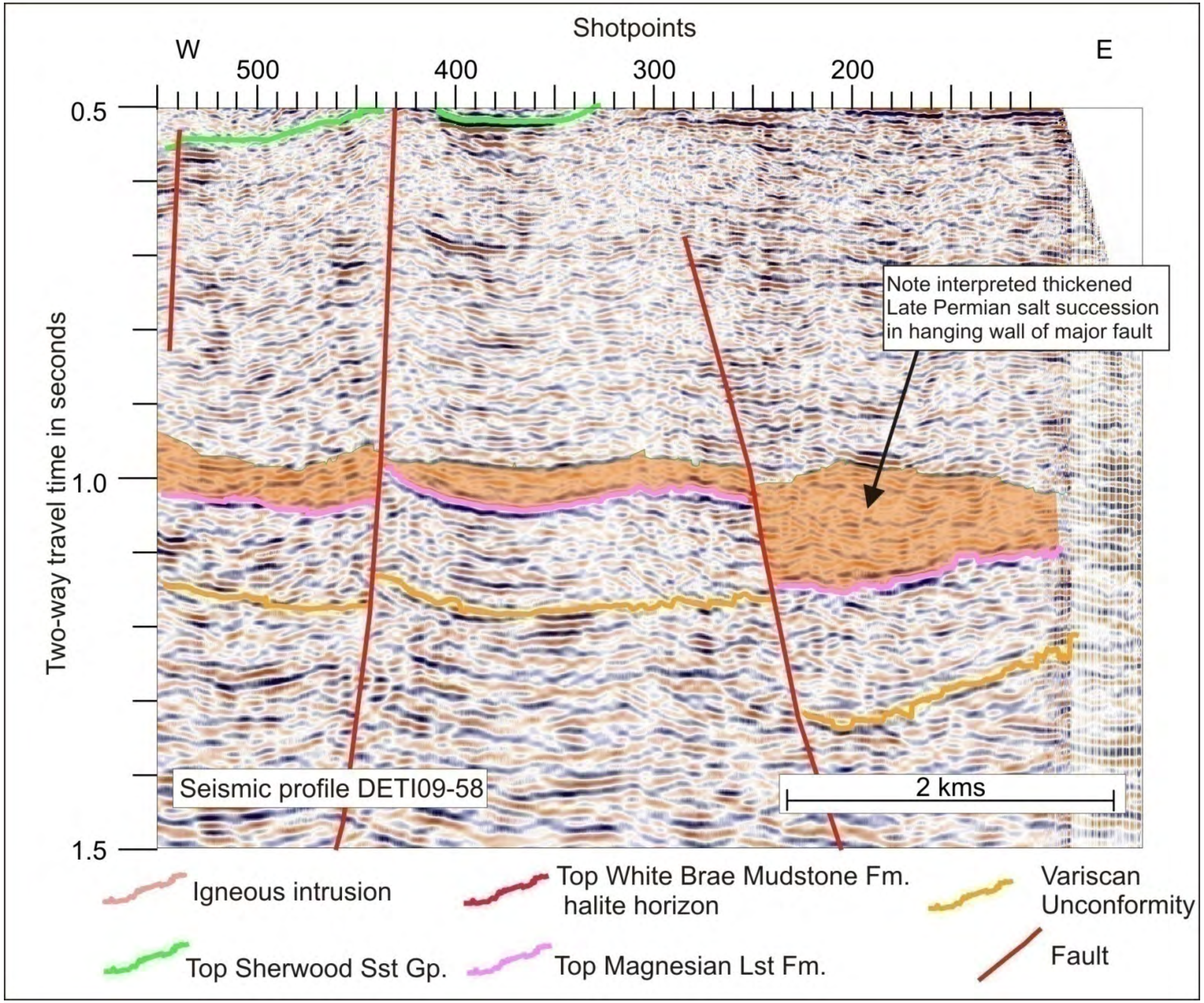

Figure 26. Seismic profile DETI09-58, located in the Southern area, showing interpreted thickening of Late Permian salt succession east of major N-trending fault (Profile location shown in Figure 1).

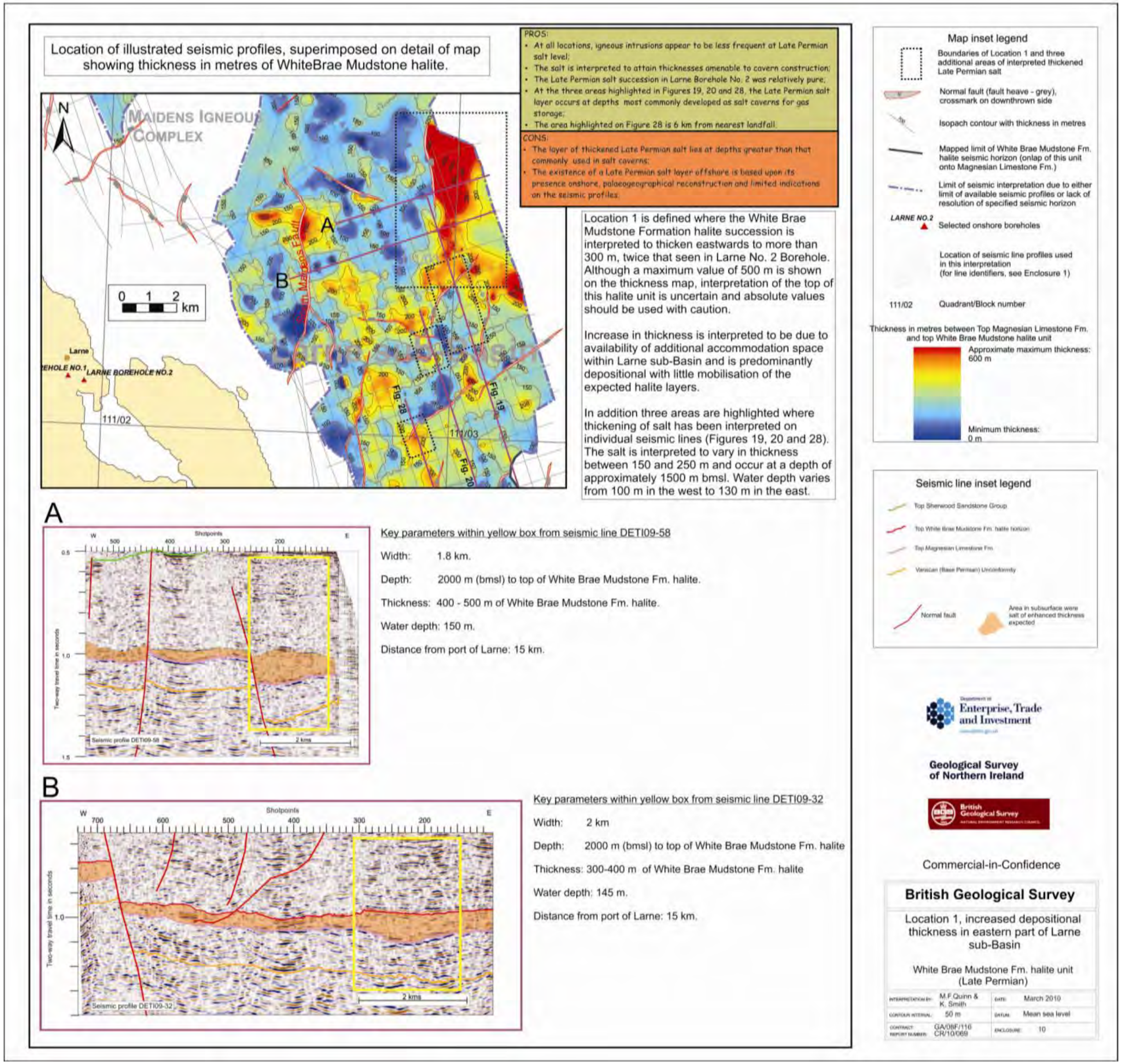

Figure 27. Location 1, increased depositional thickness in eastern part of Larne sub-basin. White Brae Mudstone Fm. halite unit (For full scale view, refer to Enclosure 10).

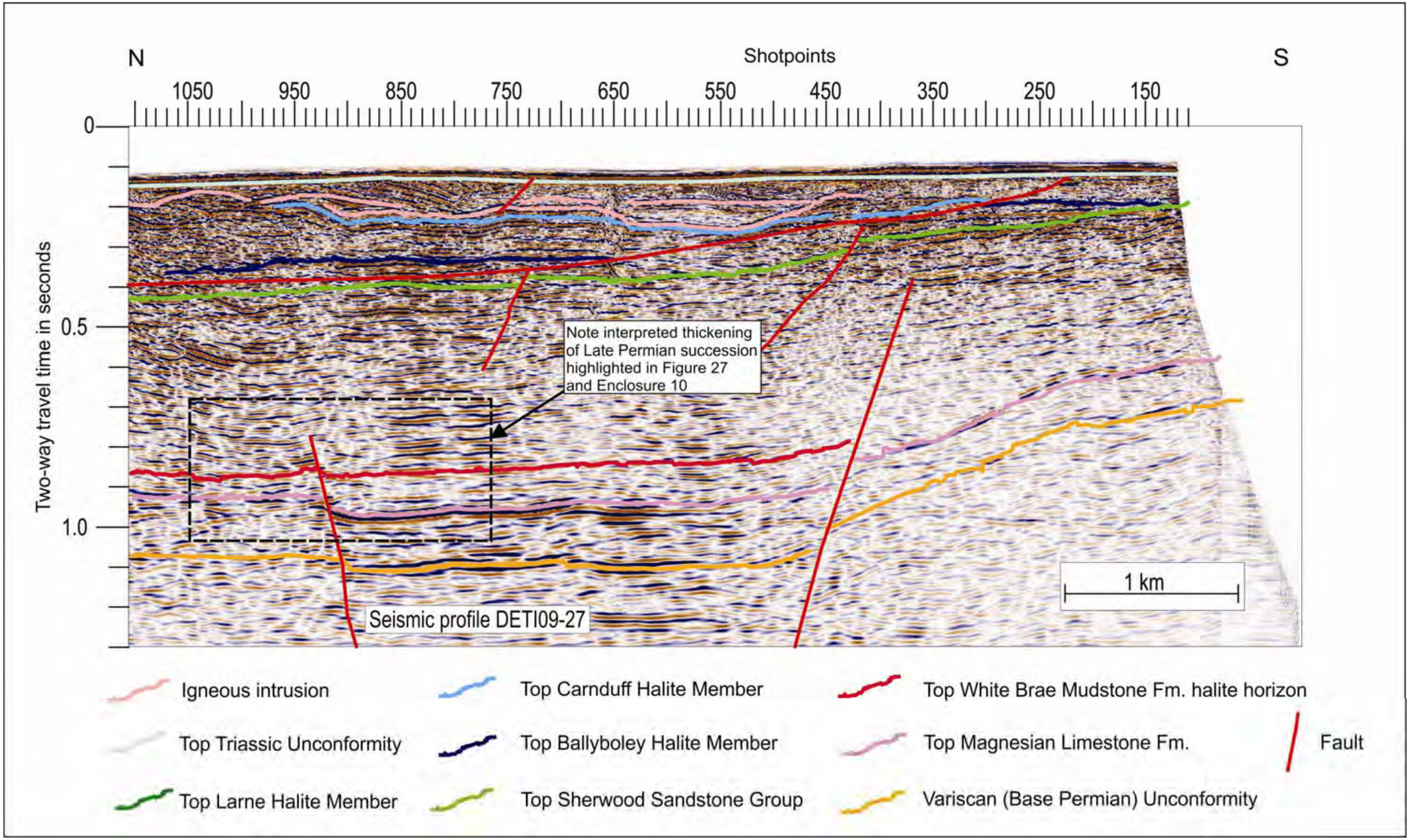

Figure 28. Seismic profile DETI09-27, located in the Southern area, illustrating interpreted thicker Late Permian salt layer south of fault cutting Permian succession (Profile location shown in Figure 1 and Figure 27).

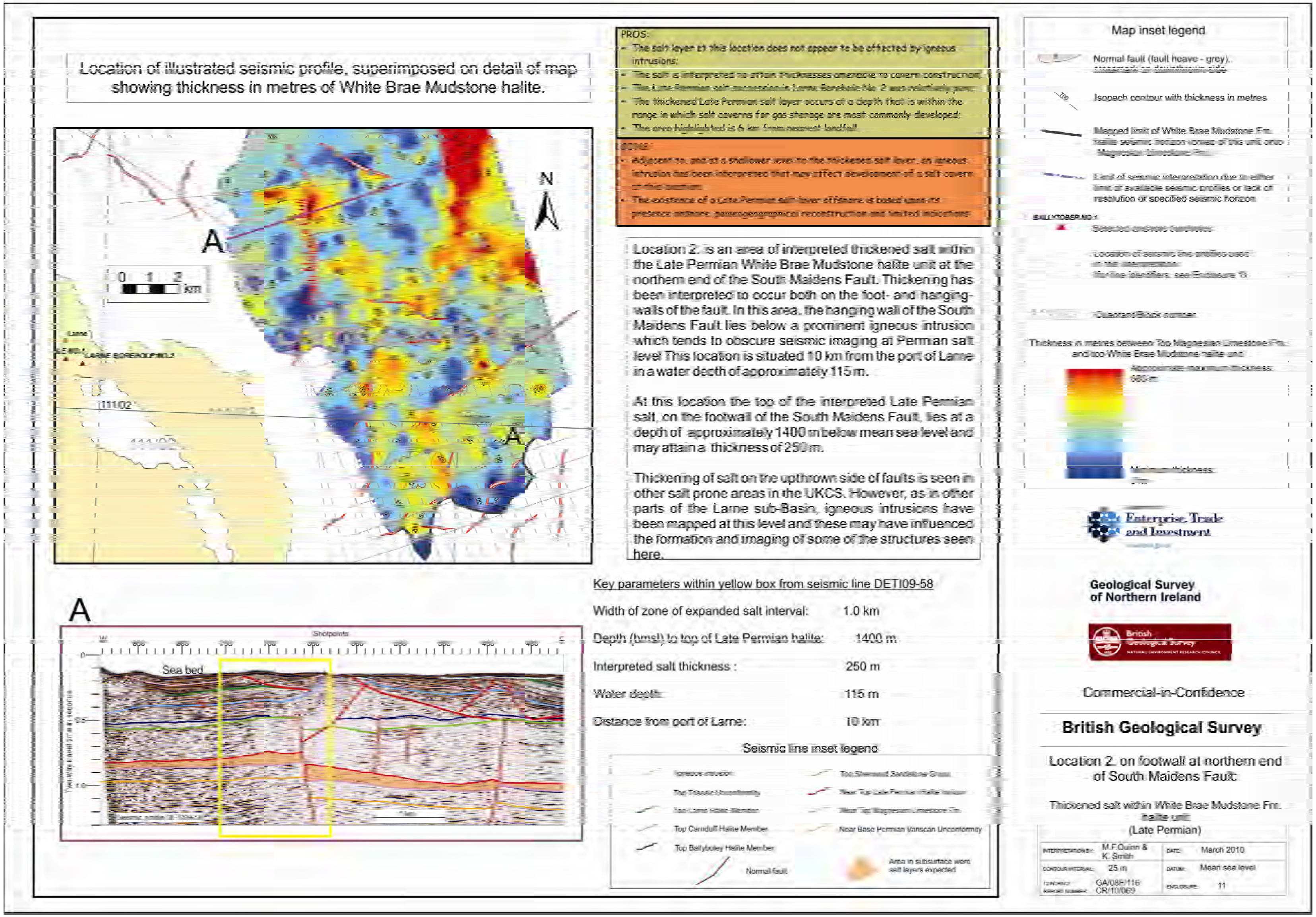
Location of illustrated seismic profile, superimposed on detail of map showing thickness in metres of White Brae Mudstone halite.
N
A
0 1 2 km
Larne
LARNE BOREHOLE NO.2
111/02
A'
PROS:
The salt layer at this location does not appear to be affected by igneous intrusions;
The thickened Late Permian salt layer occurs at a depth that is within the range in which salt caverns for gas storage are most commonly developed;
Location 2. is an area of interpreted thickened salt within the Late Permian White Brae Mudstone halite unit at the northern end of the South Maidens Fault. Thickening has been interpreted to occur both on the foot- and hanging-walls of the fault. In this area, the hanging wall of the South Maidens Fault lies below a prominent igneous intrusion which tends to obscure seismic imaging at Permian salt level. This location is situated 10 km from the port of Larne in a water depth of approximately 115 m.
At this location the top of the interpreted Late Permian salt, on the footwall of the South Maidens Fault, lies at a depth of approximately 1400 m below mean sea level and may attain a thickness of 250 m.
Thickening of salt on the upthrown side of faults is seen in other salt prone areas in the UKCS. However, as in other parts of the Larne sub-Basin, igneous intrusions have been mapped at this level and these may have influenced the formation and imaging of some of the structures seen here.
Map inset legend
Normal fault (fault heave - grey),
Isopach contour with thickness in metres
A
Sea bed
Key parameters within yellow box from seismic line DETI09-58
Width of zone of expanded salt interval: 1.0 km
Depth (bmsl) to top of Late Permian halite: 1400 m
Interpreted salt thickness : 250 m
Water depth: 115 m
Distance from port of Larne: 10 km
Seismic line inset legend
Enterprise, Trade and Investment
Geological Survey of Northern Ireland
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL
Commercial-in-Confidence
British Geological Survey
Location 2. on footwall at northern end of South Maidens Fault
(Late Permian)
M.F.Quinn & K. Smith
March 2010
25 m
Mean sea level
GA/08F/116
CR/10/069
11

Figure 29. Location 2, on footwall at northern end of South Maidens Fault: Thickened salt within White Brae Mudstone Fm. halite unit (For full scale view, refer to Enclosure 11).

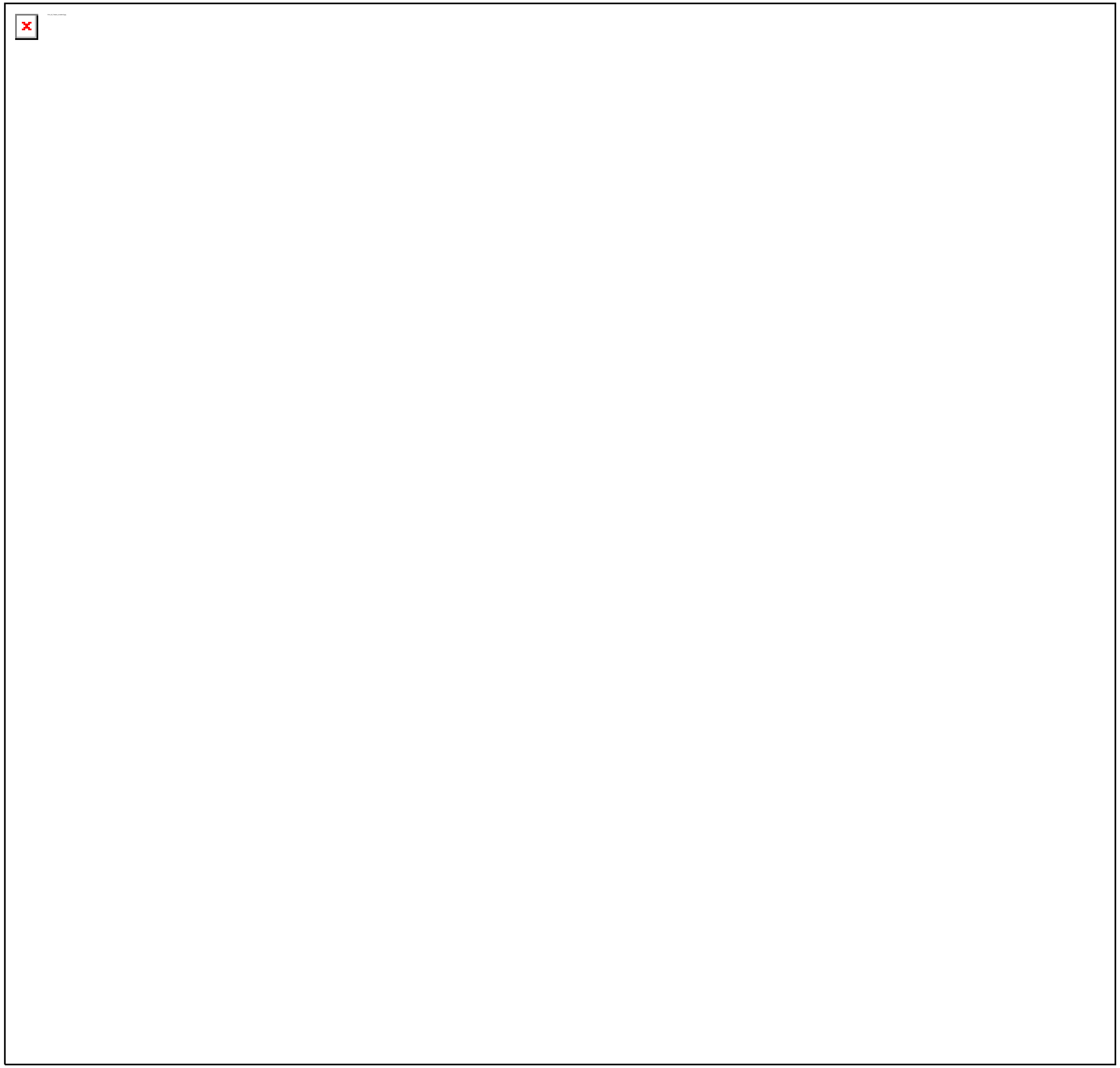

Figure 30. Location 3, NNW-trending high in Block 111/02: Thickened salt within Mercia Mudstone Fm. (For full scale view, refer to Enclosure 12).

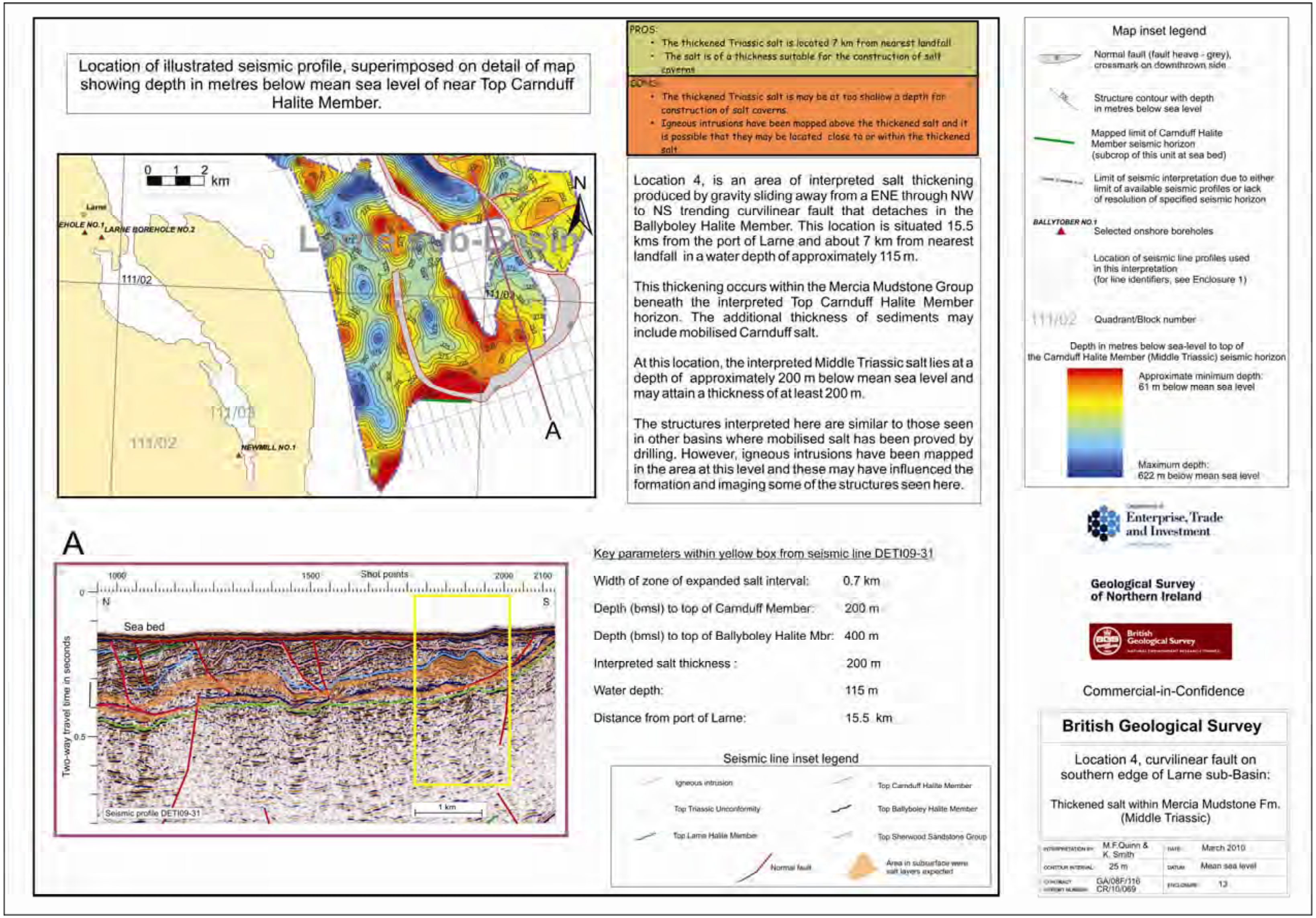

Figure 31. Location 4, curvilinear fault on southern edge of Larne sub-basin: Thickened salt within Mercia Mudstone Fm. (For full scale view, refer to Enclosure 13).