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The geology of the Preesall Saltfield area.

Sustainable & Renewable Energy Programme

Internal Report CR/05/183N

BRITISH GEOLOGICAL SURVEY

SUSTAINABLE & RENEWABLE ENERGY PROGRAMME

INTERNAL REPORT CR/05/183N

The geology of the Preesall Saltfield area.

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Foreword

This report is the published product of an appraisal by the British Geological Survey (BGS) of the geology and structural setting of the Preesall Saltfield, near Fleetwood, Lancashire. It represents a synthesis of subsurface data held by, and made available to, BGS and including borehole and seismic reflection data, to produce a three-dimensional representation of the main Triassic salt beds (Preesall Halite) near Preesall. It does not claim to be the final and definitive model, and it should be noted that outwith the area of the former brinefield, borehole data are sparsely distributed, with the model relying on the available seismic reflection data.

To date, these seismic data (including three Canatxx lines acquired in 1997) have been of limited use. However, reprocessing of British Gas and Canatxx seismic data during this study and the availability of an additional 1999 IELP line (also reprocessed during this study), has provided new data on the subsurface form of the Preesall Halite. Given the data distribution across the proposed area of development, this work can only represent a working model that is bound to be refined as more subsurface data are acquired.

Disclaimer: this is an appraisal and factual account of the geological conditions and structure of the Preesall Halite as presently understood. The model is based up on data held by BGS and those data supplied to BGS by Canatxx and/or Mott MacDonald for the purpose of this study. These data are publicly accessible. It is NOT an assessment of engineering issues or the technology of Underground Gas Storage (UGS) and the suitability of the Preesall Halite hereabouts for gas storage. Canatxx is separately advised by other experts on these issues.

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The BSI has provided the BGS with independent third party certification of its Management System and the interacting business processes across all its activities.

The scope of registration is:
Strategic, national surveys and related research, documenting the geology of the UK's onshore and offshore area, its petroleum, mineral, water and soil resources, geological hazards, and environmental vulnerability. The management and delivery of information that supports informed decision-making in respect of environmental protection and sustainable development. International operations in support of UK policies on development assistance.

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In July 2005 the BGS Keyworth and Edinburgh offices were awarded registration to ISO 14001:2004, the international environmental management standard (Registration Number EMS 80434). There is a growing demand from customers, suppliers and the community that business and industry show a visible commitment to improve environmental performance. BGS customers will now have the benefit of knowing that they are supporting an organisation, which follows the principles of environmental management with actions rather than words.

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Contents

Summary

This report was commissioned by Canatxx Gas Storage Limited, who requested BGS produce an assessment of the geology of the Preesall area and a 3D model of the (Triassic) Preesall Halite. The work was required ahead of a Public Inquiry into the proposed development of an underground gas storage facility in an area to the east of the River Wyre and west of a former ICI brinefield.

The main brief was to assess the geology, review borehole data held by BGS and additional borehole and seismic reflection data made available to BGS by Canatxx, and thereby provide the best-fit model from the current database. This has been completed.

This report therefore considers the data both held by BGS and supplied to BGS by Canatxx and/or Mott MacDonald, for the purposes of this study. The British Geological Survey (BGS) already possess a considerable borehole database. BGS was also supplied with the Canatxx database of the tabulated top and base salt of those ICI brinefield wells and shaft data that were not already available to, or held by, BGS. The result is that 745 boreholes over the western Fylde area that were pertinent to the study were coded and entered in to the model. Several seismic reflection lines were also made available and have been reprocessed as part of this study.

At a late stage, BGS gained access to velocity (sonic log) information from the Arm Hill and The Heads boreholes. These boreholes were drilled in early 2004 and permit calibration of the seismic reflection data, and identification of the Preesall Halite interval within the seismic data.

The findings and conclusions reached here will contribute to the other proofs of evidence to be submitted on behalf of Canatxx Gas Storage Limited for the Public Inquiry. It should be noted that this report forms a wholly independent assessment of the location, extent, and general characteristics of the Preesall Saltfield. The report has not considered points of issue such as rock salt (halite) quality and its suitability for underground gas storage as this is to be covered by other consultants' expert in these fields.

The main conclusions are as follows:

1. That the existing published BGS geological model for the Preesall Saltfield, published in 1975 (and later added to by Wilson & Evans, 1990), prior to the currently available seismic reflection data, requires modification. Originally shown as being preserved in the Preesall Syncline, the saltfield is now seen as preserved in a fault bounded (downfaulted) graben, the controlling faults to which are the Preesall Fault zone in the east and the Burn Naze Fault in the west.
2. Borehole data are, naturally, concentrated in the area of the former ICI brinefield. In the area of the proposed site, borehole data are fewer and more scattered, but now include two recent wells (one cored through the salt interval) drilled by Canatxx in 2004. These data are also augmented by 14 kms of seismic reflection data in the region of interest.
3. When compared with those borehole data held by BGS and to which reference could be made, inconsistencies and discrepancies regarding the borehole information, including borehole heights (ground level), terminal depths (TD) and the depths and/or thickness of the Preesall Halite exist in the Canatxx/ICI borehole database supplied to BGS.
4. The supplied borehole database implies many of the ICI wells reached TD in the Preesall Halite. However, this study would suggest that many (perhaps most?) penetrated through the halite and reached terminal depth (TD) in the underlying Thornton Mudstones.
5. The inconsistencies and differences in interpretation in some of the boreholes might be expected in a large dataset, parts of which date back to the early 1870's. BGS has, therefore, reappraised the available borehole information, providing a consistent interpretation of the lithologies encountered in the boreholes.
6. The present seismic interpretation follows on from previous studies in the area (Daran Petroleum, 1996; Jenyon, 1997). These earlier studies used seismic reflection data originally acquired in the mid-late 1980's and 1990's, and which were reprocessed during 1996. Jenyon (1997) also had access to three Canatxx lines acquired during 1997. The quality of these data was variable, but their interpretation led to a series of maps of the Preesall Halite, showing a number of generally down-west faults running NE-SW across areas of the proposed site.
7. These seismic reflection data were again reprocessed during this study. Data quality has been improved, and these data now begin to reveal the structure of the halite in the area of the

proposed site, augmenting the available borehole data and providing a better understanding of structure and distribution of the Preesall Halite.

8. From these seismic reflection data, it is thought the Preesall Halite thickens to the west within the Preesall Graben, and, along with the enclosing Triassic mudstones, is affected by smaller subsidiary down-east and down-west faults.

9. The faults are mapped trending NNW across the southern parts of the area of interest (notably between BNG Northing 445000 and 446000). The faults appear to be in the main down-east normal faults that cut both the top and base of the halite. The halite is thinned by faulting across this zone.

10. It is estimated that depths to top Preesall Halite in the west of the study area, adjacent to the down-east Burn Naze normal fault vary from around 168 m below Ordnance Datum (OD) in the ICI-E27 borehole towards the southern end of the area (west of Canatxx's The Heads borehole), to perhaps less than 150 m below OD between BNG Northings 445000 and 446000, and then deepening to around 360 m below OD in the area to the SW of the ICI-B6 and Canatxx Arm Hill boreholes.

11. The seismic reflection data indicate that the base of the Preesall Halite may deepen to around 700 m below OD (thereby thickening to circa 550 m), between BNG Northings 445000 and 446000. However, due to the relative paucity of borehole data in the area of interest, thickness and depth estimates must be viewed as not tightly constrained. Additional information will help refine the depth conversion and accuracy of subsurface mapping and hence the model of the Preesall Halite.

12. This study indicates that the seismic reflection technique, providing the data are carefully acquired and processed, provides valuable subsurface information and aids the geological characterisation of the Preesall Saltfield area.

13. Borehole geophysical logs (notably Gamma ray) from the 2004 Canatxx Arm Hill and The Heads boreholes show log characters/motifs that can be correlated between boreholes. The logs indicate that thin mudstones (or series of thin mudstones and halite beds) within the main halite are developed and can be recognised across the proposed area. They indicate that such logs in the future could be used to successfully characterise the Preesall Halite in this region.

14. Although the Preesall site is in an area which is dominated by geological structures that could be considered as liable to reactivation, observed seismicity in the recent geological past on these structures has been low. Perhaps only the 17 March 1843 earthquake was responsible for a magnitude 5.0 ML event. The likelihood of any fault reactivation near the site causing a direct rupture hazard is thus considered extremely small. The larger UK earthquakes have depths considerably in excess of their rupture dimensions. From historical records, the maximum observed intensity at site is just below the damage threshold.

15. For these reasons, a full probabilistic seismic hazard assessment (PSHA) at the Preesall site has not been undertaken. Seismic hazard at the site is seen as being dominated by the effects of large (in UK terms) earthquakes at distances of tens of kilometres, which have the potential to cause ground motion at site. The hazard at site is thus considered average for the UK.

1 Introduction

This report summarises the geology and structure of the Preesall Saltfield in the western Fylde area of Lancashire. The Preesall Halite (rock salt of Triassic age) has been worked since the late 1800's after having been discovered by accident during the exploration for iron ore (haematite).

The present work was requested following a meeting between Mr Peter Sharp of Mott MacDonald and David Evans of BGS, held at Mott MacDonald's offices in Altrincham on the 1st August 2005. At that meeting it was explained that Canatxx Gas Storage Ltd intend to develop an underground gas storage facility in caverns engineered through controlled solution mining of the Preesall Halite. As such, Canatxx asked BGS to produce an assessment of the geology and provide a geological model of the Preesall Saltfield area, defining the structure and distribution of the Preesall Halite body. This model was to use borehole and seismic reflection data available in the area (Fig. 1).

On the 24th August 2005, BGS received the signed contract from Mr Michael Brown of Canatxx Gas Storage Ltd. and instruction to commence the work.

This report, therefore, represents a wholly independent review of the geology and structure of the Preesall Saltfield area on the western Fylde. It presents a model of the Preesall Halite based upon a significant set of publicly available subsurface data in the area, which in this region is dominated by borehole information. The density of these data is greatest in the area of the former brinefield workings. Outwith the brinefield, across the area of interest, subsurface data are fewer and more scattered, but include a number of seismic reflection lines (refer Fig.1 and Appendix 1). The acquisition of further data in the latter area can only improve the present understanding of the subsurface geology and refinement of the geological model.

Prior to describing the geology of the Preesall area, brief outline of the UK halite deposits setting the Preesall Halite in regional context and a short discussion on faults, terminology and rock salt deformation is provided.

1.1 DISTRIBUTION OF UK SALT DEPOSITS

The UK possesses important salt-bearing strata of Permian and Triassic age. In England, these deposits provide huge resources, but are limited in both their geographical location (Fig. 2) and their thicknesses.

Permian salt deposits occur onshore in the UK, but are only worked in northeastern England (Fig. 2). Caverns constructed in these strata have, for many years, been used for storage of gas near Hornsea (Atwick) and there are a number of other sites currently planned or under development (e.g. Aldborough). A small number of caverns are also used for hydrogen storage in the Teesside area. There are no known equivalents onshore in the Preesall area, but thick Upper Permian halites are proved offshore to the west in the East Irish Sea Basin (Jackson et al., 1987; Jackson & Mulholland, 1993).

Onshore, the most important salt beds occur within the Triassic Mercia Mudstone Group (MMG), which has a widespread outcrop. However, salt-bearing strata are generally restricted to areas where the MMG thickens into major depositional basins that were initially fault controlled and formed part of a major rift system stretching from the East Irish Sea (Fig. 3), onshore onto the Fylde area and southwards into Cheshire, through Staffordshire Worcestershire and Somerset into Dorset and other areas of southern England (e.g. Whittaker, 1985; Chadwick & Evans, 1995).

The Cheshire Basin has the thickest and most important development of Triassic salt beds, being the source of 90% of total UK salt output (BGS, 2004). Two salt bearing formations are present in the Cheshire Basin: a lower Northwich Halite Formation (formerly the Lower Saliferous Beds) up to 280 m thick (with mudstone partings), and an upper Wilkesley Halite Formation (formerly the Upper Saliferous Beds) up to 405 m thick (BGS, 2004). The sequence between and below the salt formations consists mainly of red-brown gypsiferous and dolomitic mudstones and siltstones. Rock salt production is presently confined entirely to the Northwich Halite Formation. Cavities, created during both mining and brinefield operations, have been used for storage of gas, compressed air and certain fluids. At Holford Brinefield in Cheshire, abandoned brine cavities are used for ethylene storage, with one currently used for natural gas (BGS, 2004). For the Byley gas storage project, it is proposed to develop the salt caverns in the Northwich Halite Formation (Beutal & Black, 2004).

Triassic deposits of the Preesall study area form part of a series of rocks that extend northwards to Walney Island near Barrow-in-Furness and south to the Wirral area. Halite beds are encountered at three main levels in the Fylde area, and are known as the Rossall, Mythop and Preesall halite (Wilson & Evans, 1990). The most important is the uppermost Preesall Halite which was extracted by both mining and brine operations. Mining operations ceased in the late 1930's and the final brine extraction operation closed in 1993 because of the closure of the chlorine plant at Hillhouse in Fleetwood (Landless, 1979; BGS, 2004).

The Preesall Halite is the lateral equivalent of the Northwich Halite Formation developed in the Cheshire Basin (Wilson, 1993).

Less important salt deposits are proved in the MMG in parts of the Solway-Carlisle Basin. A thin salt bed was encountered in the Silloth borehole and salt has been worked at the Point of Ayre on the northern coast of the Isle of Man since 1891 (Notholt & Highley, 1973).

Rock salt was discovered at Larne in Northern Ireland in 1850, while drilling for coal (Griffith & Wilson, 1982; Notholt & Highley, 1973). The first mine and brine production commenced in 1897 and the Irish Salt Mining and Exploration Company Ltd. have been producing salt from the Kilroot Salt mine since 1965, operated using drift and shafts. The Triassic sequence includes three salt formations between 363 and 1027 m depth proved in the Larne boreholes, including the Larne Halite up to 481 m thick (Penn, 1981). However, in the Carrickfergus salt field the salt beds have thinned to only about 40 - 50 m (Notholt & Highley, 1973; Griffith & Wilson, 1982; Mitchell, 2004).

South of the Cheshire Basin, halite beds are also encountered within the MMG of the Staffordshire Basin (Notholt & Highley, 1973; BGS, 2004). Here, salt deposits occur beneath the town of Stafford and are preserved in a synclinal structure faulted along its eastern side (Whitehead et al., 1927). The Triassic halite (up to 21 m) occurs interbedded with mudstone in a sequence 50–65 m thick.

Rock salt is also encountered in the MMG in the Worcestershire area (Sherlock, 1921; Wills, 1970; Mitchell et al, 1961; Poole & Williams, 1980; Old et al., 1991) which is broadly equivalent to the Cheshire salt beds further north (Notholt & Highley, 1973; BGS, 2004). The saliferous sequence is about 90 m thick, of which 40% consists of siltstone and mudstone units. The depth to top salt ranges from 90 m to 125 m below ground.

Variably thick Triassic saliferous rocks occur interbedded with claystone in the Somerset area and were first discovered in a borehole drilled for coal near Puriton in 1910 (Whittaker, 1970; Notholt & Highley, 1973). The borehole proved some 427 m of MMG with halite between 183 m and 219 m (McMurtie, 1911; Usher, 1911; Whittaker, 1970). In the west of the basin at about 500 m depth, halite beds are of limited thickness, being up to a maximum of 23 m. The rock salt was extracted by brine operations for around 11 years, until its closure in 1922 (Notholt & Highley, 1973).

Hydrocarbon exploration boreholes have also proved thin halite beds in Triassic deposits of the Whitby area, with a 30 m thick halite bed near the base of the MMG. The salt beds represent the lateral extent of a major salt basin developed in the area of the southern North Sea at that time. These salt beds are not thought to be targets for the development of salt cavern storage facilities, particularly given the thicker underlying Permian salt beds (see above).

More recently, a third important Triassic saltfield has been identified during the widespread search for oil and gas in the south of England. Planning permission for the development of a salt cavern gas storage facility has recently been sought in the Weymouth area of Dorset, where the halite is approximately 2000 metres below sea level, with an anticipated thickness of in excess of 400 metres (http://www.oilvoice.com/Egdon_Moves_Into_Gas_Storage_Market_/3582.htm).

Thus there are a number of saltfields in the UK, most of which have been exploited at one time or another for their salt. However, as is presently understood, most do not contain halite beds of sufficient thickness to be considered viable for gas storage projects.

1.2 SOME COMMENTS ON FAULTS AND THEIR TERMINOLOGY, FAULTING OF SEQUENCES CONTAINING HALITE AND THE DEPICTION OF FAULTS IN HALITE BEDS ON SEISMIC REFLECTION DATA

This report clearly focuses on the geology of the Preesall Saltfield area and as such geological terminology is introduced, to which the reader might not be familiar. Consequently, a glossary of terms is included at the back of the report to assist general understanding.

Much of the report describes and discusses a number of faults that affect the area, including the Preesall Halite. A brief section outlining fault terminology and halite (rock salt) deformation that occurs in nature is perhaps pertinent to aid understanding and follows below. In reading it, reference should be made to the glossary, which includes a cartoon sketch diagram to illustrate faulting of strata.

The faults described in this report, whilst they may have had some movement during deposition, have also moved after the sediments were deposited and rock layers formed. A '*fault'* is defined as a planar discontinuity between blocks of rock (containing beds or layers) that have been displaced past one another, in a direction parallel to the discontinuity. A '*fault zone*' is a tabular region containing many parallel or anastomosing faults. It is only when a fault intersects the earth's surface that we see a major downstep across the fault and the 'creation of space'.

In the subsurface, therefore, different rock units are displaced against and past each other along the fault plane. A fault is not generally a thin clean break because during the process of faulting, the rocks are commonly broken up to a greater or lesser extent, forming a zone of damaged strata along and either side of the fault in the fault walls. Dependent on the hardness of the rocks and the depth of the faulting, various fault rocks are produced. At shallower levels, hard rocks are crushed and broken, forming angular fragments of varying size, known as fault breccias. Soft rocks (or hard rocks at greater depths and temperatures) and more intense fault movement may produce finer fragments, referred to as rock flour or fault gouge.

Consequently, various rocks may be produced along fault planes, introducing small voids between the fragments and along which fluids may move. The fluids commonly deposit minerals (e.g. clay minerals, quartz or calcite) along the fault, which leads to the cementation of the fault zone and closure of the voids. Dependant upon the main mineral deposited along the fault plane, the cemented fault rock may be harder of softer than the enclosing unfaulted rock and thus be stronger or weaker respectively.

Faults may in nature, therefore, be both barriers to the flow of fluid (sealing) or permeable and act as conduits for fluid flow.

The interpretation of the seismic reflection data in this report depict faults in the top and base of the halite, linking across the halite interval and so, to avoid misunderstanding, it is worth commenting here about rock salt behaviour and deformation mechanisms.

Deformation of halite or rock salt at geostatic pressures is commonly viscoplastic in nature with many people's perception being that it 'flows' (e.g. Jenyon, 1986a&b). In actual fact it is not flow per se, but a creep achieved through crystal plastic deformation and/or pressure solution mechanisms (e.g. Jenyon, 1986a&b). Many interpretations of seismic lines show faulting affecting only the top or base of a halite dominated succession; the faults apparently not having propagated through the halite body to displace the other boundary.

Faulting is also shown in strata overlying a halite unit and which are unconnected to faults developed in sequences underlying the halite; the salt has effectively acted as a decollément horizon, isolating the deformation between the layers (e.g. Jenyon, 1986a&b, Harvey & Stewart, 1998).

However, interpretations of many seismic lines, including those in this study, appear to show faulting of the top and base halite and which are connected/related. In these instances the fault appears to have propagated through the rock salt body, although, as described, it is commonly perceived as deforming plastically. Rock salt may, however, fail and undergo brittle fracture and faulting under certain conditions. These might be when the rock salt is:

- Exposed to high strain rates (fast movements), coupled with shallow depths (i.e. conditions of lower temperatures and confining pressures)
- Or where the salt crystals containing impurities or inclusions
- Or where the halite includes layers of mudstone or anhydrite or the salt crystals contain impurities or inclusions.

Any one of these scenarios might lead to the rock salt suffering increased local stresses, leading to strain hardening and ultimately to fracture and the propagation of a fault through the salt layer.

Following the propagation and displacement on the fault, the rock salt, being viscoplastic, will over geological time and under normal geostatic pressures, undergo crystal plastic deformation and creep. The salt will effectively self-heal (anneal) and 'repair' any areas of fault damage.

It is important, therefore, to understand that the depiction of a fault on a seismic section currently connecting through the salt may only be representational and indicating a former fault plane. Any damage to the salt, which may have existed following faulting, may well, over geological time, have subsequently been repaired by the naturally occurring viscoplastic flow of the salt under geostatic pressures.

2 Data Available

This study has been undertaken using data from a number of sources that are in the public domain (refer Appendix 1). The main subsurface information on the Preesall Halite is provided by boreholes distributed across the study area (Fig. 1). These data are held in part by BGS, or were provided either by Canatxx directly, or through Mott MacDonald. Circa 14 kms of seismic reflection data of varying vintages and provenance were also available in the area of interest (Table 1), some 10 kms of which were reprocessed for this study (see section 4.1.5).

2.1 INCONSISTENCIES FOUND IN DATA SUPPLIED TO BGS

During this study a number of inconsistencies were found in the data supplied by Canatxx to BGS. These are listed below:

- A series of pdf's containing the 1996 Daran Petroleum Consultants maps of Top Preesall Salt, Salt Isopach and Top Sherwood Sandstone all have incorrect National Grid lines on them. The grid lines appear to relate to somewhere other than the Preesall district.
- Careful review of the ICI borehole information, including examination of early well log records (as held by BGS) has indicated that, often significant, differences exist in the tabulated Fleetwood Gas Storage Borehole Data, compiled by/for Canatxx from ICI borehole data figures and supplied to BGS for this study. These are detailed further in section 6.1 and included:
    - Values for the ground level (effective start height of borehole) – found in many instances to be different to those held by BGS (perhaps 30% of the cases).
    - Values for the depth to base Preesall Halite in some boreholes compared to those held or interpreted by BGS.
    - Terminal depth (TD) values of the boreholes. For some boreholes the base Preesall Halite was indicated to be close to TD, whereas the borehole reached TD often tens of metres below in the underlying Thornton Mudstones.

The inconsistencies and differences in interpretation in some of the boreholes might be expected in a large dataset, parts of which date back to the early 1870's. BGS therefore undertook a review of all borehole data they had access to and on which the model presented here is based.

Borehole and log records held by BGS and used within the study are available for consultation from the National Geoscience Records Centre at BGS, Keyworth.

3 Geology of the Preesall area

The Preesall district lies in the western Fylde area, with the solid bedrock succession representing the onshore equivalents of major depositional sequences developed offshore in the East Irish Sea. However, a variable and often thick glacial deposit conceals the solid rocks onshore, with no surface exposures of bedrock known in the immediate vicinity (Wilson & Evans, 1990).

The first deep borehole drilled was at North Euston Hotel, Fleetwood [SD 3378,4843] in 1860, proving Triassic mudstones (Wilson & Evans, 1990). This was followed shortly afterwards by a borehole at Poulton-le-Fylde [SD 3530 4009], which was the first to record rock salt and gypsum in the Triassic rocks. The importance of deep boreholes to the greater understanding of the nature of the solid rocks in the region is illustrated by the fact that further important salt beds were discovered in the area in 1872, when boreholes were put down in the search for iron ore (Wilson & Evans, 1990). The numerous subsequent boreholes drilled to explore and exploit the salt deposits have provided valuable subsurface information on the Triassic succession across the western Fylde area. Borehole density is greatest in and around the areas of salt and brine extraction near Preesall. Outwith this area, boreholes are fewer and consequently the geological interpretation is less certain.

Two of the most recent boreholes have been drilled by Canatxx at Arm Hill and The Heads, both of which penetrated the Preesall Halite and provide important information on the nature, state and thickness of the salt to the west of the former ICI brinefield. Augmenting these borehole data are a series of seismic reflection lines, acquired between 1980 and 1999, and variously reprocessed, which have elucidated the general geological structure of the area (see below).

3.1 GENERAL GEOLOGY OF THE PREESALL AREA

3.1.1 Introduction

The area of the Fylde lies on the eastern edge of the Irish Sea Basin and as such, Permo-triassic sequences developed represent the lateral equivalents of thicker deposits offshore (Jackson et al., 1987; Jackson & Mulholland, 1993; Kirby et al, 2000).

The Preesall area was first mapped in the 19th century (De Rance, 1875), with the most recent survey having been conducted by the British Geological Survey (BGS) in the late 1960's to mid-1970's (BGS, 1975; Wilson & Evans, 1990). This latest mapping was augmented, particularly in the Preesall area, by the acquisition of a large number of boreholes and shafts drilled to exploit the Preesall Saltfield. In addition, the BGS sunk six cored boreholes to examine the lithology of the rocks of the concealed Mercia Mudstone Group (BGS, 1975; Wilson & Evans, 1990). The interpretation of the geology and structure was based on part, but not all, borehole data to that point. During the preparation of the Blackpool map and memoir, and subsequent to its publication, a number of seismic lines were acquired across the area.

These additional data have enabled a reappraisal of the geological structure of the area. The geological succession and stratigraphical nomenclature is outlined in Table 2.

3.1.1.1 1960'S-1970'S INTERPRETATION

Prior to the acquisition of seismic reflection data in the area, understanding of the geology and geological structure of the area was largely conjectural, being based on a number of deep boreholes concentrated within the area of the Preesall Saltfield (Wilson & Evans, 1990). To the north of the area, beyond ICI boreholes E1 and P1 towards the coast, the structure is entirely conjectural.

The area is underlain by rocks of Triassic age that were considered to occur in a downfolded area named the Preesall Syncline (Fig. 4a&b). This fold was considered to trend N-S and preserve younger beds of the Mercia Mudstone Group (MMG) including the Preesall Halite. The syncline was truncated by a number of faults on its eastern edge, forming the Preesall Fault-zone, into which strata show an easterly dip. Strata of the (older) Sherwood Sandstone Group (SSG) lie to the east of the Preesall Fault Zone in its footwall block. The lack of borehole information outwith the Preesall Saltfield meant that the position of these faults was not known with certainty.

Traced westwards strata generally dip steeply westwards to the eastern banks of the Wyre Estuary where scattered boreholes indicated an easterly dip, thereby defining the western limb of the syncline. However, Wilson & Evans (1990) recognised considerable uncertainty existed over the structural interpretation of this area, and raised the possibility of one or more down-east faults, antithetic to the Preesall Fault, forming a down faulted block (graben), within which the younger beds of the Mercia Mudstone Group are preserved.

3.1.1.2 1990'S INTERPRETATION

In the early to mid 1980's acquisition of a widely spaced grid of seismic reflection data provided greater insight in to the structure of the Triassic succession and faulting within the Preesall Syncline. These subsurface data, reprocessed in 1996 and in association with further seismic reflection data acquired in 1997 and 1999, illustrate the youngest Triassic sequences are preserved within a downfaulted block Fig. 4c); the Preesall Graben, bounded to the east by the Preesall Fault and to the west by the previously unknown Burn Naze Fault (Daran Petroleum, 1996). The seismic interpretation and ICI-B1 and ICI-E27 boreholes prove, and accurately locate, the position of the Burn Naze Fault in the south. However, the trend of the fault, although shown as NE-SW on the Daran maps, is not so well constrained further north. It may be imaged at depth (and hence a minimum easterly location gained) on seismic line GASGC-81-336 (see Fig. 18). But otherwise, its location was largely conjectural. Estimated downthrows on the Preesall and Burn Naze faults are in excess of 600 m.

Within the Preesall Graben seismic reflection data indicate that further smaller scale faulting affects the Triassic succession, including the Preesall Halite (Fig. 4c). The details of the Preesall Graben and its internal structure are described and discussed in more detail below.

3.2 GEOLOGICAL SUCCESSION

The geological succession of the study area is summarised in Table 2.

In Middle to Late Permian times, the onset of a major rift (faulting) phase on generally N-S trending faults led to the formation of the East Irish Sea Basin (EISB), within which, Permian and more importantly, thick sequences of Triassic strata, including the Mercia Mudstone Group (MMG), were deposited. The western Fylde area lies on the eastern flank of the EISB, which is reflected in the development of thinner Permian and Triassic sedimentary sequences. However, faulting along the eastern edge of the EISB controlled sediment thickness and distribution.

Permian rocks and the early Triassic Sherwood Sandstone Group are proved onshore at depth in isolated borehole provings. However, they are generally poorly known and are not considered further here.

The MMG largely comprises mudstones and siltstones, but also contains important halite beds, most notably the Preesall Halite, which has been variously extracted by brine pumping and mining since at least 1889. Triassic strata in the Fylde area may reach a total thickness in excess of 1400 m and are covered by thick superficial deposits, so that rockhead is below sea level over much of the area (Wilson & Evans, 1990).

3.2.1 Mercia Mudstone Group

Overlying the Sherwood Sandstone Group, the Mercia Mudstone Group (MMG) subcrops the superficial deposits across the entire area. It is subdivided into two formations, the Tarporpley Siltstone Formation and the Sidmouth Mudstone Formation (Gallois, 2001). The Tarporley Siltstone Formation has not been recognised in the Flyde area. The Sidmouth Mudstone Formation is divided into three members, in ascending order; the Singleton, Kirkham and Breckells mudstone members. The Kirkham Mudstone Member is further divided into three, which in ascending order are the Thornton Mudstone, the Preesall Halite and the Coat Walls Mudstone.

The MMG represents an alternating series of mudstones, siltstones, halites and anhydrites (refer Table 1). The mudstones and siltstones were deposited in a series of restricted sedimentary basins by both wind and water processes. The halites represent evaporite deposits that formed in shallow saline water as the restricted basins dried up. The repeated occurrence of halite beds in the southern North Sea has been seen as evidence for the periodic influx of fresh seawater through a seaway connecting the rift basins with an ocean to the north; the Boreal Ocean (e.g. Cameron et al., 1992).

3.2.1.1 HAMBLETON MUDSTONE MEMBER

The basal Hambleton Mudstone Member (circa 37 m thick) marks a distinct change from reddish brown sandstones of the underlying Sherwood Sandstone Group to dominantly grey mudstones interlaminated with grey siltstone, with pseudomorphs after halite (Wilson & Evans, 1990).

<table>
<tr><td rowspan="6">TRIASSIC</td><td colspan="4">Current Nomenclature</td><td colspan="2">Former Nomenclature (Wilson & Evans, 1990)</td></tr>
<tr><td rowspan="4">Mercia Mudstone Group</td><td rowspan="4">Sidmouth Mudstone Formation</td><td>Breckells Mudstone Member</td><td></td><td colspan="2">Breckells Mudstones</td></tr>
<tr><td>Kirkham Mudstone Member</td><td>Coat Walls Mudstone
Pressall Halite
Thornton Mudstone</td><td>Kirkham Mudstones</td><td>Coat Walls Mudstones
Preesall Halite
Thornton Mudstones</td></tr>
<tr><td>Singleton Mudstone Member</td><td></td><td colspan="2">Singleton Mudstones</td></tr>
<tr><td>Hambleton Mudstone Member</td><td></td><td colspan="2">Hambleton Mudstones</td></tr>
<tr><td>Sherwood Sandstone Group</td><td></td><td></td><td></td><td colspan="2">Sherwood Sandstone Group</td></tr>
</table>

Table 2. Nomenclature for the (Triassic) Mercia Mudstone Group in the study area.

3.2.1.2 SINGLETON MUDSTONE MEMBER

The Singleton Mudstone Member (up to 311 m thick) comprises reddish brown mudstones with impersistent beds of halite. The halite beds are found near the base (Rossall Halite) and near the top (Mythop Halite). The halite beds, variously proved in the ICI-B1 (Rossall and Mythop halites) and ICI-B8 (Rossall Halite only) boreholes, are confined to the west and centre of the Fylde and thin eastwards (Wilson & Evans, 1990) and are absent in the Kirkham borehole to the east. These halite beds were thought likely to be largely absent in the Preesall area (Wilson & Evans, 1990).

3.2.1.3 KIRKHAM MUDSTONE MEMBER (INCLUDING THE PREESALL HALITE)

The Kirkham Mudstone Member comprises a series of reddish brown and greenish grey mudstones interlaminated with thin siltstones. The lamina are often disrupted by dessication cracks. The *Thornton Mudstone* forms the lowest bed, comprising reddish brown and greyish green interlaminated mudstones, with thin halite beds near the top and base.

The *Preesall Halite* was first discovered accidentally in boreholes sunk in 1872 during the search for haematite thought to occur locally. Since then, the rock salt has been proved, and exploited by, over one hundred boreholes to the west and southwest of Preesall. The Preesall Halite is a succession of halite (rock salt) ranging in thickness from 79 m to over 280 m, with thin partings of reddish brown and greenish grey mudstones. To the east, adjacent to the Preesall Fault, the halite rises to near surface where dissolution by naturally circulating groundwater has occurred (wet rockhead). The salt dissolution leads to the collapse of overlying strata, forming collapse breccias that occur in a belt between 400 and 600 m wide immediately west of the Preesall Fault. Further west the halite deepens and is not dissolved and defines an area of dry rock head.

The Preesall Halite represents the lateral equivalent of the Northwich Halite Formation in the Cheshire Basin Wilson, 1993).

Based on the correlation of mudstone partings, Wilson & Evans (1990) divided the Preesall Halite into beds (in ascending order, A, B and C). These partings reach a maximum thickness of 2.1 m between beds B and C and were thought to be persistent, although they accounted for probably less than 5% of the Preesall Halite. The areas of halite mining were confined to beds A and C.

Gamma logs from the two Canatxx boreholes (Arm Hill and The Heads) show distinctive log characters, which are correlatable (Fig. 5). It was considered during this study whether the Preesall Halite sequence proved in the two Canatxx boreholes could be correlated with the halite subdivisions of Wilson & Evans (1990). The basis of the original subdivision is not entirely clear and it has not been possible during this study to verify or apply this scheme, or produce correlations with other ICI boreholes (due to their not having gamma logs available).

The gamma ray logs show the Preesall Halite is associated with generally low gamma values (Fig. 5), with higher values recorded at discrete levels. These higher values occur at the depths that relate to mudstones recorded during the core logging of the Arm Hill borehole (see Ratigan, 2005). For example, the higher gamma values seen in Arm Hill correspond to a series of mudstone, anhydrite, halite, mudstone beds 1.25 m, 0.85 m, 4.25m and 0.5 m thick respectively between 552.8 m and 559.34 m. Similar prominent zones are found between 420 m and 425 m, and 452.35 and 457.4 m and relate to varying mixes of thin halite and (thinner) mudstone beds (see Fig. 5).

Preesall Halite proved in boreholes pertinent to this study (refer Figs 6-11)

The depth and thickness of the Preesall Halite is well known over the brinefield area, but is less so to the west of this. The Preesall Halite is, however, proved in a number of salt wells drilled by

ICI, BGS and two recently by Canatxx (refer Figs 1 & 5 and Appendix 2). The most notable and important of these wells are noted in Appendix 2.

To date, the thickest provings of the halite are in the ICI-129 (268+ m) and ICI-130 (289+ m) boreholes (Figs 8 & 11). The depth to the top halite has been proved at over 300 m below OD in a number of boreholes, with the deepest being in the ICI-E2 (365 m), ICI-B6 (354 m) and Arm Hill (362 m) towards the north of the study area (Figs 6 & 9). To the east of the central regions of interest, in the vicinity of ICI-130, the top of the halite is at around 307 m below OD.

These depth and thickness values for the Preesall Halite are greater than indicated by Wilson & Evans (1990), particularly their estimated 175-185 m thickness values mapped across the area of interest. Their map was, however, based on fewer boreholes and is clearly in need of revision and cannot be used as a reliable indicator of the halite thickness to the west of the main brinefield.

These scattered borehole data have been used in conjunction with seismic reflection data to further constrain and characterise the distribution and form of the Preesall Halite in the central area of interest (refer Fig. 1). In this study, reprocessed versions of GasGCE-86-DV371, three 1997 Canatxx lines and a hydrocarbon exploration line acquired by Independent Energy Lancashire Plains (IELP) in 1999, have been available (see section 4.1.4). These seismic data are of sufficient quality to reveal the structure of the Preesall Halite between BNG Northing's 445000 and 447000 (Figs 1, & 12-16).

The newly reprocessed Canatxx lines F & G (Figs 12-15), in the central parts of the area of interest reveal better quality data. The seismic lines also tie to the ICI boreholes B111, B112, B129 and B130 (Line G) and the ICI-134 and The Heads boreholes (Line F). The seismic data indicate the Preesall Halite is a wedge-shaped body, thickening westwards and is affected by two or more down-east normal faults that cut both the top and base of the halite (Figs 12-15). The depths and thicknesses of the Preesall Halite may be significantly different to those previously thought and the seismic interpretation is described in more detail in section 4.2.

Both Canatxx lines G and F indicate that the top of the halite hereabouts reaches a maximum depth of just over 300 m at the ICI boreholes and just to the west (Figs 12-14). Towards the western end of the lines, however, the top of the halite may be faulted up, to perhaps less than 150 m below O.D. As suggested, the halite body appears wedge-shaped and the seismic data indicate that the base of the halite may deepen to just over 700 m, providing a maximum thickness of halite of perhaps 550 m over the western half of the line.

In the southern part of the area of interest, the ICI-E27 borehole proved the top of the halite at 168 m below O.D., but reached TD within the halite. Estimates from seismic data (GCEGC-86-DV371 - refer Figs 11 & 17) put the salt thickness hereabouts at circa 300 m. This is compared to the c. 210 at The Heads borehole to the East. The ICI-E27 borehole, together with seismic line GCEGC-86-DV371 (Fig. 17) also helped prove the presence of the Burn Naze Fault between the ICI-B1 and ICI-E27 boreholes (Daran Petroleum, 1996).

The Preesall Halite would therefore appear to have been deposited in an asymmetrical westerly tilted graben that produced thickening into the down-east Burn Naze Fault in the west.

The *Coat Walls Mudstone*, up to 122 m thick, overlies the Preesall Halite and was proved in the Coat Walls borehole (Wilson & Evans, 1990). They are a series of structureless, reddish brown mudstones interbedded with laminated, reddish brown and greenish grey mudstones and siltstones. Sporadic thin bands of mudstone with halite crystals also occur, particularly in the lower sequences.

3.2.1.4 Breckells Mudstone Member

The Breckells Mudstone Member, proved in the Coats Walls and Hackensall Hall and ICI B1 boreholes, comprise three distinct lithological sequences that may reach a total thickness of 144

m. They are dominantly reddish brown structureless mudstones with scattered greenish grey bands. The upper division, where present, often comprises largely brecciated mudstones, resulting from dissolution of thin halite beds in haselgebirge (halite-mudstone) facies.

3.2.2 Superficial Deposits

Superficial deposits comprising glacial and post-glacial (Flandrian) sequences blanket the entire western Fylde area (Wilson & Evans, 1990). They are variable in thickness, exceeding 60m in the Blackpool area.

3.2.2.1 Glacial deposits

The glacial deposits are thought to be the products of late Devensian age glaciation between 20000 and 12000 years before present (Wilson & Evans, 1990). The study area lies mainly within a region of glacial deposits that are defined as forming area B of Wilson & Evans (1990). This area comprises Till (Boulder Clay) in part overlain by post–glacial deposits (see below). The Till consists of stiff, reddish brown clay with pebbles of sandstone, limestone and igneous rocks with irregular beds and lenses of sand and gravel. The Till, which is up to 40 m thick, forms an irregular, undulating surface that in places is moulded into drumlins. Between Preesall and Hambleton, the larger drumlins are about 500 m long, 200 m wide, rise to circa 20 m above Ordnance Datum (O.D.) and trend at 150º to 170º. This reflects the last movement of ice in the Devensian Glaciation (Eyles & McCabe, 1989). The lithologies that make up the drumlins are not well known, however, they are likely to be similar in composition to the Till and to include sand and gravel.

3.2.2.2 Post-glacial deposits

Post-glacial deposits are readily distinguished from the glacial deposits in the western Fylde area. They form a flat tract of ground that comprises grey clays, yellowish brown silts and sands and gravels up to 20 m thick. They are of marine and estuarine origin, deposited in the Flandrian (the last 10 000 years) when relative sea levels rose from about 17 metres below OD to about 5 m above OD (Tooley, 1985).

3.2.3 Post-Triassic structural evolution of NW England

The post Triassic evolution of the area is poorly constrained and somewhat speculative due to the absence of any solid rock (rather than drift deposits) younger than Triassic age over the western Fylde. The following draws on depth of burial and uplift studies elsewhere onshore in the Cheshire Basin and around Sellafield (Evans et al., 1993; Chadwick et al., 1994, 1999).

3.2.3.1 Jurassic to early Cretaceous

It is likely that the post-Triassic development of the NW England region was characterised by periods of regional crustal extension, along lines of faulting established in Permo-Triassic times. However, even offshore in the East Irish Sea, where more complete stratigraphical sequences are preserved, unequivocal evidence of post-Triassic faulting is generally lacking because of the lack of post-Triassic strata. Major faults offshore have displacements at the base of the MMG greater than 500 m and up to 2000m. Some of this displacement undoubtedly accompanied deposition of the MMG, but the remainder was post-Triassic (Chadwick et al., 1994), and may account for up to one third of the total displacement on some faults (Jackson & Mulholland, 1993; Chadwick et al, 1994).

Thus the study area was probably receiving sediment at this time.

3.2.3.2 Mid- to late Cretaceous

Extension had ceased by mid-Cretaceous times (e.g. Whittaker, 1985) and post-extensional regional shelf subsidence was established with the deposition of a relatively uniform Upper Cretaceous sequence (Chalk). The end of Cretaceous times is thought to have marked the maximum post-Variscan (end Carboniferous to earliest Permian times) burial of much of NW England.

3.2.3.3 Palaeogene to Present

Regional uplift, which is thought related to the development of a mantle hot-spot immediately prior to rifting in the North Atlantic, commenced at about the Cretaceous-Palaeogene boundary (e.g. Lewis et al., 1992) and triggered a period of erosion that has probably continued to the present day in the onshore areas. Depth of burial studies indicate that post Cretaceous uplift and erosion ranges from circa 2.2 km in the Cheshire basin area (Evans et al., 1993), to 1750 m over the Lake District Block and increasing to 2 km at Sellafield (Chadwick et al., 1994). However, estimates for Tertiary erosion across the EISB and Cheshire Basin areas, though disputed (Holliday, 1993), have been as high as 3.3 km (Lewis et al., 1992).

ICI Borehole reference number	Depth top halite (m)	Depth top halite (below O.D.)	Depth base halite (m)	Depth base halite (below O.D.)	Halite thickness (m)
*E1	317	308	398	388	81 (faulted?)
E2	372	365	Not reached	Not reached	?faulted 9
E-20	Not reached				
E-27	178	168	Not reached		> 30.5
B6	362	354	557	549	195
*B-27	178				
B-43	296	288	401	393	105
B-22	Not reached				
B-111	269	264	413	409	144
B-112	283	278	478	473	195
B-123	324	319	464	459	140
B-124	226	219	363	356	137
*B-126	286	280	Not reached		> 170
*B-127	263	257	Not reached		> 193
*B-128	242	236	Not reached		> 192
*B-129	299	294	Not reached		> 268
B-130	312	307	Not reached		> 289
*B-133	277	273	Not reached		> 250
*B-134	261	255	Not reached		> 245
Coats Wall Farm	281	273	Not reached		> 4
Arm Hill	366.26	361.98	607.41	?602.98	> 236?
The Heads	226	221.95	430	c. 425.95	c. 210

* no full log in BGS

Table 3. Boreholes proving depth to top Preesall Halite, base Preesall Halite (where penetrated) and thickness of halite in the area west of the main brine field workings.

4 Seismic reflection data

Seismic reflection data of varying vintage and energy source have been acquired across the area of interest and were available to the study (Fig. 1, Table 1). The Gas Council acquired seismic reflection data during the early-mid 1980's as part of their onshore oil and gas exploration activities, of which two cross the area of interest. In 1996, as part of a study into salt cavern gas storage by Daran Petroleum Consultants Limited for British Gas Hydrocarbon Resources Limited, these data were reprocessed, interpreted and subsurface maps of key horizons produced, including the top of the Preesall Halite and salt thickness (isopach) maps (Daran Petroleum, 1996).

In 1999 three short seismic reflection lines were acquired by Canatxx as part of the investigation into the salt of the Preesall area. The processing (and possibly the acquisition) of these data appears to have been carried out under consultation with Dr M.K. Jenyon who also prepared an interpretation and report on the Preesall Saltfield in 1997 (Jenyon, 1997).

At a meeting in London on 2nd September 2005, BGS were informed of two further seismic reflection lines in the area (referred to within Canatxx as 'Archaean data' and prefixed IELP-99-) and that BGS had not previously been aware of. These two lines (IELP99-25 and IELP99-26) appear to have formed part of a later phase of oil and gas exploration in this area. Line IELP-99-25 runs across the northern area of interest, close to the Arm Hill borehole drilled by Canatxx in 2004, providing a good seismic calibration point (refer Figs 1 & 16).

The seismic lines are generally oriented E-W and rarely cross and thereby provide few points where the lines can be 'loop-tied' and the interpretation iteratively checked. The seismic interpretation is also hindered because the ties to N-S lines tend to be in the east, well beyond the area of interest, in areas of poor data quality and where the halite is at shallow depths.

4.1 SEISMIC DATA QUALITY

Since their acquisition, when data quality was often variable and generally poor, the various seismic reflection data have been subject to phases of reprocessing in an attempt to gain improvements in quality. During this study reprocessing of a number of the lines was again undertaken and which has seen a further improvement in quality from the last reprocessing or acquisition phases performed in 1996 and 1997.

Data quality at the level of the Preesall Halite has generally been improved, particularly in the data acquired by Canatxx in 1997. The process and stages of improvement are outlined below.

4.1.1 GasGC81-336

BGS initially had access to only the filtered stack version of GC81-336, oriented E-W (Fig. 1). These original data were of poor quality, particularly in the area of interest, which is affected by the Wyre Estuary and associated local ground conditions. A large omission zone exists in the seismic co-incident with the Wyre Estuary and has affected the fold of stack and thus resultant quality of the data in that region, particularly in the shallow section.

The line was reprocessed during the work undertaken by Daran Petroleum Consultants in 1996. Data quality improved, however, the large omission zone in the area of the Wyre Estuary still reduced the effective usefulness of the data over the site area to the east of the estuary (Fig. 18).

These data are difficult to interpret, of limited use and have not been used in this study.

4.1.2 GasGCE-86-DV371

BGS initially had access to the filtered migrated stack version of the line. Much of the seismic line is of good quality, imaging down to, what from regional studies, is likely to be the base of the Permian and Triassic succession. Significant effort was put into the acquisition phase with three different sources (Vibroseis, hydropulse and dynamite) aimed at trying to overcome the problems associated with the Wyre Estuary and the local ground conditions. However, the quality of the line in the area between the Preesall Fault and the western bank of the Wyre Estuary drops off markedly, being poorest across the area of the brinefield. This is perhaps not unexpected given that voids in the salt (old brine caverns) and the zone of salt dissolution close to the Preesall Fault are likely to have produced poor ground conditions for the transmission of the energy (sound waves) during seismic acquisition. The data quality picks up slightly over the unmined salt across the area of interest, where the attitude of reflections are suggestive of faulted sequences. The poor quality of the seismic hereabouts may therefore also be related to faulting. Once to the west of the Wyre Estuary, the data quality is generally very good.

The line was reprocessed during the work undertaken by Daran Petroleum Consultants in 1996 for British Gas Hydrocarbon Resources Limited. Data quality improved markedly in the area between the Preesall Fault and the western bank of the Wyre Estuary and particularly so in the area west of the brine field. Reflection continuity was greatly improved, providing data that indicate faulting of the Permian and Triassic succession (Figs 4c & 17). This faulting affects the shallower section at Preesall Halite levels. Data in the deeper section (between circa 500 and 700 milliseconds TWTT) were not so good and the nature of the geology and structure beneath the Preesall Halite levels is not unequivocal (see below).

4.1.3 Canatxx Lines D, F & G

In 1997, IMC Geophysics acquired three short, seismic reflection lines (D, F and G) for Canatxx using a dynamite source and recorded into geophones and hydrophones. Lines F and G are generally E-W, but Line D runs more ENE-WSW, providing a tie between Gas GCE-86-DV371 and Line F (see Fig. 1). They had a maximum of 96 channels at a station interval of 10m and were recorded at 1ms for 2 seconds in an attempt to increase the frequency and quality of the data in the shallow section (predicted levels of the Preesall Halite). The locations of the lines are between the two Gas Council lines described above (refer Fig. 1).

IMC Geophysics subsequently processed the lines, partially interpreted migrated stacks of which were supplied to BGS in pdf files by Canatxx. The initial copies of the three lines made available to BGS were of generally poor quality, being virtually uninterpretable over the western halves (Fig. 19). The eastern half of all three lines show somewhat better quality data with greater reflection continuity, but the data are still difficult to interpret. There is a general impression of over migrated data, particularly so in the case of line D. Reflection configurations on the western halves of lines F & G indicate faulting, which may partially explain the poor quality of the data across these areas.

On the 6th September 2005, BGS attended the offices of IMC Geophysics to discuss the reprocessing of the Canatxx data. Having viewed the final preferred processing model, and a preferred IMC processing model at that time, the decision was taken that the original (non IMC preferred) processing sequence did not produce the best quality data. So much so, that the chosen processing sequence may even have enhanced noise and degraded any real data within the section. This is illustrated in Figure 20, where the final 1997 filtered and migrated stacks used (Fig. 20a) are compared to filtered and migrated stacks resulting from the unused, IMC preferred, processing model (Fig. 20b). A flat-lying reflection at about 350 ms is present in the processing model, but is warped up and becomes lost in the final model, because easterly dipping noise ‘trains’ have been preferentially processed and obliterate the flatter-lying reflection. In the unused model originally preferred by IMC, the flatter lying reflection retains continuity, the dipping apparent reflections (noise trains) are weakened and the section looks clearer.

The same is true for line G and less so D, which may be as a result of it having a slightly different (SW-NE) orientation.

Consequently, at that meeting it was decided that an alternative processing sequence along the lines of the IMC preferred model, but with modern pre-stack processing, should be attempted in order to try and improve the quality of the Canatxx lines and remove the effects of the dipping noise trains within the data.

The seismic reprocessing sequences are detailed in Appendix 3. Results from the reprocessing are noteworthy (compare Figs 19-23). There is a significant improvement in data quality from that seen on the 1997 data finally used (Figs 20-24). However, Line D (Fig. 24), probably due to the short length but also perhaps to complex geology, remains of poor quality and difficult to interpret (see below).

4.1.4 'Archaean' Line IELP-99-25

On the 5th September BGS received a pdf file showing a partially interpreted seismic workstation print of W-E oriented line IELP-99-25 and a fuller, depth converted, interpretation of same as another pdf (Fig. 25). During the visit of BGS to IMC Geophysics on the 6th September, it was ascertained that both IELP lines had also been acquired and processed by IMC Geophysics for Independent Energy Lancashire Plains (IELP) in 1999. It would appear that these E-W and N-S lines were acquired as part of a more recent oil and gas exploration programme in the area.

Seismic line IELP-99-25 was acquired using a Vibroseis source with a short in fill section of dynamite. It has a maximum of 242 channels at a station interval of 10m and was recorded at 1ms for 3 seconds.

Initially, BGS only had access to a pdf file showing a partial interpretation, seemingly produced from a seismic workstation (Fig. 25a). The data are of good quality and show interesting structure in the northern regions of the area of interest (see below). On 6th September BGS received from IMC Geophysics digital copies of both IELP lines to load to seismic workstation and appraise.

4.1.5 2005 Seismic Reprocessing

During this study and following discussion of the requirements with IMC Geophysics, the three Canatxx lines (D, F and G), GasGCE-86-DV371 and IELP-99-25 were all reprocessed, details of which are included in Appendix 3.

The first data reprocessed were the Canatxx lines, with first results (filtered stacks) available on the 9th September. The processing sequence differed from the original 1997 sequence and there appears to be a distinct improvement in data quality (Figs 12-14). Migrated stacks are available at 100, 95, 90 and 85% of the stacking velocities (Figs 13, 14, 22 & 23).

The next line to be reprocessed was IELP99-25, with initial results made available on the 13th September. Although the original line was of good quality, reprocessing provided an improvement in data quality.

GasGCE-86-DV371 was the last to be reprocessed for reasons of time and the need to obtain the greatest amount of new, high quality data, in as timely manner as possible. The problem in the case of DV371 was that three different seismic sources were used during its acquisition, which raised problems of confirming the polarity of the data and correlating the seismic wavelet during the processing stages. Initial results were made available on the 19th September. Again there is a noticeable improvement in data quality, particularly in the deeper section, aiding interpretation of the deeper levels of the Preesall Fault and Graben.

4.2 SEISMIC INTERPRETATION

This section attempts to briefly describe and comment on existing seismic interpretations and provide interpretations of the newly (2005) reprocessed data (described above). The present interpretation follows-on from previous seismic interpretation in the area (Daran Petroleum, 1996; Jenyon, 1997), but benefits from having had access to a greater number of seismic reflection lines that have been reprocessed for this study. The quality of these seismic data has been improved and as such the study represents an advance on previous work in the area and the understanding of structure and distribution of the Preesall Halite. It has been possible to incorporate these results in the production of the geological model for the Preesall area.

4.2.1 Existing seismic interpretations relative to the site

Reports from two previous seismic interpretation studies conducted over the Preesall Saltfield were available. The following briefly outlines the main findings of these two works.

The work undertaken by Daran Petroleum Consultants (Daran Petroleum, 1996) utilised the two reprocessed E-W Gas Council seismic lines, two N-S lines that fall outwith the site area and a significant database on depths to the halite derived from borehole and shaft records held by ICI and BGS. The work mapped the top Preesall Halite and generated a salt isopach map. A second study (Jenyon, 1997) accompanied the acquisition of the Canatxx seismic lines D, F & G (Fig. 19), with rather poor quality maps depicting the contoured top and bottom Preesall Halite in the vicinity of the three Canatxx lines.

A shallow anticlinal structure running sub parallel to the eastern bounding Preesall Fault and offset circa 250 m to the west was mapped during the Daran study. The anticlinal axis is affected by a series of northerly trending down-east faults with downthrows of up to 50 m. To the east of the anticlinal axis, the beds dip eastwards into the fault and may have helped preserve a thicker salt section by inhibiting solution of deeper buried strata. To the west of the anticlinal axis the beds dip westwards, towards the Burn Naze Fault across two zones of faulting to reach estimated depths of 427 m (1400 feet) below OD 500 m – 600 m to the SW of the ICI B6, E2 and Canatxx Arm Hill boreholes.

The salt isopach map shows three areas of thinning. Two areas, aligned along northwesterly to west-north-westerly lines in the north and central parts of the salt basin are attributed to original depositional thinning along early lines of structural uplift. The third area is close to the eastern faulted boundary of the basin and is attributed to salt dissolution.

These maps were based upon the interpretation of the Gas Council data, the interpretation of which, are discussed below.

Seismic line GasGCE-86-DV371 represented then, and perhaps still, the best quality seismic line to illustrate the general structure of the Preesall Saltfield. These data, when reprocessed and combined with the ICI borehole data reveal that the Preesall Halite is preserved within a down faulted area (graben), bounded by two major faults; the normal down-west Preesall Fault and the normal down east (antithetic) Burn Naze Fault (Fig. 4c). This down faulted block was named the Preesall Graben.

There is likely to be a further easterly dipping antithetic fault (the Fleetwood Fault) to the west of the Burn Naze Fault, but which does not appear to affect the Preesall Halite.

The Daran interpretation shows a deep and narrow graben structure (Fig. 4c) with the bounding Preesall and Burn Naze faults showing between 700 and 500 milliseconds (circa 1 km and 600-750 m) downthrow respectively. Across the whole graben structure, however, there is only 200-300 milliseconds (300-450 m) of downthrow to the west of the basal Triassic and Permian succession.

Within the graben, a thick Triassic succession is faulted down and is affected by smaller scale faults with opposing westerly and easterly (antithetic) dip and downthrow directions (refer Fig. 4c). These smaller faults affect the top and base of the Preesall Halite, causing displacements in the enclosing mudstone sequences. The faults extend through the overlying Coat Walls Mudstones up to the base drift. On line GASGCE-86-DV371, in the ground to the west of the ICI brinefield, towards the southern end of the area of interest, at least three smaller normal down-west faults, with two lesser faults, are apparent (Fig. 4c).

The faults seen on the line GASGCE-86-DV371 affecting the southern areas of the area of interest, to the west of the brinefield, have been extended/mapped northwards in the Daran interpretation. However, they are shown to coalesce such that by seismic line GASGC81-336 only one down-west normal fault is recognised. As noted above, the seismic line was not of good quality and the chance remained, on the information available at that time, that faults other existed, but might not have been recognised.

As alluded to above, the original quality of the three Canatxx lines lying between the Gas Council lines 81-336 and 86-DV371 was not of good enough quality to accurately assess the likelihood of the faulting in the intervening ground. Jenyon (1997; p.7) noted that west of a fault seen about half way along lines F & G, the data quality was reduced and that meaningful interpretation was not possible. Thus the faulting indicated by the Daran mapping could not be verified at that time.

The most northerly E-W seismic line in the area is IELP-99-25. This line was not available during the 1996 Daran interpretation and was initially supplied to BGS as a pdf file showing a partial interpretation and depth migrated line drawing (Fig. 25). The line appears to have been tied to boreholes nearby, and is in agreement with the synthetic seismic panel generated from the Arm Hill sonic log in this study (Fig. 16). The line is of good quality and illustrates a minor syncline-anticline fold pair affecting the Triassic strata. The depth-converted line drawing shows the Preesall Halite interval to be thinner (circa 115 m) over the anticlinal structure and thicken slightly to the east into the Preesall Fault. In the crestal region of the anticlinal structure and just off the crest to the west on the western limb, small scale down-east faulting is evident affecting the halite. To the west, of the halite thickens to greater than 180-190 m preserved at the western end of the line, where it is tied to the ICI B6 borehole. From around shot point 250, westwards, there is little evidence of faulting of the halite on the seismic line. If any faulting is present, it is be below seismic resolution.

Beyond this seismic line, there were no further seismic reflection data to constrain the subsurface mapping.

What is therefore clear from these seismic reflection data is that the previous published BGS model for the Preesall Halite (Fig. 4a&b; BGS 1975; Wilson & Evans, 1990), established prior to the availability of seismic reflection data and some borehole information (but used as recently as 2005 – see report by T. Eyerman, 2005), is in need of revision. The Preesall Halite is not simply preserved in a synclinal fold, but is instead fault bounded to the east and west and in all probability does not come up to crop beneath the Wyre Estuary, but remains at depth.

4.2.2 New seismic interpretation – the structure of the Preesall Halite

On receipt of the 1996 reprocessed seismic reflection data from IMC Geophysics on the 8/9/05, the data were loaded to a Geographix seismic workstation. Data were rapidly assessed and hard copies to be generated for further detailed examination and depth conversion.

The interpretations of the Canatxx lines F & G presented in this work have been performed on the 2005 reprocessed filtered stacks, which were the first data to be delivered by IMC Geophysics. These were followed by receipt of the migrated stacks of D, F and G at 100% stacking velocities (Figs 13, 14 & 24). However, due to the short line lengths, migration of the data is not well constrained and the data are difficult to interpret. The migrated stacks at 85, 90 and 95% stacking velocities followed and those of lines F and G are also shown for completeness (Figs 22 & 23). They illustrate that the interpretations would vary little to those made using the filtered stacks, save the geographical position of the reflectors. The seismic migration process attempts to tidy up the seismic section and place the reflections closer to their true geographical positions. Thus the dip of surfaces on the filtered stacks and depth converted line drawings and the positioning of features in the subsurface are likely to be slightly different to those on the migrated data.

4.2.2.1 Calibration of the seismic reflection data and their depth conversion

The seismic reflection data have been tied to the two Canatxx boreholes (Arm Hill and The Heads), using the borehole sonic log data supplied to BGS on the 26/9/05. Synthetic seismograms were generated from these sonic log data (refer Figs 16 & 26), which allows accurate transfer of the stratigraphy from the borehole (in depth) to the seismic line (in two-way-travel time).

Towards the north of the area of interest, seismic line IELP-99-25 ties to the ICI-B6 borehole, for which no sonic log data are available to generate a synthetic seismogram and accurately calibrate the seismic line. The Canatxx Arm Hill borehole, for which sonic log data are available, lies offline to the south and has been used to generate a synthetic seismogram and check the seismic picks for the top and base halite. Allowing for projection back to the line and given the halite is circa 50 m thicker in Arm Hill, there is a good match to the IELP data and previous interpretation of the top and base Preesall Halite (refer Figs 1, 16 & 25). As might be expected of high velocity salt within lower velocity mudstones, the top and base of the halite would appear to be confirmed as associated with good, high amplitude, continuous reflections.

Towards the south of the area of interest, The Heads borehole has been used to tie the Canatxx Line F (refer Figs 1 and 13) and GasGCE-86-DV371 (see Fig. 26). Line F was chosen as the most important tie due to it being of better quality in the shallow section. In this case the top of the Presall Halite appears a very good tie, with good character match seen in the reflections coming from the overlying mudstone sequences. However, the reflection associated with the base of the halite hereabouts is less clear. The borehole apparently reached TD in the Thornton Mudstones, yet the high amplitude reflection anticipated from the base of the halite lies a short way below the bottom of the synthetic seismogram (Fig. 13a). It is felt that the high amplitude reflection probably arises from the base of the halite and that the borehole tie is slightly out. This can be explained in a number of ways, including:

- The projection of the borehole onto the line may be slightly out. It may be just to the east of its indicated position such that the base halite was proved in the footwall block of a fault apparent on the eastern end of the line.
- Thickening of the halite between the borehole and the seismic line. Such lateral thickening is noted between ICI-B6 and the Arm Hill boreholes further north (refer Table 3).

Depth conversion of the seismic picks seen in the seismic figures (Figs 13c, 14c & 26b) was performed using single velocities for the post-halite succession and for the halite interval consistent with those data from the sonic log in the Arm Hill and The Heads boreholes. The velocities obtained tie the known depths and thickness in nearby ICI boreholes.

It should be noted that the depths/thicknesses and placement of subsurface structures obtained during the interpretation were performed using single layer velocities. Seismic velocities vary both laterally and vertically and so more sophisticated seismic line and map depth migration routines would produce more accurate depth conversions not possible in the time available during this study. These improvements would come with added information from further studies.

4.2.2.2 THE PREESALL AND BURN NAZE FAULTS AND PREESALL GRABEN

Initially the graben model (Daran, 1996 and described above) appeared entirely reasonable, given the data quality across the area at the time and the present interpretation supports that model. The halite is preserved in a downfaulted block (graben) that is bounded to the east by the Preesall Fault and in the west by the Burn Naze Fault (Figs 4c & 17). The Preesall Fault is the major controlling fault to the graben and is probably the southern extension of the Gleaston Fault to the north across Morcambe Bay (see e.g. BGS, 1974; refer Fig. 3). Both of these faults form part of an anastomosing network of faults, believed to be linked to the Lake District Boundary Fault Zone (Jackson & Mulholland, 1993; Akhurst et al., 1998).

However, even when viewing the original 1986 data, the angle and attitude of the Preesall Fault was perhaps open to debate. Whilst not necessarily affecting the shallower rocks (including the Preesall Halite), the Preesall Fault could be interpreted as cutting down through the seismic section at a lower angle, providing a different structural style to the down-faulted graben and with it, very different thicknesses and offsets of the Triassic strata within the graben. The present interpretation suggests that the Preesall Fault cuts down to the west at a much lower angle than that in the Daran model, resulting in a less deep graben, with footwall block sequences (containing the older Triassic and Permian sequences) extending further westwards beneath the graben (compare Figs 4c and 26).

It would appear that the series of reflections interpreted as the base of the Thornton Mudstones in the Daran report, are in fact more likely to be the progressively down faulted basal Permian and Triassic strata, possibly masked by reflections from the Preesall Fault plane. A composite seismic line comprising the E-W GASGCE-86-DV371 and N-S GASGC-87-382 appears to show this quite clearly (Fig. 17). The Triassic succession can be traced into the area of the graben across the Burn Naze fault, with much of the SSG possibly faulted out; MMG lying on and dipping into the Preesall Fault plane. It should be noted that no section balancing has been done to verify the interpretation.

To assess the feasibility of such an interpretation, a gravity profile, derived from the BGS gravity database, was extracted along the line of seismic section. These data do not conflict with the new fault interpretation, but actually lend support. There is no significant decrease in the gravity values as might be anticipated in the region of the thickest graben succession (cdp's 650-750) in the Daran model (Fig. 27).

The course of the Burn Naze Fault is not generally well constrained. To the south its position can confidently be placed between the ICI-B1 and ICI-E27 boreholes, supported by the GASGCE-86-DV371 seismic line (Figs 4c & 17). It is then though to strike northeastwards beneath the Wyre Estuary, crossing GASGC81-336, which as noted above is of poor quality in this area. Reflections do give the suggestion that it might be imaged at deeper levels at around shot point 255 (Fig. 18), projecting to surface around shot point 290, within the large omission zone related to the Wyre Estuary. Further north, seismic line IELP-99-25 shows a down-east fault affecting deeper reflections from SSG rocks in the vicinity of ICI-B6 well. This fault, when extended to crop, plots some 300 and 350 metres to the west of the line end and is probably the northern extension of the Burn Naze Fault (Figs 16 & 25). To the north, the fault must pass to the west of the ICI-E1 Hackensall Hall borehole, which proved Preesall Halite at a depth of 320 m (311 below OD).

In the ground between the two Gas Council seismic lines (BNG Northings 445000 and 446000), the location of the fault is likely to be to the west of the Canatxx seismic lines, which appear to stop short and to the east of the fault.

4.2.2.3 PREESALL HALITE

The northern IELP line, acquired just south of the Hackensall Hall Farm borehole, reveals the halite is disposed about a shallow anticlinal fold in the north of the area of interest. The seismic line runs to the north of the Canatxx Arm Hill No.1 borehole, the tie to which would project towards the western end of the seismic line, somewhere east of the B6 tie point. The interpretation is supported by the known depths of the halite in the Coat Walls, ICI-B22, ICI-E2 & ICI-B6 boreholes and the seismic picks for the top and base of the halite, based upon the synthetic seismic panel generated from the Arm hill sonic log data, are in agreement with those on the interpreted IELP line supplied to BGS (Figs 16 & 25).

From the crestal area of the anticline, the top halite dips westwards and then flattens to reach a depth of just over 350 m, with base halite at around 540 m (538.9 m in the borehole) below O.D. Hereabouts, the halite thickens westwards, attaining a maximum thickness of 195 m. It is noted that the Arm Hill borehole, some 100 m to the SE, proved the base of the salt at 602 m below O.D., an increase southeastwards in depth of 50+ m and in thickness to 236 m.

However, there is a noted change in the thickness of the halite and the depth of the base Preesall Halite of around 50 m between the ICI-B6 (558 m) and the Arm Hill (circa 607 m) boreholes (refer Table 3). Borehole E2 proved the top of the halite at 373 m below ground level (365 m below OD), but penetrated only 9 m into the halite before being abandoned having lost core at around 381 m. It is noteworthy that dips of strata recorded in the borehole, whilst generally in the region of 5˚ at shallow levels become very variable and increase deeper down the borehole such that general dips of between 15˚ and 25˚ are recorded in mudstones and the halite over the bottom 21 m of the borehole.

Explanations for such changes in the depth to the base halite might be explained by either:

- An increased dip on the base of the halite; or
- Some down-south faulting occurring between the boreholes and which might account for the increased and variable dips of strata over the bottom 21 m of the E2 borehole.

Either scenario is possible on the data available. Seismic line IELP-99-25 does not indicate a fault cutting the line hereabouts and a fault, if present therefore, would have to trend WNW to NW and run to the south of the seismic line. A fault at any other angle would intersect the seismic line, for which there is no evidence. It is noted that the depth to the top of the halite in E2 is not too dissimilar between the boreholes in the immediate area and so it may be that the fault was active during deposition, which would account for at least some of the observed thickening of the halite between the B6 and Arm Hill boreholes. The observed variation in dips of strata might possibly be attributed to some later minor movement on the fault.

To the south, the ICI boreholes B111, B112, B129, B130 and B134 proving top and base of the Preesall Halite tie to the Canatxx lines G & F respectively (Figs 12-15). The 2005 reprocessed Canatxx lines G and F show an improvement in quality and as described above, the halite is here interpreted as a quieter interval with few internal reflections as interpreted by Jenyon (Fig. 19; Jenyon, 1997). The halite interval thickens westwards and can now be seen to be affected by two or more down-east normal faults that offset both top and base halite. Faulting and likely westwards thickening of the halite may be imaged. Jenyon (1997) also noted the apparent westwards thickening of the halite on these data, but was unable to interpret these data over the western halves of the lines, beyond a down-west fault, which is also seen in the newly reprocessed data (see Figs. 12-15).

The main faulting midway along both line F and G appears to be down-west. However, correlation panels generated for the western data (Fig. 15) assist correlation with sequences over the eastern parts of the line and provide improved confidence in the westwards correlation and tracing of the Preesall Halite.

Canatxx line G (Figs 12 & 14) reveals a westwards thickening of the Preesall Halite to a down-west normal fault at around cdp's 195-200. Westwards of the fault the halite is thought to be affected by a series of down-east normal faults. The halite adjacent to the fault in the downthrown block may be in the region of 350 m thick. To the west the halite is progressively faulted up to the west such that by the end of the line, it may be in the region of 150 or less below OD, and perhaps 550 m thick.

Canatxx line F (Figs 12 & 13), only a few hundred metres to the south of Line G, shows similar structuring, although the strata appear slightly domed in the centre of the line. Again the halite interval appears to thicken westwards and is progressively faulted up to the west across a number of down-east normal faults. On line F the top of the halite may reach a maximum depth of around 260 m, again rising to around 150 m below OD at the western end. The base of the halite again deepens from around 570 m on the eastern end of the line to just over 700 m in the western half, where the salt may be in the region of 550-560 m thick.

The reprocessed Canatxx Line D is still of poor quality and has proved difficult to interpret. This may be due in part to its short length, but also some complex geological structure nearby (a fault?).

Thus the newly (2005) reprocessed Canatxx seismic data appear to show that once across the down-west fault identified by Jenyon (1997) and beyond which he was unable to positively identify the Preesall Halite, the halite is progressively faulted back up to the west, across a number of the down-east normal faults.

The southern seismic line, GASGCE-86-DV371 (Fig. 27), of older vintage is less clear but is interpreted to show the Preesall Halite affected by a similar number of small faults to those described on Canatxx lines F & G (Figs 12-15). These faults map out as NW-SE trending (Fig. 27). The depth converted line when tied to the ICI-134 and ICI-130 boreholes suggests that the halite thickens to at least 300 m against the Burn Naze Fault, where the top is proved at 168 m below O.D. in ICI-E27 (Fig. 4c, 17 & 26).

The Preesall Halite would therefore appear to have been deposited in an asymmetrical, westerly tilted graben that produced thickening into a down-east fault (the Burn Naze Fault) in the west.

4.2.2.4 General Structure of the Preesall Halite and Small Scale Intragrabenal Faulting

Towards the north of the area of interest, the E-W oriented seismic line IELP99-25 shows a gentle anticlinal structure, with the proposed site lying on the basically simple western limb, which dips towards the Burn Naze Fault (Fig. 16). To the north of the seismic line data are sparse, but the top of the Preesall Halite rises towards the ICI-E1 borehole where it is at 308 m below O.D. and beyond which it may deepen again northwards.

The seismic line does not appear to show evidence of any faulting of significance, although as discussed above, a fault downthrowing southwards and trending parallel to, and just south of the seismic line, cannot be ruled out on the data currently available.

South of this region, however, between BNG Northings 445000 and 446000, the Preesall Halite is clearly affected by a series of small faults that appear to offset both top and base of the halite, or just the top or base (Figs 12-15 & 26). The current rapid interpretation of the Canatxx seismic lines would indicate that down-east faulting exists and which is likely to be oriented NW-SE in the area of interest (Figs 9, 13, 14, 26 & 28).

This faulting and its trend is opposite to those faults mapped during the Daran Petroleum interpretation in 1996, which as noted elsewhere, was based on fewer data of poorer quality. Data at the western ends of Canatxx lines F and G (Figs 12-14) indicate the presence of a down-east fault cutting the base Preesall Halite but not the top Preesall Halite on the section, although it must displace the top of the halite upwards and off the end of the section. The present interpretation suggests the fault can be found on both Canatxx lines and would thus have a NW-SE trend and that it is not the Burn Naze Fault, but a smaller fault that is presently depicted as truncating against the Burn Naze Fault.

The complicated style and nature of these faults is reminiscent of structures developed along faults with some component of lateral (strike-slip) movement on them and perhaps even an element of compression (transpression). Reflection relationships on the western ends of the migrated versions of lines G and F could certainly be interpreted as showing minor down-east, westerly dipping reverse faulting. The reflection relationships and poor data quality seen on Line D might therefore be due in part to intersecting a complex structure at an oblique angle.

The seismic lines and ICI borehole data indicate that a down-west fault intersects the eastern ends of the Canatxx data (Figs 12-14). This structure is required to account for the difference in depth of the depth converted base salt along the line and the depths proved by the nearby ICI boreholes ICI boreholes B111, B112, B129 and B130 on Line G and ICI-130 and ICI-134 for line F. As noted above, the synthetic seismic tie to line F is not unequivocal and the question is raised, could the base halite be proved in the footwall (upthrown) block of a down-west fault? Referencing the Daran top salt structure contour map, it is possibly the N-S trending fault mapped previously from borehole data at top salt level within 100 m of the line ends. However, due to the short line lengths, data are insufficient to confirm this.

5 Gravity data

The British Geological survey holds a databank comprising some 168000 land gravity measurements covering the whole of Great Britain, which are available from BGS under licence. These data are generally displayed as contoured anomaly maps, which can be used qualitatively or modelled quantitatively by geoscientists to assist in determining the geological structure of an area. Further discussion on the gravity method is given in Appendix 4.

Areas of low anomaly value ('gravity lows') are associated with lower density bodies, for example sedimentary basins and granites. High-density bodies, such as metamorphic (and crystalline) basement and gabbros, give rise to gravity 'highs'. Steep anomaly gradients occur where density variations are rapid, for example across a geological fault.

It was decided, as part of this study, to investigate the gravity data held by BGS and to see if other data existed in an attempt to see if they could be used to elucidate the geological structure of the area.

Various datasets were identified (Fig. 29), with the Bouguer gravity anomaly values showing the highest values in the north-east corner of the district, where the (denser) Carboniferous basement is nearer the surface, beneath the Sherwood Sandstone. The values fall most rapidly to the west but also show a general decrease to the south and southwest. The general reduction in Bouguer anomaly values is coincident with the thickening of lower density Permo-Triassic rocks away from the Pennines, towards the East Irish Sea Basin.

Just west of the Preesall fault, from Preesall to Thornton, there is a weak ridge of slightly higher values (seen as tight contour bends in Figure 29), suggesting a density increase on the downthrown (western) side of the fault. This is counter to what might be anticipated and has been discussed above as relating to the Preesall Fault dipping westwards at a low angle (section 4.2.2.2).

The area of interest and the Preesall syncline are not completely covered by gravity observations so the anomalies are not tightly constrained in this area. The gravity data that do exist in the area appear to show only the regional decrease to the west. Locally low values, which might be expected due to an increased thickness of low-density materials, are not apparent in the data.

6 3D-modelling

BGS have used the available borehole and geophysical (seismic reflection and potential field) data to construct a 3D model of the Preesall Halite to the east of Fleetwood. As has been described in previous sections, it is clear that faulting affects the Preesall Halite. Due to the severe time constraints placed on BGS, no new general seismic mapping across the area has been conducted during this project. The decision was taken to use the existing map developed by Daran Petroleum Consultants Ltd during their work for British Gas in 1996, unless it could be demonstrated to be incompatible with newer or reprocessed seismic reflection data obtained during the study. The Daran fault map provided indications of where faults exist cutting the top of the salt body and is a significant improvement on simply connecting horizon depths in boreholes, which was effectively all that the earlier BGS mapping could do (BGS, 1975; Wilson & Evans, 1990), prior to these data being acquired.

6.1 DATA COLLATION AND PREPARATION

The BGS 3D modelling has been performed using the software packages GSI3D (developed by Dr H Sobisch of the University of Cologne) and Gocad. The benefit of using the GSI3D package is that it models using a series of manually constructed cross sections, not computer generated surfaces based on widely scattered data points. Figure 30 illustrates the general flowpath of the modelling process.

Datasets used to build the model are listed in Table 4.

Geological information from all borehole logs held by BGS or supplied by Canatxx for National Grid 1:10 000-scale sheets SD34NE, and a selection of boreholes that proved stratigraphically significant surfaces from SD34NW, SW and SE was extracted and loaded into the BGS Borehole Geology database. The final number of boreholes coded for the study was 745. Boreholes were coded according to the lithological description recorded on the log held by BGS or supplied by Canatxx.

In addition, the proved successions were classified lithostratigraphically into:

Glacial Till (Superficial Deposit)

Coat Walls Mudstone Formation

Preesall Halite

Thornton Mudstone and older deposits.

The proposed site of development/interest lies in an area of sparse borehole data when compared to the brinefield to the east. In an attempt to constrain the modelling and supplement the borehole information, the top and base Preesall Halite picks were interpreted on the reprocessed seismic reflection data lines (IELP99-25, DV371, Can97F and Can97G). These data were depth converted, and calibrated by nearby boreholes ensuring that the depths obtained were consistent with the stratigraphic horizons identified from the borehole logs. The values were entered into Borehole Geology; so that within the model these points effectively plot as a series of closely spaced boreholes and were used to construct and tie in crossing sections.

All data was classified using BGS corporate dictionaries:

BGS Stratigraphic Lexicon (http://www.bgs.ac.uk/lexicon/lexicon.html)

BGS Rock Classification Scheme (RCS): (http://bgs.ac.uk/bgsrcs/searchRCS.html)

Initial viewing of the Canatxx tabulated data, when compared to the records held by BGS revealed differences in the values of ground level (GL), borehole Terminal Depths (TD) and depth to base halite in numerous boreholes. This can be demonstrated by:

- GL differences – Borehole ICI borehole 24 (Canatxx well reference 12). Canatxx value is 19 feet (5.8 m), actual value from BGS records, 65 feet (19.8 m).
- In some cases the lithostratigraphic analysis of a borehole log involved a degree of interpretation, especially when identifying the base of the Preesall Halite. In a number of boreholes, the Canatxx data indicated that the base of the salt was not reached (i.e., the borehole terminated within the Preesall Halite and not the underlying Thornton Mudstone), whereas this work suggests that the uppermost levels of the underlying Thornton Mudstones may well have been reached. The run of boreholes known as ICI-111 to ICI-134 are particular examples of where this is likely to be the case and there may well be others.
- Uncertainty exists over the actual final depths (TD) quoted for some boreholes and what appeared in BGS records. For example, the TD of ICI boreholes 47 and 48 were 837 feet and 580 feet respectively. However, BGS logs would indicate TD in these boreholes was 928 feet (ICI-47) and 760 feet (ICI-48); at variance by 91 feet and 180 feet respectively.

Because of these differences between the BGS borehole data and the tabulated data supplied by Canatxx, BGS undertook a review of all borehole data they had access to and on which the model presented here is based. Borehole records used within the study are available for consultation from the National Geoscience Records Centre at BGS, Keyworth. Only boreholes proving the top or base of the Preesall Halite were used in the modelling process; these numbered approximately 190.

Due to the time constraints of the modelling process, the start height of each borehole could not be verified, and it was decided to assign a start height from the digital terrain model. Also, depths and halite thicknesses are not at this stage corrected for dip. This is not thought to be significant in the few boreholes available in the area of interest.

6.2 THE MODELLING PROCESS

The 3D model of the Preesall brinefield was constructed by correlating boreholes along a network of 44 cross-sections. Only those data points holding stratigraphcally significant information were used in the modelling process. Coded boreholes, or data points from seismic reflection lines, were imported into GSI3D from Borehole Geology, where they are displayed in their correct spatial position (easting, northing and level relative to OD). Section lines were constructed in roughly orthogonal directions, enabling ‘loop tying’ to iteratively check on borehole correlations across the study area. Correlation lines composed of a series of linked nodes and representing the main stratigraphic horizons (including base and top of the Preesall Halite) were manually constructed. The spatial position of nodes in 3D, attributed with lithostratigraphic data, defined the bases of geological surfaces. The Daran Fault Map was used as a guide as to where faults may be present at the top of the Preesall Halite. The correlation between fault blocks was not carried out at this stage; faulted strata were left uncorrelated and fault planes were inserted into the model in a later iteration (see below). Additional nodes (‘control points’) that constrained the model were added along the correlation lines. Computation of the nodes as triangulated irregular surfaces (TINs) created an unfaulted 3D stacked model of the base and top of the Preesall Halite and Glacial Till. However in the regions immediately adjacent to the faults, processing-induced inconsistencies (data spikes) remained in the modelled surfaces exported to GoCad. In areas of sparse borehole and seismic data, additional cross sections were constructed. Correlation points within these sections were based on projected intersections from nearby cross sections, and an interpretation of the surface morphology of the top of the Pressall Halite as indicated by the Daran fault map.

The nodes generated in GSI3D were exported to GoCad as scattered data points. The data spikes in the vicinity of the fault planes and which originated during the GSI3D modelling process, were removed manually in GoCad. Faults were inserted into the model with planes defined by their position at the top and base of the Preesall Halite horizon. The position of the faults in the top and base of the salt was taken from the seismic lines Can F and G or the Daren fault map, with the hade estimated from the throw of the fault.

7 Preesall Saltfield Model

For the first time a 3D geological model for the Preesall Saltfield area has been generated, based upon available borehole and 2005 reprocessed seismic reflection data. This provides a better understanding of the nature and distribution of the Preesall Halite (see Fig. 31). Although borehole data are fewer in the areas of interest, the availability of newly reprocessed seismic reflection data, effectively providing a line of closely spaced boreholes, assists the appraisal of the distribution and extent of the Preesall Halite. Depth conversion of the seismic picks seen in the various figures detailing the seismic interpretation process was performed using single velocities for the post-halite succession and for the halite interval derived from sonic log data in two 2004 wells and that tie nearby ICI boreholes.

It should be noted that the understanding of the subsurface distribution and character of the Preesall Halite is ongoing and the model will undoubtedly be refined as further borehole information and more sophisticated seismic line and depth migration routines are performed.

The model thus reveals that the Preesall Halite is preserved within a downfaulted block (the Preesall Graben) that is bounded by the Preesall Fault in the east and the Burn Naze Fault in the west. The Triassic sequences within the graben are affected by smaller scale faults with between 5 and 100 m displacement. NW-SE trending down-east faulting of the Triassic mudstones enclosing the Preesall Halite is evident on seismic lines in the area of interest between BNG Northings 445000 and 446000 and which leads to areas of tectonically thinned salt.

Between Northing 446700 and the seismic line IELP-99-25 the effects of faulting are much reduced, such that by the seismic line there is little or no evidence of faulting of the Kirkham Mudstone Member (including the Preesall Halite) on faults with NW trend. However, faulting just to the south of and along the same orientation of line IELP-99-25 cannot be ruled out at this stage.

To the east of the Preesall Fault the halite lies at shallow depths, forming an area of wet rockhead. Adjacent to the Preesall Fault, the Preesall Halite dips eastwards, however, these dip directions quite quickly change to westwards dipping across a shallow anticlinal structure imaged on seismic line IELP-99-25.

Traced westwards the halite deepens and a series of ICI and two Canatxx boreholes prove the top of the salt to be at depths of around 300 to 360 m. These borehole data help to calibrate seismic reflection lines that provide important subsurface information on the disposition of the halite over the proposed site area, where borehole data are unavailable.

Across the area of interest it is estimated that, adjacent to, and east of the down-east Burn Naze Fault, depths to top Preesall Halite vary from south to north. In the south of the area top halite lies at around 168 m below Ordnance Datum (OD), as proved in the ICI-E27 borehole, to the east of the ICI-B1 borehole that proved older Thornton Mudstones at crop. From seismic data, the thickness of the halite hereabouts is estimated at around 300 m. The top halite is thus shallower than the circa 222 m below OD recorded in Canatxx's The Heads borehole just over a kilometre to the east. Further north, seismic lines indicate the top of the halite rises to perhaps less than 150 m below OD near the Burn Naze Fault between BNG Northings 445000 and

446000, and may be up to 550 m thick. Hereabouts there is a possibility that the halite could be affected by wet rockhead conditions.

Further north it deepens to around 360 m below OD in the area to the SW of the ICI-B6 and Canatxx Arm Hill boreholes, where the thickness has reduced to around 195 m. The structure controlling the halite hereabouts is seen on IELP-99-25, which as mentioned, shows the area lies on the western limb of a shallow anticline, dipping into the Burn Naze Fault. The map showing depth to top Preesall Halite (Fig. 8) indicates it may locally, to the SW of the B6 and Arm Hill boreholes, reach circa 500 m against the Burn Naze Fault.

These depths are however, based upon the trend of the surface from the ICI-B6 borehole and the ICI-E1 Hackensall Hall borehole to the north, where it was proved to have risen to circa 307 m below OD. Hereabouts, it is only 81 m thick and may be faulted. The top of the halite is very poorly controlled to the west of ICI-B6 and it may be that the top halite maintains a steady depth between ICI-B6 and the Burn Naze Fault. Further borehole or seismic reflection data would help resolve the attitude of the surface and further constrain the model.

Northwards of ICI-E1 the top halite surface appears to deepen again, however, borehole and seismic reflection data are non-existent and details of the halite are not known.

The nature of the Preesall Halite to the south, beyond the ICI-E27 borehole is not known. The presence of subsidence hollows may indicate it continues southwards at shallow depths. Boreholes near Churchtown and Mythop penetrated breccias at roughly the same stratigraphic level as the Preesall Halite, suggesting that the Preesall Halite may have extended even further south (Wilson & Evans, 1990).

In summary therefore, the Preesall Halite would appear to have been deposited in an asymmetrical, westerly tilted graben that produced thickening into the Burn Naze Fault.

Within the Preesall Graben, the Triassic rocks are affected by smaller subsidiary down-east and down-west faults. These faults generally displace the top and base of the halite and thus moved post depositionally.

Thickening of the halite into some of these smaller faults within the graben also indicates they moved syndepositionally. However, faulting of the overlying mudstones by the same faults also indicates some post depositional faulting on most of the faults.

This and former studies indicate that the seismic reflection technique, providing the data are carefully acquired and processed, provides valuable subsurface information and aids the geological characterisation of the Preesall Saltfield area.

8 Seismic Hazard

In this section, the seismic hazard at the Preesall site is briefly discussed. It should not be read in isolation from the fuller account provided by Dr R Musson and included in Appendix 4.

The Preesall site is within a structural area dominated by north-south trending faults, which includes the East Irish Sea Basin and the Cheshire Basin. The area is not however, seismically active and faults in the East Irish Sea and Cheshire Basins have not shown strong seismic activity, even by UK standards. The regional seismicity from the BGS database is plotted (Fig. 32), with symbol size related to magnitude, and colour to depth.

The known larger UK earthquakes have depths considerably in excess of their rupture dimensions and the likelihood of any fault reactivation near the site causing a direct rock rupture hazard is considered extremely small. Such an event is not thought to have occurred anywhere in the UK since Quaternary times (up to 1.8 million years ago).

In all, between the 7th October 1690 (Caernarfonshire quake) and 19th July 1984 (also Caernarfonshire), there have been 8 eathquakes felt at site with intensities that might generally be perceived indoors or cause windows and doors to rattle. Seismic events felt in the area have not been of sufficient intensity or magnitude (refer Table 5) to cause damage. The three largest earthquakes felt most strongly at site have been:

- 20 August 1835 Lancaster earthquake (4.4 ML), about 24 km to the north-east. Damage to field walls and buildings, was reported. At Poulton-le-Fylde (the nearest location to the site from which reports survive), the shock was severely felt, with light articles shaken although no damage occurred. Burton et al. (1984) give an intensity of 5 EMS hereabouts and the estimated intensity at site using UK intensity attenuation (Musson, 2005b) is also 5 EMS (i.e. shaking is strong but not damaging; EMS = European Macroseismic Scale).

- The second event of note occurred only eight years later, and was larger. The 17 March 1843 Irish Sea earthquake had a magnitude of 5.0 ML, and was felt over a wide area of north-west England, eastern Ulster, and the Isle of Man. The epicentre was offshore in the eastern Irish Sea, but is not known precisely. The shock felt at Fleetwood woke most residents and caused people to leave their houses, caused bottles to fall from shelves and broke several windows. The intensity at Fleetwood is considered 4-5 EMS by Musson (1991a).

- A similar intensity event is likely to have occurred at site from one other earthquake that took place on 17 March 1871. The epicentre was nearly 100 km away to the north-east, near Appleby, and thus well away from the basin structures of the eastern Irish Sea – Cheshire – Lancashire area. However, it was sufficiently large (4.9 ML) to be felt strongly in Fleetwood (Musson, 1991a&b).

No other earthquake has produced an event at site as high as those discussed above. Generic hazard maps suggest that the hazard at site is about average for the UK, and of the order of 0.15 g with annual probability of 10^{-4} and perhaps about 0.05 g at $2x10^{-3}$. An intensity of 6 EMS is 90% probable not to be exceeded in 50 years (6 EMS = slight damage).

Future seismic hazard at the site is, therefore, dominated by the effects of large (in UK terms) earthquakes at moderate distances. The maximum observed intensity at site in historical times is 5 EMS, which is just below the damage threshold (Table 5)

9 Hydrogeology

The hydrogeological summary has been prepared jointly by Anthony Feigl of Mott MacDonald and Dr N Robins of BGS Wallingford and this summary should not be read independently from that report (refer Appendix 6).

The scope of evidence is to provide a summary of existing information on the hydrogeology of the area around Preesall, near Fleetwood in Lancashire (Appendix 6).

9.1 HYDROGEOLOGY OF THE SHERWOOD SANDSTONE GROUP

The Sherwood Sandstone Group (SSG) is a major aquifer of regional importance where at economically exploitable depths (known as the Fylde Aquifer in northwest Lancashire). However, within the proposal area the sandstone is deeply buried beneath the Mercia Mudstones, due to the presence of local faults. In this area groundwater flow in the sandstone is interpreted to be very low. Moreover, the hydraulic connectivity between the SSG in the area of the proposal and the Fylde Aquifer is likely to be very limited. This interpretation is based on observations made during this and previous studies and the context of the 'Preesall Graben', the latter likely to be limiting groundwater flow within the SSG of the downthrown block due to deep burial and also limiting flow in the surrounding SSG perpendicular to the bounding faults.

Vertical permeability within the sandstone has been noted to be restricted by marl (mudstone) beds. Recharge to the sandstone aquifer is predominantly from rivers to the east and south east of the proposal area and potentially from Carboniferous strata at the Pennines, with basin-scale flow generally westwards. Seasonal changes in water level are generally low, typically less than a metre, due to the high storage capacity of the Sherwood Sandstone.

9.2 HYDROGEOLOGY OF THE MERCIA MUDSTONE GROUP

The Mercia Mudstone Group overlies the Sherwood Sandstone Group and attains a thickness of over 800 m in the vicinity of Fleetwood (Wilson & Evans, 1990). Members of the group consist of alternating sequences of salts and mudstones, including the Preesall Halite, which is the thickest of the halite beds in the Fleetwood area.

Around Preesall, the Preesall Halite has been thrown down and tilted by faulting, so that in places it is in contact with ('subcrops') the overlying superficial drift. This has caused the Preesall Halite to be naturally sub-eroded (dissolved) by groundwater in subcrop zones and replaced by collapsed overlying deposits. This is known as the 'wet rockhead' phenomena. Wet rockhead generally extends 50 to 75 m below the base of the drift. Historically, brine groundwater has been extracted at Preesall from immediately above wet rockhead ('wild brining'), exacerbating sub-erosion of the rock salt and the subsequent collapse of overlying formations. This has led to localised ground subsidence. Conversely, in 'dry rockhead' zones, the thick sequence of Mercia Mudstone Group overlying the Preesall Halite protects the latter from sub-erosion by shallow groundwater within the drift. It is of note that the proposed new natural gas caverns are to be constructed by solution mining below dry rockhead.

In general the Mercia Mudstone Group is an aquitard (i.e. very low permeability), with very minor vertical or horizontal flows of groundwater. The BGS note that low yields of up to 5 l/s have been observed from the more permeable units within the group, principally the Tarporley Siltstone, but this formation is not present within the proposal area.

The salt deposits themselves are poorly permeable. In situ hydraulic testing carried out for the proposed scheme indicated approximate rock mass hydraulic conductivities of $5x10^{-6}$ metres per day (m/d) to $8x10^{-6}$ m/d for the depth interval 200 m to 355 m below ground level and $1x10^{-6}$

m/d to $3x10^{-6}$ m/d for the interval 400 m to 575 m below ground level. This range in hydraulic conductivity is comparable to fine clay or unfractured igneous and metamorphic rocks. Fracture tests were also conducted during the same investigation, resulting in an estimated fracture hydraulic conductivity of around $9x10^{-3}$ m/d when the injection pressure is above the fracture opening pressure. This value is typical for rocks with relatively tight fracture sets. The fracture conductivity of the salt deposit at injection pressures below the fracture opening pressure are likely to be significantly less than $9x10^{-3}$ m/d.

9.3 HYDROGEOLOGY OF THE SUPERFICIAL DEPOSITS

The bulk of the drift deposits in the proposal area are Till (previously known as 'Boulder Clay'). The principal hydrogeological significance of Till is that it limits recharge and confines water within underlying formations (namely the Sherwood Sandstone and Mercia Mudstone groups in the proposal area). More localised Marine and Estuarine Alluvium, consisting predominantly of mud, clay and silt are also found within the proposal area and probably act as aquitards. However sands and gravels may exist at depth.

Saturated horizons within the drift and in the proposal area will generally be confined from below at relatively shallow depths, either by less permeable Mercia Mudstone Group or less permeable drift deposits. The shallow hydrogeology of marine and estuarine alluvium, and to a lesser extent the Till, is likely to be related to the hydrology of the marshes in the proposal vicinity. Very little field data exists on the hydraulic properties of the drift, due to its very limited potential for supplying groundwater at economic yields, although values have been derived from modelling studies.

9.4 GROUNDWATER ABSTRACTION

North-east of the proposal area, the Sherwood Sandstone has historically been utilised as a water supply for the Preesall saltfield and other industrial applications (BGS, 1990). The Sherwood Sandstone is also utilised extensively further east and south east of the proposal area, within the Fylde Aquifer area, for public water supplies and industrial applications. The Mercia Mudstone Groups have been tested for water supply but boreholes have been dry or yielded saline water. Some success has been gained historically from the Glacial Sand (a drift deposit), although probably from areas closer to Blackpool as this unit is almost completely absent in the proposal area. Generally, water from the glacial deposits has been noted as brackish to saline.

Based on an Envirocheck report (Landmark, 2005; refer Appendix 6), there are no registered groundwater abstractions or known private drinking water supplies within a 1 km buffer surrounding the proposal area, nor any groundwater source protection zones.

9.5 POTENTIAL GROUNDWATER POLLUTION

There does not appear to be any potential for pollution of the Sherwood Sandstone aquifer in the immediate proposal area, given the thick and poorly permeable sequence of Mercia Mudstone Group overlying the aquifer.

There is a known mercury sulphide repository, adjacent to the proposal area, which utilises a former brine cavern in the ICI brinefield.

The Envirocheck report (Landmark, 2005; refer Appendix 6) indicates the locations of numerous landfills, waste management facilities and industrial land uses, as well as some forty pollution incidents to controlled waters and two prosecutions related to land and water.

10 Conclusions and Recommendations

This study has reviewed the many data available in the area of the Preesall Saltfield. Boreholes generally provide definitive information at specific points. If sufficient, closely spaced boreholes are available then more detailed assessment of the subsurface can be performed. However, boreholes have limitations with the characteristics of the intervening ground unknown. Seismic reflection data, accurately calibrated by borehole data, provide greater coverage of the subsurface. The acquisition of good quality seismic reflection data in the area of interest and the western Fylde area in general, has proved difficult with results of variable quality. However, reprocessing of some of these data in 1997 and further reprocessing during this study has led to significant improvements in the quality of these data, which now provide the opportunity to characterise the subsurface.

The available data have been used to construct a 3D geological model of the Preesall Saltfield, which shows the Kirkham Mudstone Member (including the Preesall Halite) is preserved in a down faulted block, the Preesall Graben. This is bounded by the Preesall and Burn Naze Faults to the east and west respectively.

Faulting of the Triassic succession within the graben is apparent and affects the former brinefield area and the southern area of current interest, leading to areas of tectonically thinned halite. Further north, faulting of the Kirkham Mudstone Member appears to lessen and may be absent around the area of the ICI-B6 borehole and eastwards.

The Preesall Halite is seen to dip westwards into the Burn Naze Fault to depths approaching 350 m below OD. In the areas adjacent to the fault depths vary along the length of the fault from 168 m in the south, to perhaps less than 150 m before deepening to circa 350 m at ICI-B6 and rising again to circa 307 m at ICI-E1. Beyond that, it appears to deepen again, but the data do not allow accurate mapping at his time.

The Preesall Halite is seen to thicken to the west across the former brinefield and into the Burn Naze Fault. In the north at ICI-B6 it is 178 m thick and some 220 m thick in the Canatxx Arm Hill borehole. Traced southwestwards it appears to thicken in the region of the Canatxx lines, being perhaps 550 m thick. Further southwest in the vicinity of ICI-E27 it may have reduced to circa 300 m thick.

Gamma ray logs acquired during the logging of the Canatxx Arm Hill and The Heads boreholes show a stratigraphy to the halite. If more boreholes are drilled or older ICI wells are logged then these logs could be readily used to correlate the halite across the saltfield.

A recommendation is therefore that these data, carefully acquired (including acquiring longer lines than the Canatxx lines) and processed, can provide an important source of information with which to characterise and gain further understanding of the subsurface in the area. Further studies or development of the area should therefore make use of these data to assist in the appraisal of any individual cavern location.

Establishing baseline and monitoring systems ***prior*** to any work commencing is recommended and which would be ongoing throughout the life of the facility. Such systems and processes to generally include the following:

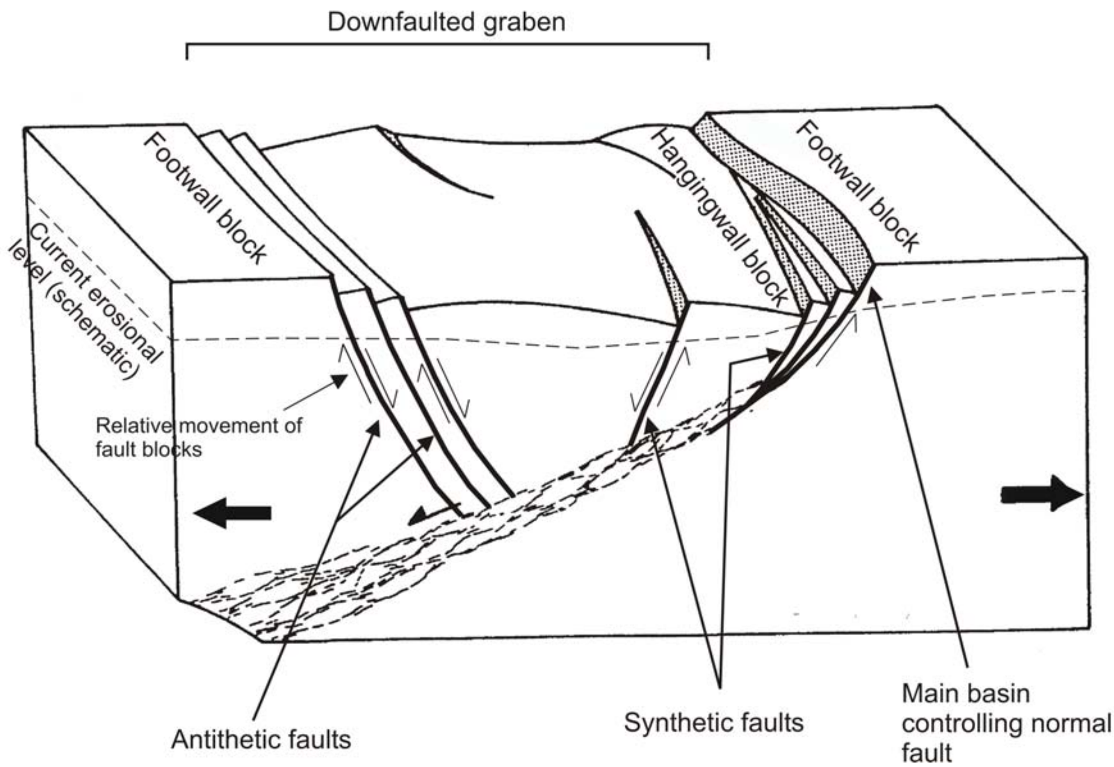
a. monitoring soil and groundwater for gas leakage;

b. monitoring pressure in subsurface layers (Coats Wall Mudstones) above the Preesall Halite; and

c. monitoring for any fracturing of the cap rock during the operation of the gas storage facility.

11 Glossary of terms

Anhydrite	mineral, $CaSO_4$, forms rock
Antithetic	a lesser fault with opposite dip and downthrow to another fault (see fault)
Aquifer	water-bearing layer/rock
Borehole	a hole drilled down into the rock from which samples or cores can be taken, or measurements of the rocks can be made
Breccia	rock fragments, caused by either faulting or collapse of intact beds
Brinefield	an area of salt mined by solution processes, in this case the Preesall Brinefield
Cretaceous	the geological period immediately after the Jurassic
Crustal extension	the process of extending the earth's crust through pulling apart and faulting
Downthrow	the downward movement of beds along a fault
Drift	unconsolidated superficial deposit
Erosion	the weathering and removal of rock at surface
Evaporite	a sediment resulting from the evaporation of saline water
Fault	planar discontinuity between blocks of rock (containing beds or layers) that have been displaced past one another, in a direction parallel to the discontinuity. Refer cartoon sketch below for additional main fault terminology included in the glossary (note, this is NOT a representation of the Preesall Graben, although similarities do exist).



Fault zone	tabular region containing many parallel or anastomosing faults.
Graben	a downfaulted block bounded by two faults, in this case the Preesall Graben bounded by the (eastern) Preesall and (western) Burn Naze faults
Halite	salt mineral, NaCL, rock forming
Hangingwall/ Footwall block	forming the downthrown (hangingwall) and upthrown (footwall) sides of faults
"Haselgebirge"	halite crystals set in mudstone, forming a rock intermediate between halite and mudstone
Intensity	measurement of strength of shaking produced by an earthquake at a certain location. Intensity is determined from effects on people, human structures and the natural environment
Jurassic	the geological period immediately after the Triassic
Magnitude	energy scale used for earthquakes, measuring the energy released at the source of the earthquake. Determined from measurements on seismographs
Marl	claystone, slightly calcareous and/or silty
Mudstone	claystone

Normal fault	a fault with dip slip movement and the hangingwall block is on the downthrown side
Orogenesis	period(s) of mountain building
Outcrop	The area where a particular geological strata occurs at the surface.
Permian	the geological period immediately before the Triassic
Post-sedimentary	having taken place after the sedimentation of a bed
Post-Triassic	having taken place after the Triassic period
Quaternary	youngest age of earth's history, including the ice age to now
Rockhead	top of a geological formation at base of drift deposits
Seismic Reflection Data	data imaging the subsurface, acquired by recording sound waves reflected from rock layers in the subsurface. Measured and generally displayed in time.
Sedimentation	the act of depositing sediment to form beds and eventually rock
Solid rock	the rocks below the drift (Quaternary) deposits
Strike-slip	normal faulting with a component of lateral movement, along the fault plane
Syncline	rocks bent in a down fold, the opposite of an anticline
Synsedimentary	an action that took place during sedimentation, e.g. faulting of an area during sedimentation, which can cause thickening of beds into a fault
Tectonic	subsurface movements caused by forces in the earth's interior
Tectonic thinning	having been thinned by a tectonic structure, in this case the halite by faulting
Transpressional	lateral movement along a fault that has some element of compression, often causing apparent reversal of downthrow and slight upfolding of strata.
Triassic	a geological period, the time of sedimentation of the Mercia Mudstone Group, including the Preesall Halite

Wet/dry rockhead	wet rockhead is an area where the halite beds rise towards the surface and are progressively dissolved by groundwater. Thus there is a belt where only part of the halite sequence is preserved and across which the halite overlain by collapse breccias of the overlying mudstones. Dry rockhead is the area of halite beneath the surface which is not affected by groundwaters and a complete sequence is preserved.

Tables

Table 1. Seismic reflection data across the area of interest, with various processing/reprocessing dates.

Seismic line	Dated acquired	Source	Date processed	Reprocessed (date)
GasGC81-336	Oct 1981	Dynamite	Nov 1981-Apr 1982	1996
GasGCE-86-DV371	Dec 1986	Vibroseis, hydropulse and dynamite	Jan-May 1987	1996
Canatxx Line D	Sept 1997	Dynamite	Oct 1997	Mid-Sept 2005
Canatxx Line F	Sept 1997	Dynamite	Oct 1997	Mid-Sept 2005
Canatxx Line G	Sept 1997	Dynamite	Oct 1997	Mid-Sept 2005
‘Archaean’ Line IELP-99-25	1999	Vibroseis + short fill of dynamite	1999	Mid-Sept 2005

Table 2. Nomenclature for the (Triassic) Mercia Mudstone Group in the study area.

<table>
<tr><td rowspan="6">TRIASSIC</td><td colspan="4">Current Nomenclature</td><td colspan="2">Former Nomenclature (Wilson & Evans, 1990)</td></tr>
<tr><td rowspan="4">Mercia Mudstone Group</td><td rowspan="4">Sidmouth Mudstone Formation</td><td>Breckells Mudstone Member</td><td></td><td colspan="2">Breckells Mudstones</td></tr>
<tr><td>Kirkham Mudstone Member</td><td>Coat Walls Mudstone
Pressall Halite
Thornton Mudstone</td><td>Kirkham Mudstones</td><td>Coat Walls Mudstones
Preesall Halite
Thornton Mudstones</td></tr>
<tr><td>Singleton Mudstone Member</td><td></td><td colspan="2">Singleton Mudstones</td></tr>
<tr><td>Hambleton Mudstone Member</td><td></td><td colspan="2">Hambleton Mudstones</td></tr>
<tr><td>Sherwood Sandstone Group</td><td></td><td></td><td></td><td colspan="2">Sherwood Sandstone Group</td></tr>
</table>

Table 3. Boreholes proving depth to top Preesall Halite, base Preesall Halite (where penetrated) and thickness of halite in the area west of the main brine field workings.

ICI Borehole reference number	Depth top halite (m)	Depth top halite (below O.D.)	Depth base halite (m)	Depth base halite (below O.D.)	Halite thickness (m)
*E1	317	308	398	388	81 (faulted?)
E2	372	365	Not reached	Not reached	?faulted 9
E-20	Not reached				
B6	362	354	557	549	195
*B-27	178	168	Not reached		> 30.5
B-43	296	288	401	393	105
B-22	Not reached				
B-111	269	264	413	409	144
B-112	283	278	478	473	195
B-123	324	319	464	459	140
B-124	226	219	363	356	137
*B-126	286	280	Not reached		> 170
*B-127	263	257	Not reached		> 193
*B-128	242	236	Not reached		> 192
*B-129	299	294	Not reached		> 268
B-130	312	307	Not reached		> 289
*B-133	277	273	Not reached		> 250
*B-134	261	255	Not reached		> 245
Coats Wall Farm	281	273	Not reached		> 4
Arm Hill	366.26	361.98	607.41	?602.98	> 236?
The Heads	226	221.95	430	c. 425.95	c. 210

Table 4. Datasets used in the 3D modelling of the Preesall area.

Dataset	Source	Comment
Digital Terrain Model (DTM)	Centre of Ecology and Hydrology (CEH)	Low resolution from BGS data holdings
Map of the top Preesall Halite, indicating the position of postulated faults	Darren Petroleum Consultants Ltd.	1: 10 000-scale, digitised by BGS
Borehole database	BGS Single Onshore Borehole Database (SOBI) and Borehole Geology Database (BOGE)	745 records with lithological and stratigraphical interpretation for the Preesall Halite interval
Seismic reflection data (lines GasGCE-86-DV371, Can97D, F and G, IELP99-25)	Reprocessed (IMC 2005) seismic lines, held as data within Borehole Geology	Depth converted seismic picks and input into GSI3D for correlation

Table 5. Earthquake magnitude/EMS-98 intensity comparison.

Magnitude	Intensity	Description
1.0 – 2.9	I	*I – Not felt* Not felt, even under the most favourable circumstances
3.0 – 3.9	II – III	*II – scarcely felt* Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings *III – Weak* The vibration is weak and is felt indoors by a few people. People at rest feel a swaying or light trembling
4.0 – 4.9	IV – V	*IV – Largely observed* The earthquake is felt indoors by many people, outdoors by very few. A few people are awakened. The level of vibration is not frightening. Windows, doors and dishes rattle. Hanging objects swing *V – Strong* The earthquake is felt indoors by most, outdoors by few. Many sleeping people awake. A few run outdoors. Buildings tremble throughout. Hanging objects swing considerably. China and glasses clatter together. The vibration is strong. Top-heavy objects topple over. Doors and windows swing open or shut.
5.0 – 5.9	VI – VII	*VI – Slightly damaging* Felt by most indoors and by many outdoors. Many people in buildings are frightened and run outdoors. Small objects fall. Slight damage to many ordinary buildings e.g. fine cracks in plaster and small pieces of plaster fall. *VII – Damaging* Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many ordinary buildings suffer moderate damage: small cracks in walls; partial collapse of chimneys.
6.0 – 6.9	VII – IX	*VIII – Heavily damaging* Furniture may be overturned. Many ordinary buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse *IX – Destructive* Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely.
7.0 and higher	X or higher	*X – Very destructive* Many ordinary buildings collapse *XI – Devastating* Many ordinary buildings collapse *XII – Completely devastating* Practically all structures above and below ground are heavily damaged or destroyed.

12 Main Report References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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13 APPENDICES

Appendix 1 Data supplied to BGS by Canatxx/Mott MacDonald

Various reports on earlier geological studies, borehole and planning application information were also copied to BGS by CanatxxMott MacDonald. These were:

Provided on August 1st 2005:

- Fleetwood Project – salt cavern gas storage for British Gas Hydrocarbon Resources Limited – Daran Petroleum Consultants Limited (1996)
- Core Logging, well logging, well testing, and laboratory core testing Canatxx exploratory wells at Fleetwood, United Kingdom. Topical Report PB-0104. JL Ratigan (2005)
- Atkins report to Lancashire County Council, Appendix 1 (part – pp 1-10). Geological aspects of a planning application by Canatxx for gas storage in salt caverns at Preesall, preliminary review (2005)
- CD containing various tables in pdf format of brine, shaft and exploration borehole information on top salt, base salt and salt thickness (isopach) in the area of study.
- Geology of the Preesall Salt Field. Short report (to Canatxx?) by T. Eyreman (2005).

Provided via email (pdf's in 3 zip files) from Mott MacDonald on 8/8/05:

- copies of the three 1997 Canatxx lines
- copies of maps (pdf format; maps A-D) in the study area with Canatxx line locations and hand drawn contours for depths to top salt (in feet).

Provided via email (pdf's in zip files) from Mott MacDonald on 5/9/05:

- zip files containing Canatxx'x Arm Hill and The Heads borehole info, including logging runs (giffs and HTML files).
- pdf files of the interpreted ?Irish Sea Oils (?Archaean) line IELP-99-25 and Gas Council DV371 seismic lines
- pdf files of ?Irish Sea Oils seismic line locations, depth converted IELP-99-25 line
- pdf file of Canatxx borehole database, containing tabulated data on top salt, base salt and salt isopachs for ICI shaft, brine and exploration boreholes in the study area.

Provided on CD by Mott MacDonald on 7/9/05 (files previously sent by Canatxx to Mott MacDonald via email):

- pdf files of some data sent on the 5/9/05 by email including
    - pdf files of the interpreted ?Irish Sea Oils (?Archaean) line IELP-99-25 and Gas Council DV371 seismic lines
    - pdf files of ?Irish Sea Oils seismic line locations, depth converted IELP-99-25 line

- pdf file of Canatxx borehole database, containing tabulated data on top salt, base salt and salt isopachs for ICI shaft, brine and exploration boreholes in the study area.

various drawing files of cavern location, borehole sites etc.

Provided via email by Richard Glover (Hammonds Solicitors) on the 22/9/05:

- pdf of Malcolm Jenyon report to Canatxx in 1997 on the Preesall Salt basin.

Provided on CD by Michael Brown (Canatxx) on the 26/9/05:

Digital borehole geophysical logs for Arm Hill and The Heads boreholes. Including various sonic logs (both p and s), density, neutron and gamma logs.

Seismic reflection data received:

These included data acquired between 1980 and 1999 – see Table below:

Seismic line	Dated acquired	Source	Date processed	Reprocessed (date)
GasGC81-336	Oct 1981	Dynamite	Nov 1981-Apr 1982	1996
GasGCE-86-DV371	Dec 1986	Vibroseis, hydrapulse and dynamite	Jan-May 1987	1996
Canatxx Line D	Sept 1997	Dynamite	Oct 1997	Mid-Sept 2005
Canatxx Line F	Sept 1997	Dynamite	Oct 1997	Mid-Sept 2005
Canatxx Line G	Sept 1997	Dynamite	Oct 1997	Mid-Sept 2005
'Archaean' Line IELP-99-25	1999	Vibroseis + short fill of dynamite	1999	Mid-Sept 2005

Seismic reflection data across the area of interest, with various processing/reprocessing dates.

Data held by BGS:

Borehole information held in the NGRC by BGS was available and these data were checked against the tabulated borehole and shaft database supplied by Canatxx.

Appendix 2 Table of BGS borehole number relative to original ICI well numbering (for use with Figures 6-11).

BGS Borehole Number (QS and number)	Original Borehole Name (ICI wells named 'Preesall No. #')
SD34NE2	PREESALL NO. 101
SD34NE3	PREESALL NO. 100
SD34NE4	PREESALL NO. 99
SD34NE5	PREESALL NO. 104
SD34NE6	PREESALL NO. 103
SD34NE7	PREESALL NO. 75
SD34NE8	PREESALL NO. 94
SD34NE9	PREESALL NO. 97
SD34NE10	PREESALL NO. 96
SD34NE11	PREESALL NO. 93
SD34NE12	PREESALL NO. 95
SD34NE13	PREESALL NO. 88
SD34NE14	PREESALL NO. 87
SD34NE15	PREESALL NO. 86
SD34NE16	PREESALL NO. 70
SD34NE17	PREESALL NO. 62
SD34NE18	CORCAS FARM BRINE WELL NO. 85
SD34NE19	PREESALL NO. 89
SD34NE20	CORCAS FARM BRINE WELL NO. 80
SD34NE21	PREESALL NO. 60
SD34NE22	PREESALL NO. 71
SD34NE23	PREESALL NO. 76
SD34NE24	PREESALL NO. 64
SD34NE25	PREESALL NO. 63
SD34NE26	PREESALL NO. 59
SD34NE27	PREESALL NO. 57
SD34NE28	PREESALL NO. 52
SD34NE29	PREESALL NO. 53
SD34NE30	EXPLORATORY BORING E6
SD34NE31	PREESALL NO. 48
SD34NE32	PREESALL NO. 47

SD34NE33	PREESALL NO. 78
SD34NE34	PREESALL NO. 98
SD34NE35	PREESALL NO. 45
SD34NE36	PREESALL NO. 9
SD34NE37	PREESALL NO. 49
SD34NE38	PREESALL NO. 102
SD34NE39	PREESALL NO. 46
SD34NE40	PREESALL NO. 51
SD34NE41	PREESALL NO. 50
SD34NE42	PREESALL NO. 44
SD34NE43	PREESALL NO. 66
SD34NE44	PREESALL NO. 67
SD34NE45	PREESALL NO. 74
SD34NE46	PREESALL NO. 69
SD34NE47	PREESALL NO. 72
SD34NE48	PREESALL NO. 65
SD34NE49	PREESALL NO. 68
SD34NE50	PREESALL NO. 83
SD34NE51	PREESALL NO. 81
SD34NE52	PREESALL NO. 82
SD34NE53	PREESALL NO. 73
SD34NE54	PREESALL NO. 79
SD34NE55	MESSERS SILCOCKS BORE, PREESALL
SD34NE56	PREESALL NO. 5
SD34NE57	PREESALL NO. 1
SD34NE58	PREESALL NO. 3
SD34NE59	PREESALL NO. 4
SD34NE60	PREESALL NO. 2
SD34NE61	PREESALL NO. 6
SD34NE64	PREESALL NO. 7
SD34NE65	PREESALL NO. 8
SD34NE68	PREESALL NO. 35
SD34NE69	PREESALL NO. 21
SD34NE70	PREESALL NO. 26
SD34NE71	PREESALL NO. 23
SD34NE72	PREESALL NO. 29
SD34NE73	PREESALL NO. 28
SD34NE74	PREESALL NO. 30
SD34NE75	PREESALL NO. 31
SD34NE76	PREESALL NO. 58

SD34NE78	PREESALL NO. 77
SD34NE79	PREESALL NO. 32
SD34NE80	PREESALL NO. 56
SD34NE81	PREESALL NO. 54
SD34NE82	PREESALL NO. 55
SD34NE83	PREESALL NO. 33
SD34NE84	PREESALL NO. 43
SD34NE87	MESSERS SEEDS BH
SD34NE89	PREESALL NO. 24
SD34NE90	PREESALL NO. 22
SD34NE91	PREESALL NO. 5 SHAFT & BORING
SD34NE93	PREESALL NO. 84
SD34NE94	PREESALL NO. 90
SD34NE95	MESSERS FAIRBROTHERS NO.2
SD34NE109	PREESALL NO. 36
SD34NE110	PREESALL 106
SD34NE111	PREESALL NO. 107
SD34NE112	PREESALL 112
SD34NE113	PREESALL NO. 108
SD34NE114	PREESALL NO. 109
SD34NE115	PREESALL NO. 110
SD34NE116	PREESALL NO. 111
SD34NE117	PREESALL NO. 115
SD34NE118	PREESALL NO. 116
SD34NE119	PREESALL NO. 113
SD34NE120	PREESALL NO. 114
SD34NE121	PREESALL NO. 117
SD34NE122	PREESALL NO. 118
SD34NE123	PREESALL NO. 119
SD34NE124	PREESALL NO. 120
SD34NE125	PREESALL NO. 121
SD34NE126	PREESALL NO. P1
SD34NE127	PREESALL NO. 122
SD34NE128	PREESALL NO. 123
SD34NE130	COAT WALLS FARM
SD34NE132	PREESALL NO. 124
SD34NE133	PREESALL NO. 125
SD34NE153	PREESALL NO. 133
SD34NE154	PREESALL NO. 134
SD34NE164	ICI PREESALL 126

SD34NE165	ICI PREESALL 127
SD34NE166	ICI PREESALL 128
SD34NE167	ICI PREESALL 129
SD34NE168	ICI PREESALL 130
SD34NE169	ARM HILL NO 1
SD34NE170	THE HEADS NO 1
SD34NW4	HACKENSALL HALL FLEETWOOD
SD34NW11	ICI EXPLORATORY BORING E2
SD34NW12	6
SD34NW61	HACKENSALL HALL FARM BH
SD34SE1	BURROWS FARM STALMINE E7
SD34SE2	BURROWS FARM STALMINE E5
SD34SE8	STAYNALL
SD34SW2	ICI EXPLORATORY BORING B1
SD34SW3	THORNTON 27

Appendix 3 Seismic Processing Summary for Canatxx Preesall Project (30/09/05)

The following seismic reflection lines have been re-processed:-

CAN97-D

CAN97-F

CAN97-G

IELP-99-25

86DV371

Acquisition Summaries:-

CAN97-D, F and G were acquired with dynamite recorded into geophones and hydrophones. Maximum of 96 channels at a station interval of 10m. Recorded at 1ms for 2 seconds

IELP-99-25 was acquired with Vibroseis with a short in fill section of dynamite. Maximum of 242 channels at a station interval of 10m.

Recorded at 1ms for 3 seconds

86DV371 was mostly acquired with Vibroseis, with Hydropulse and dynamite in fill. Maximum number of 120 channels at a geophone and hydrophone station interval of 25m.

Recorded at 2ms for 3 seconds

Processing and Re-processing Summary for the following lines:-

CAN97-D

CAN97-F

CAN97-G

IELP-99-25

Some of the original processes remain unchanged. Where processing parameters were changed and additional processes applied these are indicated in bold type

Refraction statics

Refraction statics analyses were carried out on all five lines using GMG Millennium software. The first break picks were made manually at the first peak immediately following the leading trough.

One refractor V1, was identified from the first break picks and included in the refraction model.

V1 was varied from 1700 m/s to 1900 m/s on the CAN97 lines, 1900 m/s to 2300 m/s on ielp9925 and 2200 m/s to 2600 m/s on 86dv371.

V0 velocities were for ielp-99-25 and 86dv371 taken from the LVL surveys conducted at the time of their acquisition. The V0 velocities were slow 100 to 450 m/s

No LVL data were available for the CAN97 lines, so V0 was assumed at a constant 500 m/s. (the record V0 from the LVL data seems too slow)

For each line a refraction static solution was derived to the processing datum of MSL. Generally the static was about 5ms to 10ms greater than that of the elevation static.

Velocity	m/s	thickness (m)
V0	100 to 450 (500)	1 to 10
V1	1700 to 2600	

After refraction statics the stacking velocities were re-picked and DMO and auto statics were re-run

1. re-processed to 1 second at 1ms sample rate
2. Crooked line binning
3. bad trace edit
4. spherical divergence correction
5. time offset gain correction
6. elevation static correction to MSL

   The CAN lines used uphole times from production shots

   and a replacement velocity of 2000 m/s

   IELP-99-25 used a LVL derived variable replacement velocity

6. deconvolution minimum phase spiking with 40ms operator for the CAN data and 60ms operator for IELP-99-25

7. Interactive velocity analysis

8. Ensemble DMO was used to enable velocity analysis independent of dip and give improved signal to noise ratio, particularly attenuating dipping linear noise. DMO can be generally more effective than F/K. F/K filtering was applied to the original processing of CAN97-D, F and G.

9. Surface consistent residual statics with flat single gate of 500ms and +-4ms

10. Interactive velocity analysis

11. Interactive NMO stretch muting

12. Surface consistent residual statics with two contoured gates each of 500ms and +-4ms

13. Non-surface consistent residual statics with two contoured gates each of 500ms and +-4ms

14.CMP stack

15.Time Variant Bandpass Filter:-

0-100ms 40-100Hz

200ms 30-100Hz

500ms 30-80Hz

1000ms 25-50Hz

16. ACC 300ms

17. Back ground random noise attenuation with FX Deconvolution. For IELP-99-25 the FX was blended in the ratio of 1 to 1, original to FX.

18. Finite Difference Steep Dip Time Migration using a single interval velocity function derived from the RMS stacking velocities. Migrations at 100%, 95%, 90% and 85% of the interval velocity function.

Re-processing Summary for 86dv371

Some of the original processes remain unchanged. Where processing parameters were changed and additional processes applied these are indicated in bold type

1. re-processed to 1 second at 2ms sample rate
2. **Crooked line binning**
3. bad trace edit + **further bad trace editing**
4. spherical divergence correction
5. time offset gain correction
6. **a 25ms static shift up was applied to the dynamite and hydropulse data to match the vibroseis data**
7. separate recording filters were applied to the geophone and hydrophone stations (analogue recording syytem)
8. some of the hydrophone stations were reversed
9. **20Hz low cut cone filter was applied to reduce near trace source noise**
10. elevation static correction to MSL
11. with a replacement velocity of 2000 m/s
12. deconvolution minimum phase spiking with 60ms operator for the
13. Interactive velocity analysis
14. **Ensemble DMO was used to enable velocity analysis independent of dip and give improved signal to noise ratio, particularly attenuating dipping linear noise. DMO can be generally more effective than F/K. F/K filtering was applied post stack in the original 1996 re-processing of 86DV371**
15. **Surface consistent residual statics with flat single gate of 1000ms and +-8ms**
16. **Interactive velocity analysis**
17. **Interactive NMO stretch muting tighter mute picked**
18. **Surface consistent residual statics with two contoured gates each of 500ms and +-8ms**
19. **Non-surface consistent residual statics with two contoured gates each of 500ms and +-4ms**
20. CMP stack
21. Time Variant Bandpass Filter:-
22. 0-700ms 15-60Hz
23. 1300ms 15-50Hz
24. 2000ms 10-45Hz
25. ACC 300ms

26. Back ground random noise attenuation with FX Deconvolution was blended in the ratio of 1 to 1, original to FX.

27. Finite Difference Steep Dip Time Migration using a single interval velocity function derived from the RMS stacking velocities. Migrations at 100%, 95%, 90% and 85% of the interval velocity function.

Further comment:-

1. For the CAN lines, hydrophone and geophone matching was not done originally, possibly because there were no coincident hydrophone and geophone stations.
2. In the original processing of IELP-99-25, the short dynamite in fill data was not matched with the Vibroseis data. A match of the dynamite data to the Vibroseis data was tried in the current reprocessing. The result however proved disappointing, and therefore not included.
3. Similar poor data phase matching results were experienced on 86DV371 and therefore not applied. The static shift of 25ms for the dynamite and hydropulse data proved necessary where these data types over lapped with the Vibroseis data.
4. The 1996 re-processing of 85DV371 was archive on a much older version of ProMAX consequently on restore a new crooked line track had to be picked and the data re-binned. Originally in 1996 this was 12.5m inline by 250m crossline, this time in was increased to 350m crossline to include all of the data.
5. 5 .Due to the tight re-processing schedule 2D refraction statics analysis and application has not been done. Although the elevation is low there may still be significant lateral velocity variations in the near surface that do not express themselves in topography and are not modelled by the production shot upholes of the CAN lines or the LVLs of IELP-99-25.
6. The refraction static solution made no improvement to CAN97d and 86dv371 and therefore the stack data from the refraction solution were not provided.
7. On CAN97g the refraction solution showed some improvement in the middle section of the tvf stack.
8. CAN97f on both tvf and mig showed some reflection continuity improvement mid section.
9. And IELP-99-25 exhibited continuity improvement between cdps 360 to 460 above 150ms
10. Small local reflection enhancements on three lines, but no overall significant improvement in continuity.

Chris Robson 30/09/05

Appendix 4 Gravity data

THE GRAVITY METHOD

The gravity method is based on the principle that masses exert an attractive force upon one another. This gives rise to a gravitational field which varies across the surface of the earth due to many factors, including the distance from the centre of the earth (i.e. centre of mass), variations in the shape of the surface – i.e. topography, and variation in the density of the subsurface.

The effects of many of these factors, e.g. elevation, distance from the centre of the earth, local topography etc. can be calculated and removed to leave a value which is related to density variations, occurring at various depths, within the earth's crust. The Bouguer gravity anomaly results from a particular method of removing these factors.

The gravity field is usually measured with a gravimeter. The commonly used type are highly sensitive and accurate and capable of determining the earth's gravity field to better than 0.1 milligal (1mGal = 1 x 10^{-5} ms^{-2}), or better than 0.01 milligal for the most modern instruments.

Measurements are taken at points of accurately known (or calculated) location and height to allow the various corrections to be made. These points may be scattered across an area or along traverse lines.

Gravity anomaly maps are often presented as contoured maps. Areas of low anomaly value ('gravity lows') are associated with lower density bodies, for example sedimentary basins and granites. High-density bodies, such as metamorphic (and crystalline) basement and gabbros, give rise to gravity 'highs'. Steep anomaly gradients occur where density variations are rapid, for example across a geological fault.

The gravity anomalies can be used qualitatively or modelled quantitatively by geoscientists to assist in determining the geological structure of an area.

BRITISH GEOLOGICAL SURVEY NATIONAL GRAVITY DATABANK

The British Geological survey holds a databank comprising some 168000 land gravity measurements covering the whole of Great Britain. The data are available from BGS under licence.

The points were located primarily along roads and tracks but additional measurements were made in remote areas using helicopters and in intertidal areas using hovercraft and boats. Data density is between 1 and 2 stations per $2km^2$, with generally better coverage in lowland areas.

FLEETWOOD GRAVITY DATA

The BGS gravity data for the Fleetwood area (Fig 29, blue points) were acquired by the Geological Survey and Museum in 1963. Data coverage is typical of lowland areas, except in the corridor occupied by the River Wyre where the data density is low due to the width of the estuary and the inaccessibility of the adjacent areas.

The marine area to the north and west of Fleetwood was surveyed during the 1970s as part of the Morecambe Bay Hovercraft survey.

In 1968 a more detailed local survey was made in the area, during the geological mapping of the Blackpool district. The station density is much higher than the original survey. (Fig 29, red points) It also includes two micro-gravity traverses, with points at 30m intervals. These traverses are relatively short (~2km) and cross the Preesall Fault at Preesall and Staynall. Neither traverses extend fully into the area of prime interest for this study.

The dataset from the 1968 survey was used to produce the Bouguer gravity anomaly map included on the Blackpool 1:50 000 scale geological map, published in 1975. As the new survey had greater station density the old data were omitted from the dataset. The contours from this dataset are shown in Figure 29 with the data points show as red points. The original (1962) survey points are shown in blue and the 1968 traverse points in green.

The 1968 survey, like the original 1963 survey, also has a large area lacking data in the region of the Wyre Estuary and adjacent land.

The Bouguer gravity anomaly values show the highest values in the north-east corner of the district, where the (denser) Carboniferous basement is nearer the surface, beneath the Sherwood Sandstone. The values fall most rapidly to the west but also show a general decrease to the south and southwest. The general reduction in Bouguer anomaly values is coincident with the thickening of lower density Permo-Triassic rocks away from the Pennines, towards the East Irish Sea Basin.

Just west of the Preesall fault, from Preesall to Thornton, there is a weak ridge of slightly higher values (seen as tight contour bends in Figure 29), suggesting a density increase on the downthrown (western) side of the fault. This is counter to what might be anticipated and has been discussed above as relating to the Preesall Fault dipping westwards at a low angle (section 4.2.2.2).

The area of interest and the Preesall syncline are not completely covered by gravity observations so the anomalies are not tightly constrained in this area. The gravity data that do exist in the area appear to show only the regional decrease to the west. Locally low values, which might be expected due to an increased thickness of low-density materials, are not apparent in the data.

MICRO-GRAVITY SURVEYS AND GRAVITY MONITORING

Micro-gravity surveys have the potential to resolve near-surface faulting, given sufficient density contrasts in the rocks of an area. Additional gravity data could also provide additional control for the interpretation of other data, for example seismic data.

Performing micro-gravity surveys in the area of interest might well be problematic due to the presence of the estuary of the River Wyre. The presence of variable thicknesses of low-density drift deposits could also give rise to significant anomalies. These near-surface anomalies would combine with those due to deeper rocks, making interpretation of the rocks below difficult, or even impossible.

Time-lapse micro-gravity surveys have been used to monitor the storage of liquid and gas in sub-surface cavities in a number of projects both in UK and abroad. The technique relies on there being a bulk density contrast between the liquid and the gas filling the cavity. By regularly taking readings from a network of sites in the area above and around the storage facility a series of anomaly values can be obtained when the cavity is liquid filled and gas filled. A series of difference maps can be generated, reflecting the different states of the cavity. A set of gravity readings taken during the operation of the facility can then be modelled in 3D to determine how full the cavity is and help potentially verify volumes in storage.

Appendix 5 Seismicity report

The following text, prepared by Dr R Musson of BGS, outlines the seismic hazard at the Preesall site and is discussed without going to the extent of a full probabilistic seismic hazard assessment (PSHA).

General background to seismicity in the UK

Some words about seismic hazard in the UK in general are appropriate to start with, since some misconceptions are common. These are due to the extent to which, issues relevant to seismic hazard in California have created expectations concerning procedures, which are not always appropriate in less seismically active parts of the world such as the UK.

In places like California, approaches to seismic hazard are strongly directed to consideration of individual faults. For a given site, one is concerned with questions along the lines of: is this fault, which is near my site, active? And: if not, what is the closest active fault to my site? And: is this site best avoided because it lies so close to the trace of an active fault that surface displacement may occur across it in a future earthquake?

In the UK, by contrast, the concept of an "active fault" is probably inappropriate altogether (Musson, 2005a). Conventional definitions, largely developed in active tectonic areas, refer to any fault that has demonstrably moved in the past x years as active, where x is some large number extending certainly beyond historical times, usually back to the beginning of the Quaternary. It is common practice to examine known faults one by one, compare them to this definition, and decide if they are active or not. The number that meets this criterion indicates the number of "active faults".

This process is unhelpful in the context of intraplate areas, such as the UK. The number of "active faults" as defined above can be directly estimated by approaching the question from the other direction. All earthquakes occur on faults; there are approximately 300-400 distinct epicentres in mainland UK; therefore there must be about this number of active faults in the UK, even though most cannot actually be recognised in the field.

It has proved up to now extremely difficult to reliably associate any British earthquakes with specific known faults. Since the typical British earthquake is small, its rupture dimensions are also small. The hypocentre is likely to be located only to an accuracy of ± 5 km or so in three dimensions, and within this crustal volume several faults may occur.

The typical British earthquake occurs at depths of between 5 and 15 km, and what faulting occurs at these depths is usually poorly known; certainly looking at a map of faults that shows only their surface traces is of limited use.

In the case of major earthquakes worldwide, causative faults can be identified in one of a number of ways. In the first case, since major earthquakes require large structures to host them, the fault may already be well known. In the second case, the fault may be directly observable through surface rupture. Thirdly, the fault plane is often imaged by the distribution of aftershocks. Fourthly, waveform inversion can be applied to map not only the fault itself but the distribution of rupture along it.

These methods are of limited application in the UK. As a result, very few British earthquakes have fault attributions that seem at all reliable. One can mention the 15 February 1865 Barrow earthquake (Musson, 1998), the 16 September 1985 Ardentinny earthquake (Redmayne and Musson, 1987), and the 22 September 2002 Dudley earthquake (Baptie et al., 2005) as three cases where named faults can be cited as causative features with some certainty; there are a few others, but not many.

This is typically the case in intraplate areas, due to the absence of significant tectonic deformation. At plate boundaries and other areas of active deformation, large-scale differential movement within the crust requires fault planes on which to accommodate this movement. Most large faults were originally created in this way. The rocks that comprise the British Isles have been subjected to various phases of orogenesis and active deformation in the past, leaving behind many fault structures which were once active but are now relict features. These faults can, however, be reactivated in the context of the quite different tectonic circumstances that exist today.

Thus present day seismic activity in the UK is principally explained in terms of reactivation of old features under the roughly north-west-south-east oriented stress field generated by the ridge-push force originating at the Mid-Atlantic Ridge (Whittaker et al., 1989; Zoback, 1992). The dominant earthquake mechanism in the UK is strike-slip faulting on near-vertical faults, as is to be expected when the maximum and minimum stress directions are both in the horizontal (Baptie, 2002). With the maximum compression being roughly north-west-south-east, faults that are oriented north-south or east-west are most favourable to being reactivated. Any fault with this favourable orientation can be considered as capable of reactivation. This applies not only to mapped faults with a surface expression, but also (really, even more) to basement faults, and these may have no surface expression and thus not be mapped.

The typical damaging British earthquake in the past has been around 5 ML (ML = local or "Richter" magnitude) in magnitude (no onshore event is known to have exceeded 5.4 ML) and such an earthquake requires movement on a fault no more than a few kilometres long. An earthquake of around 5.8 ML, similar to the 1992 Roermond earthquake in the southern Netherlands, and which can be considered the typical scenario event for the UK (Musson, 2004a) can originate from 6 km of fault rupture, using the relations of Wells and Coppersmith (1994). Faults large enough to host such an earthquake are rather common in the UK. Major fault structures are not required.

As a result, seismic hazard assessment in the UK tends not to be a search for the nearest active fault, but proceeds on the basis that a damaging earthquake can effectively happen anywhere. However, based on historical experience, it is clear that some parts of the country are more prone than others. The geological reason for this variation is not very clear (Musson, 1996), but it is statistically certain that the distribution of earthquake epicentres across the UK is not random or even (Musson, 2000). Normal hazard assessment procedure is to take account of these regional variations to construct a probabilistic model of earthquake occurrence that can be used to assess the likelihood of any degree of ground shaking within a specified interval of time (Musson, 2004b; Musson and Winter, 1997).

The issue of hazard from ground rupture does not really arise. This can be demonstrated with Figure 1. This figure shows all earthquakes > 3 ML with known depths in mainland UK and the Irish Sea, plotted by latitude and depth as a north-south cross section. The vertical bars show the extent of the fault rupture calculated from Wells and Coppersmith (1994), assuming that all ruptures are circular and that rupture length is the predicted value plus one standard deviation. None of the ruptures intersect the surface and very few even come close. And this is with what can be considered a pessimistic model; Burton and Marrow (1989) predict much smaller ruptures for the same size of earthquake in Britain than are given by Wells and Coppersmith's (1994) global regressions, which are primarily based on large magnitude earthquakes.

Not only are British earthquakes generally small; the larger, more infrequent, events tend to be of deeper focus. This can be seen in Figure 1, and is clearer still in Figure 2, which plots magnitude against depth for a slightly larger area than is covered in Figure 1. Only two events in the last 400 years are identified that are both >4 ML and have depths in the top 5 km of crust.

Seismotectonics relating to the site

The Preesall site is within a structural area dominated by north-south trending faults, which includes the East Irish Sea Basin and the Cheshire Basin. The structural geology is shown in Figure 3, which is a detail from Figure 2 in Jackson and Mulholland (1993). It has been suggested (Akhurst et al., 1998) that two of the closer known faults to the site, the Preesall Fault and the Formby Point Fault, may be structurally related to the Lake District Boundary Fault Zone (LDBFZ). The LDBFZ is a complex feature on the western boundary of the Lake District, oriented mostly north-north-west-south-south-east. In the north it is an anastamosing (braided and branching) structure, and one of its splays in the Furness peninsula, the Yarlside Fault, is almost certainly the fault responsible for the small but damaging 1865 Barrow earthquake; it is because this earthquake was small and very shallow (perhaps 1-2 km) that this association can be advanced with some confidence (Musson, 1998). Another small, shallow earthquake, the 17 November 1755 Whitehaven earthquake, occurred within the traces of the LDBFZ and must have been related to it. The much larger 11 August 1786 earthquake (5.0 ML), which had an epicentre offshore from Whitehaven, may also have been linked to the LDBFZ.

Thus, given that the LDBFZ has been seismogenic (i.e. responsible for an earthquake - which is different from saying that it is "active" in the sense that, say, the San Andreas Fault is active), it is possible that reactivation could in theory shift to the Preesall Fault at some point in the future, but there is no evidence that this has taken place.

Seismicity of the site and its environs

However, whatever may be said about favourable fault orientations, the East Irish Sea and Cheshire Basins have not shown strong seismic activity even by UK standards. Figure 4 plots the regional seismicity from the BGS database. Symbol size is related to magnitude, and colour to depth, with shallower events being lighter (unknown depths are coloured red). Events discussed in the text are labelled. The nearest earthquake to the site, excluding very minor events, is the 20 August 1835 Lancaster earthquake (4.4 ML), about 24 km to the north-east.

This is one of two past earthquakes that can be considered to be of particular interest to the site. The epicentre was in the hills east of Lancaster, perhaps in the northern part of the Bowland Fells (Burton et al 1984). The shock was strong enough to throw down field walls, and in a few cases minor damage to buildings was reported. At Poulton-le-Fylde, which is the nearest location to the site from which reports survive, the shock was severely felt, causing many to rise from bed in alarm. Light articles were shaken considerably, but no damage occurred. Burton et al. (1984) give an intensity of 5 EMS to Poulton-le-Fylde, and the estimated intensity at site using UK intensity attenuation (Musson, 2005b) is also 5 EMS (i.e. shaking is strong but not damaging; EMS = European Macroseismic Scale).

The second event of note occurred only eight years later, and was larger in magnitude. The 17 March 1843 Irish Sea earthquake had a magnitude of 5.0 ML, and was felt over a wide area of north-west England, eastern Ulster, and the Isle of Man. The epicentre was evidently offshore in the eastern Irish Sea, but how far offshore is open to debate. At Fleetwood some people left their houses through alarm; almost everyone was woken by the shock; some bottles fell from shelves and several windows were broken (intensity 5 EMS).

Intensity 5 EMS is likely to have occurred at site also from one other earthquake, which by coincidence also took place on 17 March, this one in 1871. The epicentre was nearly 100 km away to the north-east, near Appleby, and thus well away from the basin structures of the eastern Irish Sea – Cheshire – Lancashire area. However, it was sufficiently large (4.9 ML) to be felt strongly at some distance. In Fleetwood, most people were woken, chairs rocked slightly and clocks were stopped (Musson, 1991a; Musson, 1991b). The intensity at Fleetwood is considered 4-5 EMS by Musson (1991a), but the site itself lies within the isoseismal (contour) for 5 EMS (intensity varies over short distances and is not completely uniform within isoseismals).

No other earthquake seems to have produced an intensity higher than 4 EMS at site. The number of earthquakes with estimated intensities of 4 EMS (i.e. generally perceived indoors, windows and doors rattle) at site is eight, from 7 October 1690 Caernarfonshire to 19 July 1984 (also Caernarfonshire).

Seismic hazard assessments

Existing seismic hazard maps for the UK (Jackson, 2004; Musson, 1997; Musson, 2004b; Musson and Winter, 1996; Musson and Winter, 1997) show that hazard for the site is average in UK terms, with an expected peak ground acceleration (PGA) of about 0.15 g at an annual 10^{-4} probability, and an intensity of 6 EMS 90% probable not to be exceeded in 50 years (6 EMS = slight damage). These hazard values are, of course, influenced by the possibility of earthquakes occurring close to the site, but are controlled to a greater degree by seismicity connected with the Pennines, and especially the southern end of the Pennines, where a concentration of seismicity has been observed from Skipton to Altrincham (most noticeable recently for the Manchester earthquake swarm of 2002). It has been suggested that seismicity within the Pennine chain may be due to rotational movement of rigid blocks within the structure (Chadwick et al., 1996). Models used for the calculation of probabilistic seismic hazard generally treat the Pennines and Lake District as relatively high seismicity areas, and the Irish Sea and Lancashire coast as a relatively low seismicity area.

Conclusions

To conclude: although the Preesall site is in an area which is dominated by geological structures which could be considered as liable to activation, observed seismicity in the past on these structures has been low, although one of them was probably responsible for the 17 March 1843 earthquake, which had a magnitude of 5.0 ML. The likelihood of any fault reactivation near the site causing a direct rock rupture hazard is extremely small; such an event has never happened anywhere in the UK in historical times, as the larger UK earthquakes have depths considerably in excess of their rupture dimensions. The maximum observed intensity at site in historical times is 5 EMS, which is just below the damage threshold.

Future seismic hazard at the site is therefore dominated by the effects of large (in UK terms) earthquakes at moderate distances. A site-specific analysis to assess the hazard values for given return periods has not been conducted in this study, but could be if required in future. Generic hazard maps suggest that the hazard at site is about average for the UK, and of the order of 0.15 g with annual probability of 10^{-4} and perhaps about 0.05 g at $2x10^{-3}$.

Figures:

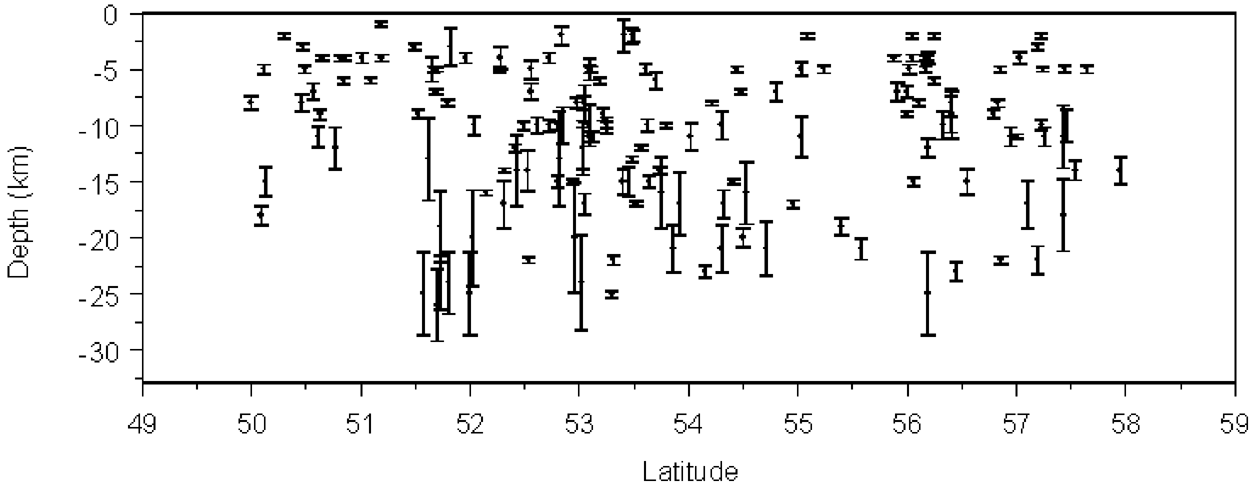

Figure 1 - Cross section of UK seismicity from south to north, showing probable maximum vertical extent of ruptures.

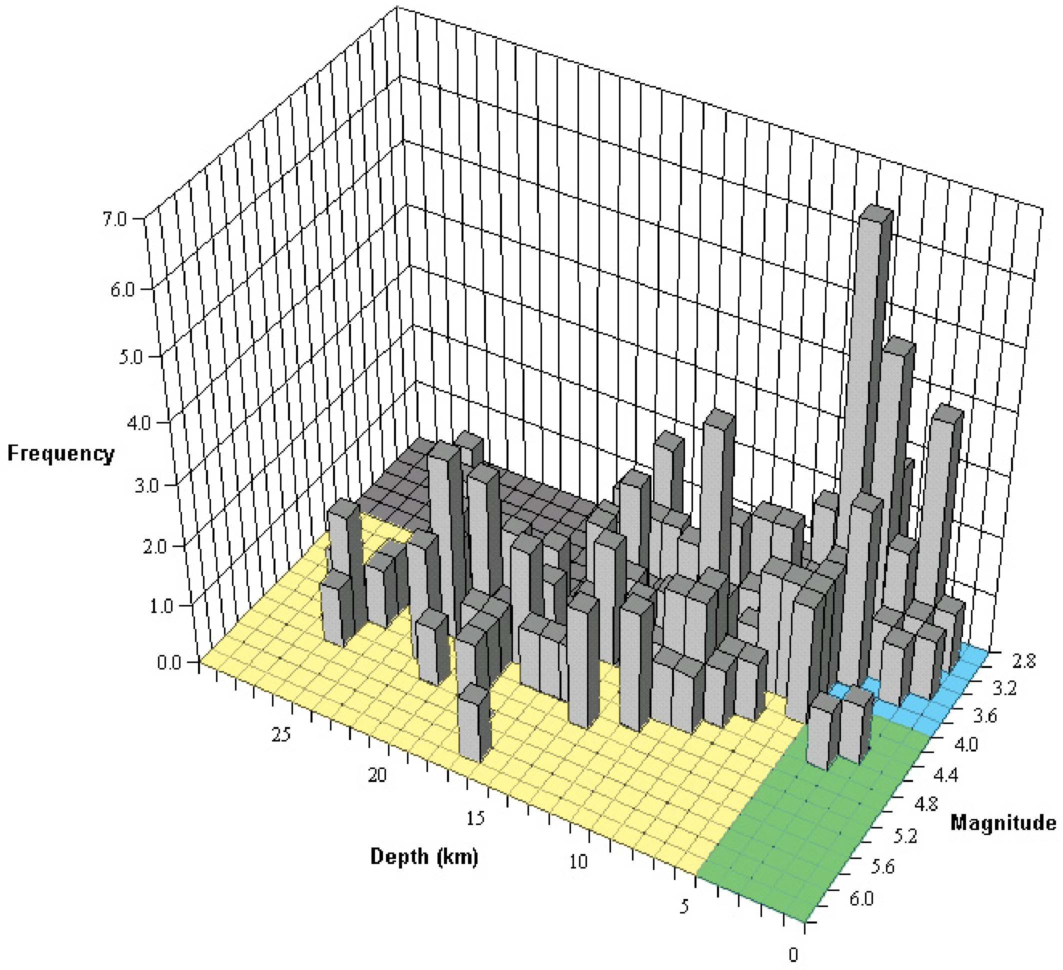

Figure 2 - Numbers of UK earthquakes classed by magnitude and depth

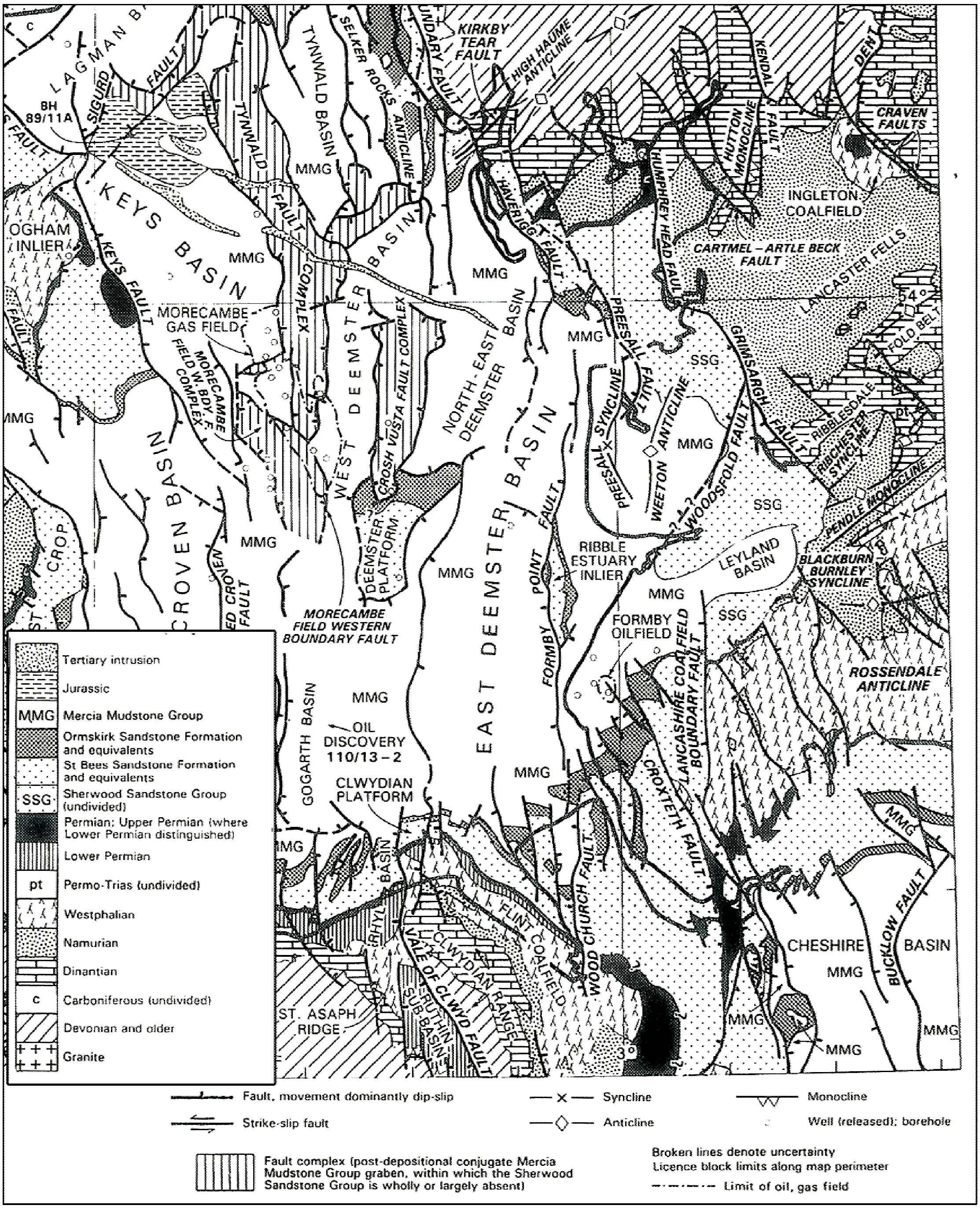

Figure 3 - Structural geology of the area, after Jackson & Mulholland (1993)

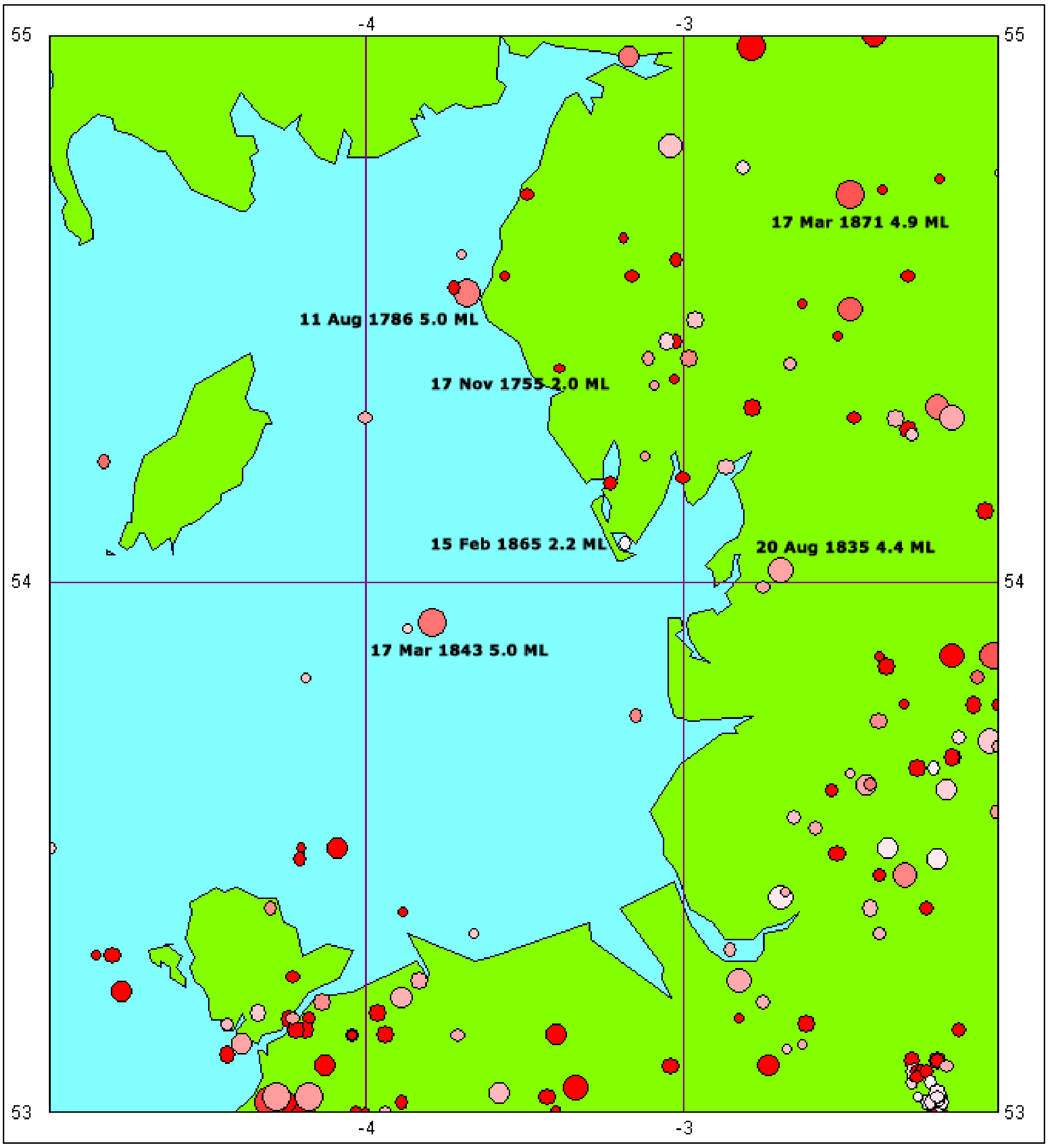

Figure 4 - Seismicity of north-west England and eastern Irish Sea

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Appendix 6 Hydrogeology

The following hydrogeological summary has been prepared jointly by Anthony Feigl of Mott MacDonald and Dr N Robins of BGS Wallingford.

The scope of evidence is to provide a summary of existing information on the hydrogeology of the area around Preesall, near Fleetwood in Lancashire.

HYDROGEOLOGY OF THE SHERWOOD SANDSTONE GROUP

The Sherwood Sandstone Group (SSG) is a major aquifer of regional importance where at economically exploitable depths (known as the Fylde Aquifer in north west Lancashire). However, within the proposal area the sandstone is deeply buried beneath the Mercia Mudstones, due to the presence of local faults. In this area groundwater flow in the sandstone is interpreted to be very low. Moreover, the hydraulic connectivity between the SSG in the area of the proposal and the Fylde Aquifer is likely to be very limited. This interpretation is based on observations made during previous studies (refer Section 0) and the context of the 'Preesall Graben', the latter likely to be limiting groundwater flow within the SSG of the downthrown block due to deep burial and also limiting flow in the surrounding SSG perpendicular to the bounding faults.

Vertical permeability within the sandstone has been noted to be restricted by marl (mudstone) beds. Recharge to the sandstone aquifer is predominantly from rivers to the east and south east of the proposal area and potentially from Carboniferous strata at the Pennines, with basin-scale flow generally westwards. Seasonal changes in water level are generally low, typically less than a metre, due to the high storage capacity of the Sherwood Sandstone.

HYDROGEOLOGY OF THE MERCIA MUDSTONE GROUP

The Mercia Mudstone Group overlies the Sherwood Sandstone Group and attains a thickness of over 800 m in the vicinity of Fleetwood (Wilson & Evans, 1990). Members of the group consist of alternating sequences of salts and mudstones, including the Preesall Halite, which is the thickest of the halite beds in the Fleetwood area.

Around Preesall, the Preesall Halite has been thrown down and tilted by faulting, so that in places it is in contact with ('subcrops') the overlying superficial drift. This has caused the Preesall Halite to be naturally sub-eroded (dissolved) by groundwater in subcrop zones and replaced by collapsed overlying deposits. This is known as the 'wet rockhead' phenomena. Wet rockhead generally extends 50 to 75 m below the base of the drift. Historically, brine groundwater has been extracted at Preesall from immediately above wet rockhead ('wild brining'), exacerbating sub-erosion of the rock salt and the subsequent collapse of overlying formations. This has led to localised ground subsidence. Conversely, in 'dry rockhead' zones, the thick sequence of Mercia Mudstone Group overlying the Preesall Halite protects the latter from sub-erosion by shallow groundwater within the drift. It is of note that the proposed new natural gas caverns are to be constructed by solution mining below dry rockhead.

In general the Mercia Mudstone Group is an aquitard (i.e. very low permeability), with very minor vertical or horizontal flows of groundwater. The BGS note that low yields of up to 5 l/s have been observed from the more permeable units within the group, principally the Tarporley Siltstone, but this formation is not present within the proposal area.

The salt deposits themselves are also essentially impermeable. In situ hydraulic testing carried out for the proposed scheme indicated approximate rock mass hydraulic conductivities of $5x10^{-6}$ metres per day (m/d) to $8x10^{-6}$ m/d for the depth interval 200 m to 355 m below ground level and $1x10^{-6}$ m/d to $3x10^{-6}$ m/d for the interval 400 m to 575 m below ground level. This range in hydraulic conductivity is comparable to fine clay or unfractured igneous and metamorphic rocks.

Fracture tests were also conducted during the same investigation, resulting in an estimated fracture conductivity of around $9x10^{-3}$ m/d when the injection pressure is above the fracture opening pressure. This value is typical for rocks with relatively tight fracture sets. The fracture conductivity of the salt deposit at injection pressures below the fracture opening pressure are likely to be significantly less than $9x10^{-3}$ m/d.

HYDROGEOLOGY OF THE SUPERFICIAL DEPOSITS

The bulk of the drift deposits in the proposal area are Till (previously known as 'Boulder Clay'). The principal hydrogeological significance of Till is that it limits recharge and confines water within underlying formations (namely the Sherwood Sandstone and Mercia Mudstone in the proposal area). More localised Marine and Estuarine Alluvium, consisting predominantly of mud, clay and silt are also found within the proposal area and probably act as aquitards. However sands and gravels may exist at depth. Saturated horizons within the drift and in the proposal area will generally be confined from below at relatively shallow depths, either by less permeable Mercia Mudstone Group or less permeable drift deposits. The shallow hydrogeology of marine and estuarine alluvium, and to a lesser extent the Till, is likely to be related to the hydrology of the marshes in the proposal vicinity. Very little field data exists on the hydraulic properties of the drift, due to its very limited potential for supplying groundwater at economic yields, although values have been derived from modelling studies.

GROUNDWATER ABSTRACTION

Based on the Envirocheck report and correspondence with the Wyre Borough Council, there are no registered groundwater abstractions or known private drinking water supplies within a 1 km buffer surrounding the proposal area nor any groundwater source protection zones.

POTENTIAL GROUNDWATER POLLUTION

There does not appear to be any potential for pollution of the Sherwood Sandstone aquifer in the immediate proposal area, given the thick and poorly permeable sequence of Mercia Mudstone Group overlying the aquifer (see below).

There is a known mercury sulphide repository, adjacent to the proposal area, which utilises a former brine cavern in the ICI brinefield.

The Envirocheck report indicates the locations of numerous landfills, waste management facilities and industrial land uses, as well as some forty pollution incidents to controlled waters and two prosecutions related to land and water.

SCOPE OF EVIDENCE

The evaluation of the hydrogeology is based on existing published, public domain and project-commissioned reports and information.

A full list of references is presented below. The following is a summary of the information sources used as the basis for this report.

Published and public domain maps and reports

- British Geological Survey (BGS) published geological maps and geological memoirs
- British Geological Survey / Environment Agency published groundwater maps and reports
- Ordnance Survey published topographical maps

Existing groundwater assessments and models

- Fylde Aquifer / Wyre Catchment Water Resources Study, completed in 1997 by Mott MacDonald for the Environment Agency North West Region

- The Lancashire Conjunctive Use Scheme Groundwater Model, completed in 1975 by the Water Research Centre

Project commissioned investigations

- Daran Petroleum Consultants' geological report to British Gas Hydrocarbon Resources Ltd
- MESY GmbH's report on hydraulic tests within the Arm Hill No. 1 borehole, for Canatxx Gas Storage Ltd
- Hyder Consulting's Environmental Statement on behalf of Canatxx Gas Storage Ltd
- Landmark Envirocheck report on the Preesall area, prepared for Mott MacDonald Ltd on behalf of Cantaxx Gas Storage in September 2005

Topography, hydrology and land use

The proposal area covers an extensive irregularly shaped area comprising open agricultural land with associated hedged field boundaries and salt marsh to the east of the Wyre Estuary, approximately 3.2 km north to south and 1.8 km west to east at its maximum extents. The land is generally flat but undulating in parts rising to a height of 20 metres above Ordnance Datum (m aOD) at Burrows Farm in the south.

The principal surface water features in the proposal area are the Wyre Estuary and its associated marshlands in low-lying areas. Within the proposal area, a number of minor tributaries and drainage channels flow into the Wyre Estuary, as well as numerous small lakes and ponds, some infilled.

The Landmark Envirocheck report, includes a map showing general land use in the vicinity of the proposal area, including surface water features.

Rainfall

From rainfall records provided by the Environment Agency as part of the Fylde Aquifer study (Mott MacDonald, 1997), an average annual rainfall of approximately 960 mm could be representative for the proposal area. This is based on a largely complete data set over the period 1973 to 1994 at two locations: Hambleton (Station No. 578978) and Pilling (Station No. 579149 / 579155).

Evapo-transpiration

The Fylde Aquifer study derived potential evapo-transpiration (PE) from a program developed by R Manley for the Environment Agency (1995) called PET-CALC, which requires input of latitude, longitude and altitude. The Fylde study applied the program to an area 10 km to 20 km east of the current proposal area. However, given that the variations in estimated PE across the Fylde area were minor, it is considered appropriate for the purpose of this report to approximate PE in the current proposal area by taking the closest estimated PE from the Fylde study.

For the period 1918 to 1991, the annual PE estimated by PET-CALC for the Garstang catchment (approximately 10 km east-north-east of the proposal area and at similar elevation) was 556 mm.

Occurrence of aquifers and aquitards

Sherwood Sandstone Group

In the proposal area the thickness of the Sherwood Sandstone Group (SSG) has been proved at over 150 m (BGS, 1975) and its total thickness is projected to be far greater (proved at over 1,300 m near Knutsford, approximate National Grid Reference 370000, 380000, (BGS, 1989)). The SSG, and for that matter the solid geology in general, does not outcrop in the vicinity of Preesall due to extensive cover by glacial drift deposits.

Where at depths allowing economical abstraction of groundwater the Sherwood Sandstone Group represents a major aquifer, known as The Fylde Aquifer in north-west Lancashire.

Regional conceptual model of the Fylde Aquifer

The Fylde is the relatively flat coastal plain west of a line through Preston, Garstang and Lancaster. It is largely Till covered, with the Sherwood Sandstone Group bedrock further concealed by the younger Mercia Mudstone Group adjacent to the coast between Fleetwood and the lower reaches of the River Wyre and Lytham on the Ribble Estuary. The Fylde Aquifer therefore covers an area roughly from Morecambe Bay in the north (at its closest point approximately 1 km east of the proposal area) to Preston in the south-east and the Ribble Estuary in the south-west, but not present within the proposal area itself due to deep burial by the Mercia Mudstone Group.

The aquifer is a fine to medium grained, largely well-cemented sandstone with numerous mudstone partings, generally with inter-granular porosity but locally with fissures (Mott MacDonald, 1997). It is inherently inhomogeneous. Groundwater storage relies on intergranular voids whereas groundwater transport is principally dependent on fracture flow.

Although the sandstone thickens in West Lancashire to over 1000 m, active groundwater flow is probably restricted to the uppermost 200 m (Mott MacDonald, 1997); however little is known of the deep groundwater system since boreholes seldom penetrate more than 120 m of section.

In the Fylde Aquifer area, clayey beds within the overlying drift generally confine the top of the sandstone. The drift-sandstone boundary is however irregular, since drift filled glacial channels occur within the top surface of the sandstone. Wherever granular glacial deposits are in contact with the aquifer they are in hydraulic continuity with it and provide small recharge windows. These largely occur along the rivers which cut through the Till cover, the valleys later partly infilled with granular alluvial material. The aquifer mostly gains, from losing reaches of rivers, particularly the Wyre, wherever they traverse the sand and gravel drift deposits. Inflow to the aquifer is partly influenced by local pumping. However, the Wyre becomes a gaining river as it approaches St Michael on Wyre.

The source of most of the inflow to the aquifer has been interpreted by some as the more permeable horizons in the Carboniferous strata, which abut the SSG along the foot of the Pennines approximately 15 km east of the proposal area (e.g. Oakes & Skinner, 1975). However, others have interpreted the majority of volumetric recharge to be where Till is absent beneath river beds, allowing water to flow between the river, alluvial deposits and the aquifer as discussed above (e.g. Mott MacDonald, 1997). Based on the Fylde Aquifer study (Mott MacDonald, 1997) approximately 10% of potential recharge infiltrates through the drift (spatially averaged across the model domain). In areas covered by greater than 2 m of clay (the majority of the deposit's outcrop area), the BGS have estimated that only approximately 2% of the potential recharge infiltrates into the sandstone (BGS, 1989). It is apparent that the distribution of drift deposits is a major control on recharge to the aquifer but that recharge (and discharge) of the Fylde Aquifer is complex and variable, on both regional and local scales.

Oakes & Skinner (1975) state that groundwater levels within the Sherwood Sandstone aquifer are above sea level in the area of the Morecambe Bay coast and, further to this, Oakes & Skinner (1975) and Mott MacDonald (1997) propose that groundwater discharge under natural conditions occurs to Morecambe Bay via diffuse seepage through sea-floor drift geology. The qualification that groundwater discharge to sea occurs under natural conditions implies that this could be altered by groundwater abstractions near to the Morecambe Bay coast, i.e. inducing saline intrusion to the aquifer. The latter study proposes that groundwater discharge from the Sherwood Sandstone as river base flows, as discussed above, is the principal means of discharge within the Fylde study area.

The conceptual groundwater flow model for the Fylde Aquifer is based on groundwater flowing from beneath the higher ground adjacent to the Pennines towards the lower ground in the west

(Sage & Lloyd, 1978). Piezometric heads fall from 20 to 25 m aOD in the east to only 5 to 10 m aOD as the aquifer passes beneath the Mercia Mudstone Group in the west. No significant groundwater flow occurs beneath the Mercia Mudstone Group (e.g. the proposal area) and the groundwater rapidly becomes saline in response to this beneath the confining cover. In the Till covered part of the aquifer, flow concentrates on baseflow discharge to the River Wyre immediately above St Michael on Wyre, with additional discharge towards the north west into Morecambe Bay and the south west towards the Ribble estuary. The groundwater flow system is further complicated by faulting and structural constraints as well as local recharge through the granular superficial deposits along the rivers. In these areas to the east of the Mercia Mudstone Group cover, the groundwater is of the Ca-HCO_3 type with total dissolved solids concentrations in the range 100 to 500 mg l^{-1}.

The hydraulic connectivity between the Sherwood Sandstone Group in the immediate proposal area and the Fylde Aquifer is likely to be very limited. This interpretation is based on observations made during previous studies (summarised in the paragraphs above) and the structural context of the area: groundwater flows are likely to be very low within the SSG of the Preesall Graben due to deep burial; and further, faults bounding the graben are likely to be inhibiting flows in the SSG perpendicular to the fault planes (and therefore in to and out of the graben).

Water balances for the Fylde Aquifer are estimated in Mott MacDonald (1997) and readers are referred to that report if further (quantitative) information is required.

Hydraulic characteristics

Mott MacDonald (1997) noted that within the Sherwood Sandstone there are no obvious patterns to the transmissivity distribution. However, they did note that a number of observed higher transmissivity zones could be associated with faults and that transmissivities (and associated groundwater flows) are generally lower in the Morecambe Bay area. Groundwater flow near faults appears to be complex and highly variable, as one might expect, with observations from the Fylde study suggesting that horizontal permeability in the sandstone may be locally restricted perpendicular to faults. Similar observations have been made by the BGS (BGS, 1989).

From BGS (1989), porosity in the Sherwood Sandstone Group ranges from 0.2 to 0.3. Although primary hydraulic conductivity can be very low (less than 10^{-3} metres per day (m/d)), the total hydraulic conductivity measured from field tests is usually significantly greater due to fracture flow, generally in the order of 0.1 m/d to 10 m/d in the Fylde Aquifer area (Mott MacDonald, 1997). These fractures have been logged at depths of up to 150 m in the sandstone, with transmissivity varying in relation to degree of fracturing from less than 10 m^2/d (approaching purely inter-granular flow) to in excess of 10,000 m^2/d (approaching purely fracture flow) and average transmissivity from field tests in the range 100 to 400 m^2/d (BGS, 1989). Regarding vertical permeability within the sandstone, the Fylde study noted that it is "restricted by 'marl' (mudstone) beds, typically thin (0.6 m) and occurring more frequently in the basal part of the sequence".

Borehole yields are related to transmissivity and therefore are also highly variable in the Sherwood Sandstone Group. In those areas where the Group is not overlain by Mercia Mudstone Group, yields of 50 l/s are common and over 100 l/s can sometimes be obtained (BGS, 1989). Specific yields are generally in the range 6-14% (a value of 6% was adopted for the Fylde aquifer model), with storage coefficients in the confined areas of the aquifer ranging from 10^{-4} to 10^{-3}.

Seasonal changes in water level are generally low, typically less than a metre (BGS, 1989), due to the high specific yield of the Sherwood Sandstone Group.

Groundwater quality

Natural groundwater quality in the Sherwood Sandstone is hard but otherwise of good quality overall across the Group. In the proposal area there may be local factors affecting water quality, such as saline intrusion from the sea (as is the case near Mersey estuary and the Manchester Ship Canal) and naturally high mineralisation due to long groundwater residence times.

Mercia Mudstone Group

The Mercia Mudstone Group conformably overlies the Sherwood Sandstone Group and attains a thickness of over 1300 m in the vicinity of Fleetwood. The Group comprises an alternating sequences of salts and structureless mudstones. The Preesall Halite is the thickest of the Triassic halite beds in the Fleetwood area, occurring above the Thornton Mudstone and below the Coat Walls Mudstone. Within the central part of the salt deposit (beneath the eastern bank of the River Wyre) the maximum proved thickness of the salt is 289 m in ICI-B130 borehole.

Around Preesall, the Breckells Mudstone Member, Coat Walls Mudstone, Preesall Halite, Thornton Mudstone and Singleton Mudstone Member subcrop beneath the glacial till, due to an asymmetrical graben structure. However, the Preesall Halite has been naturally sub-eroded (dissolved) by groundwater in the areas where it had originally sub-cropped and has been replaced by collapses of the overlying strata (referred to as collapse breccias). The surface of such eroded zones are referred to as 'wet rockhead' and generally extend 50 m to 75 m below the base of the drift, with collapsed Coats Walls Mudstones largely taking the place of the dissolved Preesall Halite (BGS, 1990). These collapse breccias form a belt between 400 and 600 m wide immediately west of the Preesall Fault. The surface of those zones of salt which are deeper and not eroded by solution, and for which there is no collapse strata above, are referred to as 'dry rockhead'. Historically, brine groundwater has been extracted at Preesall from the shallower salt beds, within the areas of wet rockhead (known as 'wild brining'), exacerbating sub-erosion of the rock salt, and inducing collapse in the overlying formations, already weakened by ancient collapse structures, and leading to localised ground subsidence.

The Mercia Mudstone Group is an aquitard, with very minor vertical or horizontal flows of groundwater. In the proposal area, the Mercia Mudstone Group acts to confine groundwater within the underlying Sherwood Sandstone Group. The BGS note that low yields of up to 5 l/s have been observed from the more permeable units within the group, principally the Tarporley Siltstone Formation (BGS, 1989), but this formation is not present within the proposal area. There is no pumping test data for this formation within the Minor Aquifer Properties Manual specific to the West Lancashire Basin, the manual describing the formation as "traditionally [being] regarded as predominantly impermeable and at best a poor aquifer".

Relative to most natural strata, the salt deposits are essentially impermeable. In situ hydraulic conductivity testing was carried out on the Arm Hill No. 1 borehole by MESY GmbH on behalf of Canatxx Gas Storage Ltd (MESY GmbH, 2004) which indicated approximate rock mass permeabilities in the range $5x10^{-18}$ m^2 to $10x10^{-18}$ m^2 for the depth interval of 200 m to 355 m below ground level, and $1x10^{-18}$ m^2 to $3x10^{-18}$ m^2 for the interval 400 m to 575 m below ground level. These permeability values relate to approximate hydraulic conductivities of $5x10^{-6}$ m/d to $8x10^{-6}$ m/d and $1x10^{-6}$ m/d to $3x10^{-6}$ m/d respectively, based on a brine density of 1200 kg/m^3 and a brine viscosity of 1 cPoise. Fracture tests were also conducted in the Arm Hill No. 1 borehole by MESY GmbH, resulting in an estimated fracture conductivity "of about 10^{-7} m/s…when the injection pressure is above the fracture opening pressure" (MESY GmbH, 2004). It is unclear from the MESY GmbH report what the fracture conductivity of the salt deposit would be at injection pressures below the fracture opening pressure, but it is likely to be significantly less than that above (note 10^{-7} m/s ≈ $9x10^{-3}$ m/d).

Superficial deposits

Mott MacDonald (1997) noted in relation to the Fylde area, almost no field data exist on the hydraulic properties of the drift and that its principal hydrogeological importance is control on recharge to the Sherwood Sandstone. For the purpose of assessing the latter, vertical permeability values for the Till in the range of 10^{-4} to 10^{-3} m/d were considered likely.

<u>Glacial deposits</u>

The proposal area is covered by Till (previously known as 'Boulder Clay') and in places the Till is overlain by post-glacial deposits (see below). Due to its glacial origins, the Till is poorly sorted and ranges in grain size from clay to boulders although predominantly fine-grained. Occasional lenses of sand and gravel within the Till can provide limited groundwater yields.

The principal hydrogeological significance of the Till is that it limits recharge to and confines water within the underlying formations (Sherwood Sandstone and Mercia Mudstone in the proposal area). Further, in low-lying areas the confining property of the Till can create substantial artesian heads in the Sherwood Sandstone Group BGS (1989).

<u>Post-glacial deposits</u>

The post-glacial (Flandrain) deposits of the proposal area comprise Marine and Estuarine Alluvium, consisting predominantly of mud, and Older Marine and Estuarine Alluvium units, consisting predominantly of clay and silt. The lithologies of these units would imply that their hydraulic conductivities would be very low, acting probably as aquitards, although the Older Marine and Estuarine Alluvium is noted by BGS (1975) to include widespread sands and gravels at depth, interpreted as old beach deposits.

Granular deposits, where present within the drift, would have the potential to transmit groundwater under localised flow regimes. Recharge to these superficial granular deposits is likely to be principally from rainfall, with flow direction and discharge being dominated by topography and hydraulic interaction with the Wyre Estuary. The hydrology of the marshes in the proposal vicinity are probably related to shallow hydrogeology within the drift. Saturated horizons within the drift and in the proposal area will generally be confined from below at relatively shallow depths, either by less permeable Mercia Mudstone Group or less permeable drift deposits. Further to the east (at least 1 km from the proposal area), where the Sherwood Sandstone subcrops beneath the drift, groundwater within the latter is in places hydraulically connected with the deeper sandstone aquifer.

GROUNDWATER ABSTRACTION

History

North-east of the proposal area, the Sherwood Sandstone has historically been utilised as a water supply for the Preesall saltfield and other industrial applications (BGS, 1990). The Sherwood Sandstone is also utilised extensively further east and south east of the proposal area, within the Fylde Aquifer area, for public water supplies and industrial applications. The Mercia Mudstones have been tested for water supply but boreholes have been dry or yielded saline water. Some success has been gained historically from the Glacial Sand (a drift deposit), although probably from areas closer to Blackpool as this unit is almost completely absent in the proposal area. Generally, water from the glacial deposits has been noted as brackish to saline.

Protected groundwater abstractions

Based on the Envirocheck report, there are no registered groundwater abstractions within the search area (NGR 333800E to 337000E and 443000N to 448000N).

Three surface water abstractions are registered with the search area, on the western shore of Wyre Estuary; the source for all three is recorded as tidal.

Restricted rights groundwater abstractions

Wye Borough Council was contacted to identify any protected rights groundwater abstractions within the proposal area; the council is not aware of any private drinking water supplies within the area bounded by Fleetwood, Knott End-on-Sea, Preesall, Hambleton and Thornton (personal correspondence on 23rd September 2005 with Helen Layfield, Health & Safety, Wyre Borough Council).

Source protection zones

The Environment Agency specifies groundwater source protection zones (SPZs) in order to protect sensitive groundwater abstractions. The Landmark Envirocheck report indicates that no SPZ's have been defined within the proposal area.

Groundwater vulnerability

The Groundwater Vulnerability Map of Central Lancashire (Environment Agency, 1996) shows those areas overlain by drift comprising Till (the greater proposal area) as 'Non-Aquifer' and therefore of low vulnerability. Localised areas of drift comprising Marine and Estuarine Alluvium (post-glacial deposits) are shown as Minor Aquifers of high leaching potential, the latter classification due to their shallow depth. Within the proposal area, the post-glacial deposits occur as a 30 m to 50 m wide east-west orientated strip from the Preesall Park area to the River Wyre and fanning out in the marshes along the eastern bank of the Wyre (based on Environment Agency (1996) and BGS (1975)).

KNOWN EXISTING IMPACTS TO GROUNDWATER REGIME

Sherwood Sandstone Group

<u>Resource depletion and well interference</u>

The Fylde Aquifer study (Mott MacDonald, 1997) indicated that abstractions from the aquifer for water supplies and industrial applications were exceeding natural recharge. The difference was interpreted by Mott MacDonald as being replaced by reductions in river base flows. The Environment Agency is responsible for regulating the use of this aquifer, with the aim of balancing the demand for the aquifer's water resources against environmental impacts and long-term sustainable use.

<u>Saline intrusion</u>

Based on Oakes & Skinner (1975) and Mott MacDonald (1997), there appears to be a potential for saline intrusion to the Sherwood Sandstone aquifer in the coastal area around Morecambe Bay. However, the actual degree of saline intrusion (if any) has not been determined as part of this report. Again, the Environment Agency are responsible for regulating groundwater abstractions in the area in order to prevent deterioration of its quality.

<u>Pollution</u>

There is a potential for both point source and diffuse pollution to the Sherwood Sandstone aquifer in areas where the overlying drift is thin, absent and/or highly permeable. This is demonstrated by the high vulnerability classification given to the aquifer in the Morecambe Bay area (Environment Agency; 1996). However, there does not appear to be any potential for pollution of the Sherwood Sandstone aquifer in the immediate proposal area, given the thick and poorly permeable sequence of Mercia Mudstone Group overlying the aquifer.

Mercia Mudstone Group

There is a known mercury sulphide repository, adjacent to the proposal area, which utilises a former brine cavern in the ICI brinefield. Any other impacts to groundwater within the Mercia Mudstone Group are likely to be very limited in spatial extent, due to the low permeability of this formation.

<u>Drift</u>

The Envirocheck report indicates the locations of numerous landfills, waste management facilities and industrial land uses, as well as some forty pollution incidents to controlled waters and two prosecutions related to land and water.

GLOSSARY OF TECHNICAL TERMS

Alluvium Sediment deposited by the action of rivers.

Artesian head Where the hydrostatic head within an aquifer is at a pressure sufficient to bring water to the surface when penetrated by a well.

Aquifer A geological formation containing sufficient saturated material to be considered economical in the supply of water.

Aquitard A saturated geological formation, relatively lower in permeability than an *aquifer* and subsequently poor at supplying water economically.

Conformable Describes a continuous series of geologic strata, without any break in sediment deposition.

Graben Structural term for a downthrown block between normal faults.

Hydraulic conductivity The overall ability of a geological strata to pass a fluid of given density and viscosity, determined by the volumetric rate of flow of fluid per unit cross sectional area of material per unit time under unit hydraulic gradient (commonly expressed in terms of metres per day).

Outcrop The area where a particular geological strata occurs at the surface.

Permeability The intrinsic capacity of a geological material to transmit fluids.

Porosity The percentage of the total volume of rock or soil that consists of pore space.

Potential Evapo-transpiration (PE) The total amount of water which could be evaporated directly and by plant transpiration assuming a limitless supply of water.

Recharge The addition of water to the saturated zone.

Specific Yield The fraction of the saturated bulk volume of a geological strata consisting of water which will drain by gravity.

Sorting Degree of grain size distribution of a sediment. Also referred to as *grading*.

Storage capacity	Volume of water given up (or taken in) per unit horizontal area of a confined aquifer per unit fall (or rise) of the aquifer's hydrostatic head. Similar to ***specific yield*** for an unconfined aquifer.
Subcrop	A subsurface ***outcrop***, such as where a geological strata intersects a subsurface plane.
Transmissivity	The volume of water per unit time that can be transmitted (horizontally) by the full saturated thickness of an aquifer through a unit width under a unit hydraulic gradient.

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Appendix 7 Figure Captions

Figure 1. Map showing the distribution of borehole and seismic lines (black lines) used during this study.

Figure 2. Distribution and age of salt deposits in England.

Figure 3. Structural geology of the area. a) the East Irish Sea Basin (after Jackson and Mulholland, 1993) and b) the Permo-Triassic rift system onshore the UK (after Chadwick & Evans, 1996).

Figure 4. The 1975-1990 BGS model for the structure of the Preesall Salt and the 1996 Daran Petroleum Consultants Ltd model. a) BGS map of the Blackpool district, b) BGS ribbon cross section illustrating simple synclinal structure, c) Daran seismic interpretation ilustrating a major fault bounded down faulted graben structure, with smaller faults affecting graben sequences.

Figure 5. Gamma ray logs for the Canatxx Arm Hill and The heads boreholes, showing halite thicknesses and correlation of internal beds based upon increased gamma values relating to ?mudstone beds.

Figure 6. Map showing the depth below ground level of the top of the Preesall Halite encountered in boreholes across the study area.

Figure 7. Map of boreholes proving the base of the Preesall Halite (green values) and where the Preesall Halite was not bottomed in the boreholes (red values).

Figure 8. Map showing the thickness of the Preesall Halite where proved in boreholes.

Figure 9. Shaded contour map (contours in metres below ground level) of the top of the Preesall Halite with faults mapped at this level. Also shown, borehole values of the depth of the top of the Preesall Halite and the position of seismic lines that were used to constrain the surface.

Figure 10. Shaded contour map (contours in metres below ground level) of the base of the Preesall Halite. Also shown borehole values of the base of the Preesall Halite or the lowest proved Preesall Halite where appropriate, and the position of the seismic lines that were used to constrain the surface.

Figure 11. Shaded isopachyte (thickness) map of the Preesall Halite with the thickness of the Pressall Halite where proved in boreholes.

Figure 12. Interpreted 2005 reprocessed versions filtered stacks of Canatxx 1997 E-W oriented seismic lines. a) line G b) line F. Seismic lines illustrate westwards thickening of the Preesall Halite and down-east faulting in the western half of the line. Seismic picks: green,intra Coat Walls Mudstone reflector; yellow, top Preesall Salt; pink, intra salt reflector; blue,base Preesall Halite.

Figure 13. 2005 reprocessed Canatxx seismic line F, calibrated by synthetic seismic panel generated from sonic log data from the Heads borehole inserted. (a) interpreted filtered stack with synthetic seismic panel (b) migrated stack and (c) depth conversion of top and base Preesall Halite. Also ties ICI-134 borehole.

Figure 14. 2005 reprocessed Canatxx seismic line G. (a) interpreted filtered stack (b) migrated stack and (c) depth conversion of top and base Preesall Halite, tieing ICI-130 borehole.

Figure 15. Correlation panels (outlined in white) for Canatxx lines G (a) and F (b). Data show panels from the western ends of the sections to illustrate the similarity with sequences to

the east of the faulting and which are tied to ICI boreholes in the central area of sections and provide the evidence for extending the Preesall Halite westwards.

Figure 16. Seismic reflection line IELP-99-25 showing the tie to the synthetic seismic generated from Arm Hill #1and the structure of the Preesall Halite north of BNG Northing 446000 (viewed looking to the north). Sequences dip westwards towards the Burn Naze Fault with only minor apparent faulting. (a) 2005 reprocessed version (b) existing interpretation and depth conversion supplied to BGS.

Figure 17. Interpretation of GasGCE-86-DV371seismic line (shown here as a composite with GasGCE-87-382) to illustrate the Preesall Graben and main controlling faults: the Preesall and Burn Naze faults. Thickness variations in the Triassic interval across the Preesall Fault suggest some synsedimentary movements, but lateral movement along the faults and the effects of lower halites cannot be ruled out. Note difference in structural style of the graben and the attitude of the Preesall Fault to the 1996 Daran Petroleum interpretation. Preesall Halite proved by ICI-E27 and 134 wells as indicated. ICI-B1 spudded in Thornton Mudstones beneath the Preesall Halite, proving the Burn Naze Fault between the B1 and E27 boreholes. Seismic picks: purple intra-MMG; light yellow, near top Preesall Halite; darker blue, near base Preesall Halite; green, near base MMG; light blue, intra SSG; dark yellow, near base SSG.

Figure 18. Reprocessed (1996) Gas Council GASGC81-336 seismic line. (a) migrated and (b) filtered stacks. Area of interest falls in the large omission zone on the western end of the line. The Burn Naze Fault as mapped by Daran Petroleum (1996) lies somewhere in this region.

Figure 19. Canatxx data from 1997, showing original quality of processed data and with interpretations of Preesall Halite (from Jenyon, 1997). Red seismic pick is top Preesall Halite, blue seismic pick is base Preesall Halite. Vertical red bars indicate where halite is thought to be. Note how data quality in left half of all seismic lines across a fault is poor, restricting correlation of reflections.

Figure 20. The filtered and migrated stack for the three processed versions of Canatxx line G. (a) original 1996 version, as used (b) the version preferred by IMC Geophysics, but not used and (c) the 2005 reprocessed version. As can be seen there is an improvement in data quality from versions (a) to (c).

Figure 21. Original 1997 and 2005 reprocessed versions of Canatxx lines D and F, showing the improved data quality achieved during reprocessing. (a) and (b) show original an reprocessed filtered and migrated stacks of Line D. (c) and (d) show the same for Line F. line D

Figure 22. Plots of the 85, 90 and 95% stacking velocity migrated stacks for the 2005 reprocessed Canatxx line G.

Figure 23. Plots of the 85, 90 and 95% stacking velocity migrated stacks for the 2005 reprocessed Canatxx line F.

Figure 24. Reprocessed (2005) migrated (a) and filtered stacks (b) of Canatxx line D. Complex faulting apparent in central parts of the line, but line length and possibly direction do not permit reliable interpretation.

Figure 25. Seismic reflection line IELP-99-25 showing the (a) existing interpretation and (b) depth conversion supplied to BGS.structure of the Preesall Halite north of BNG Northing 446000 (viewed looking to the north). Sequences dip westwards towards the Burn Naze Fault with only minor faulting. Seismic picks tied to ICI boreholes as indicated.

Figure 26. 2005 reprocessed GasGCE-86-DV371 seismic line showing ties to relevant boreholes. (a) interpreted migrated section with correlation panel of the Heads borehole synthetic

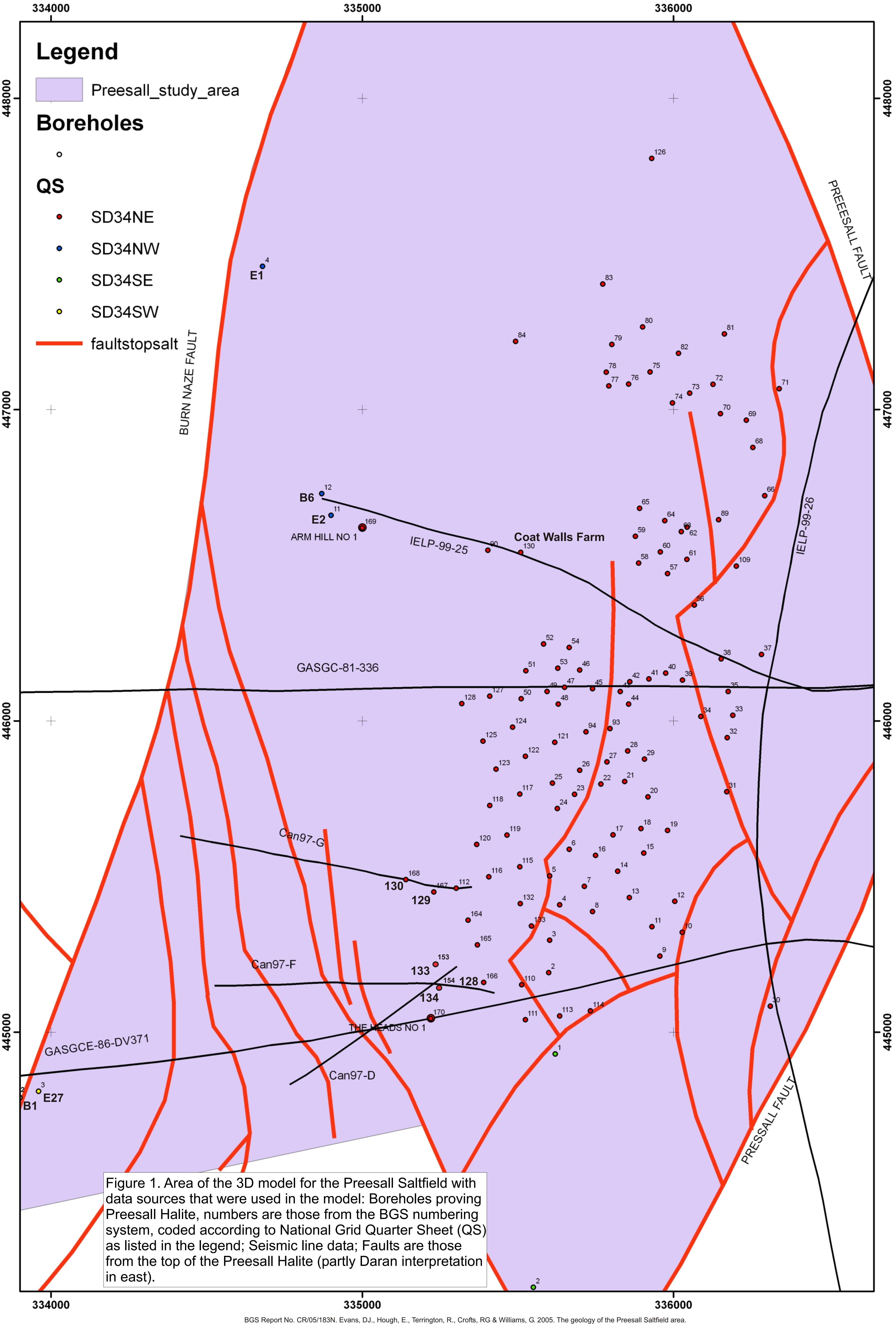


Figure 1. Area of the 3D model for the Preesall Saltfield with data sources that were used in the model: Boreholes proving Preesall Halite, numbers are those from the BGS numbering system, coded according to National Grid Quarter Sheet (QS) as listed in the legend; Seismic line data; Faults are those from the top of the Preesall Halite (partly Daran interpretation in east).

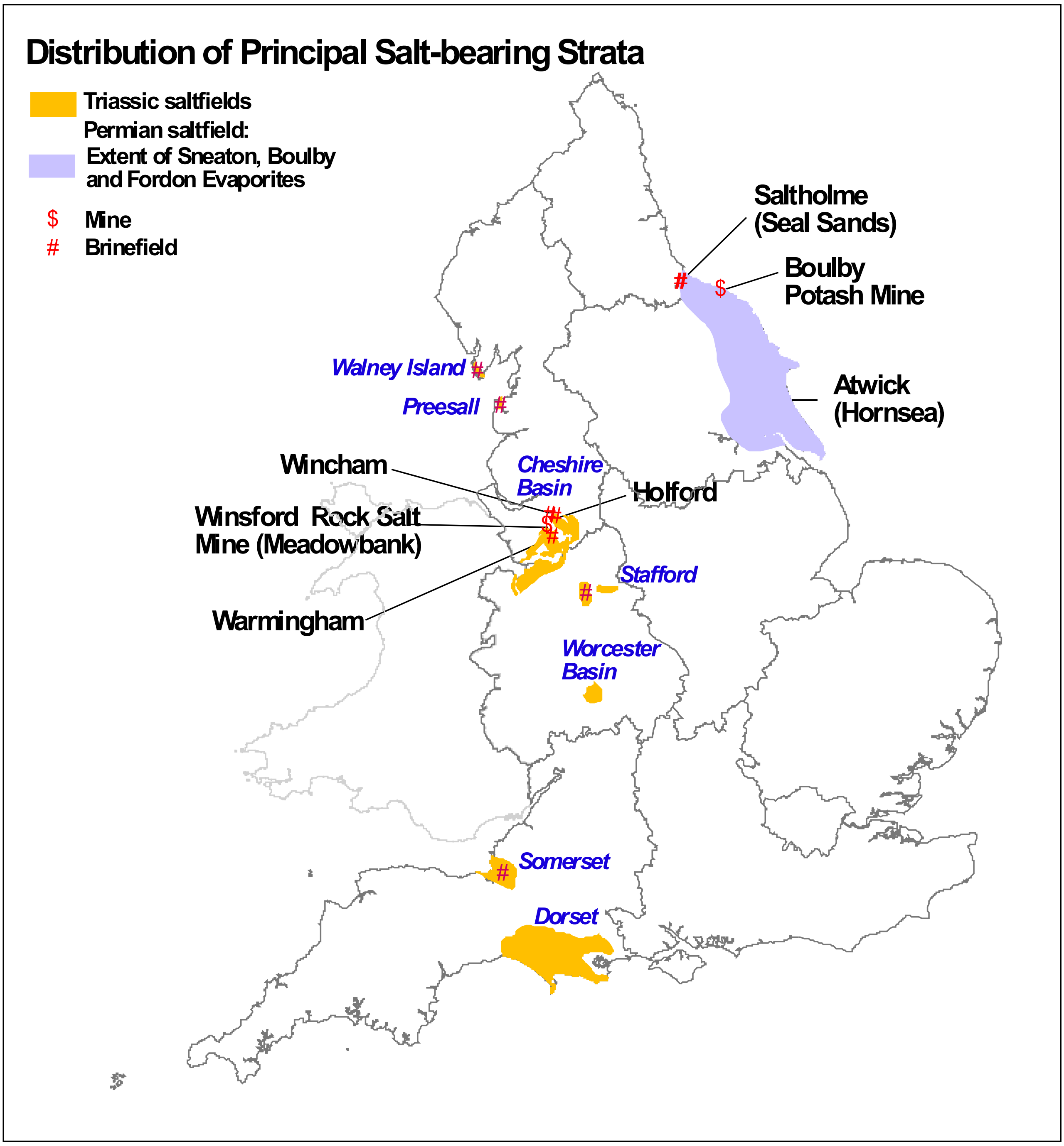


Figure 2. Distribution and age of salt deposits in England.

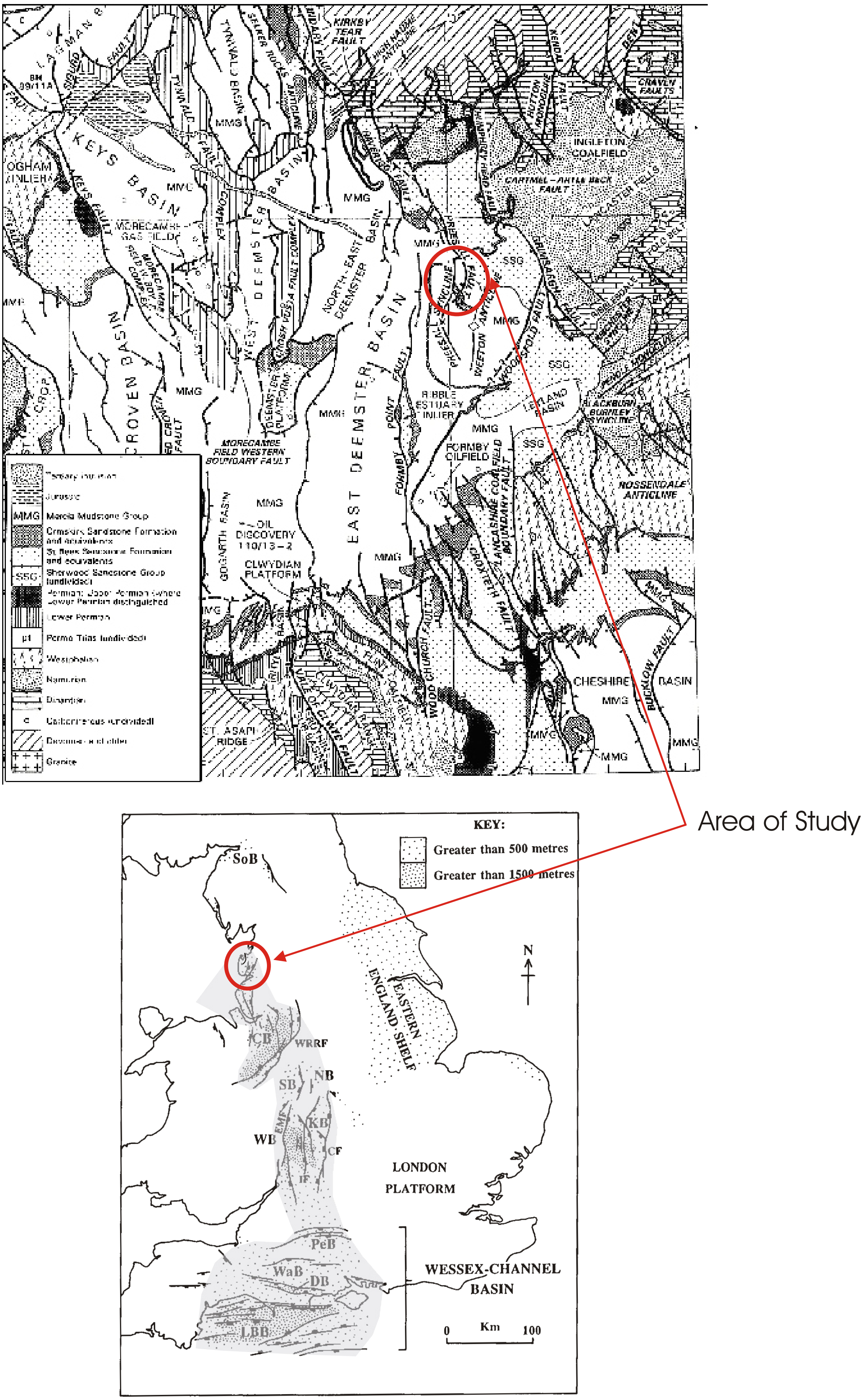


Figure 3. Structural geology of the area. a) the East Irish Sea Basin (after Jackson and Mulholland, 1993) and b) the Permo-Triassic rift system onshore the UK (after Chadwick & Evans, 1995).

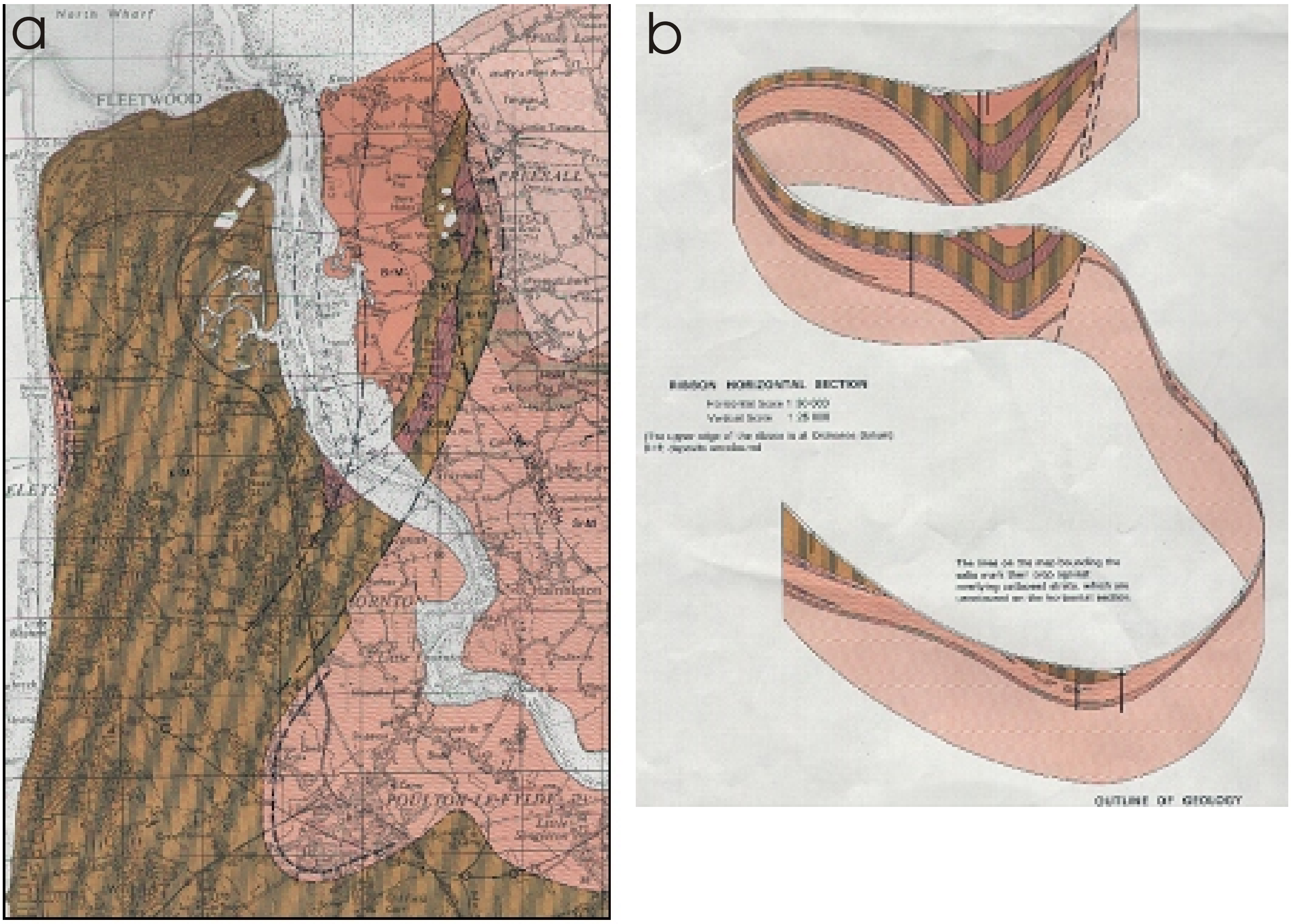
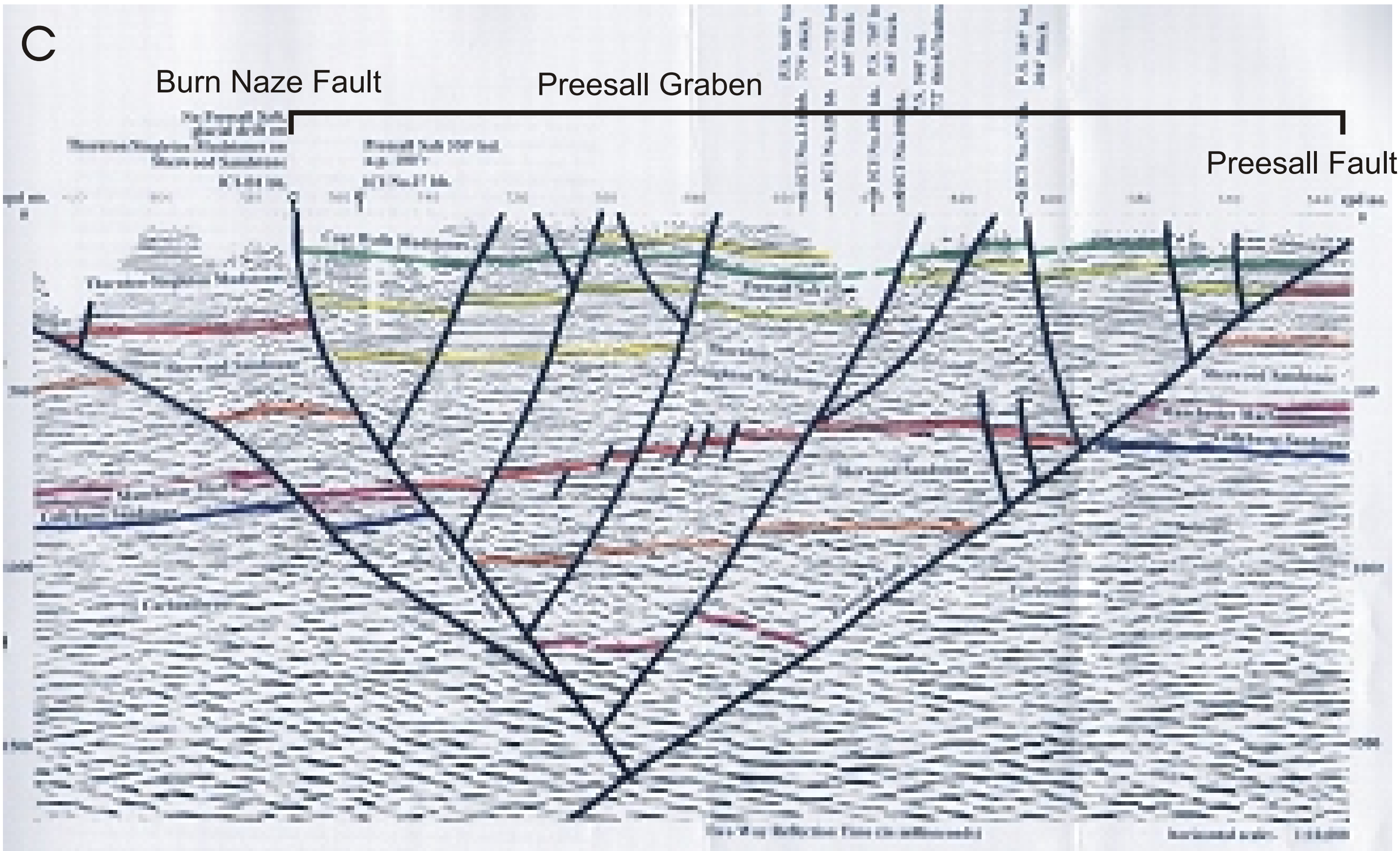


Figure 4. The 1975-1990 BGS model for the structure of the Preesall Salt and the 1996 Daran Petroleum Consultants Ltd model. a) BGS map of the Blackpool district, b) BGS ribbon cross section illustrating simple synclinal structure, c) Daran seismic interpretation ilustrating a major fault bounded down faulted graben structure, with smaller faults affecting graben sequences.



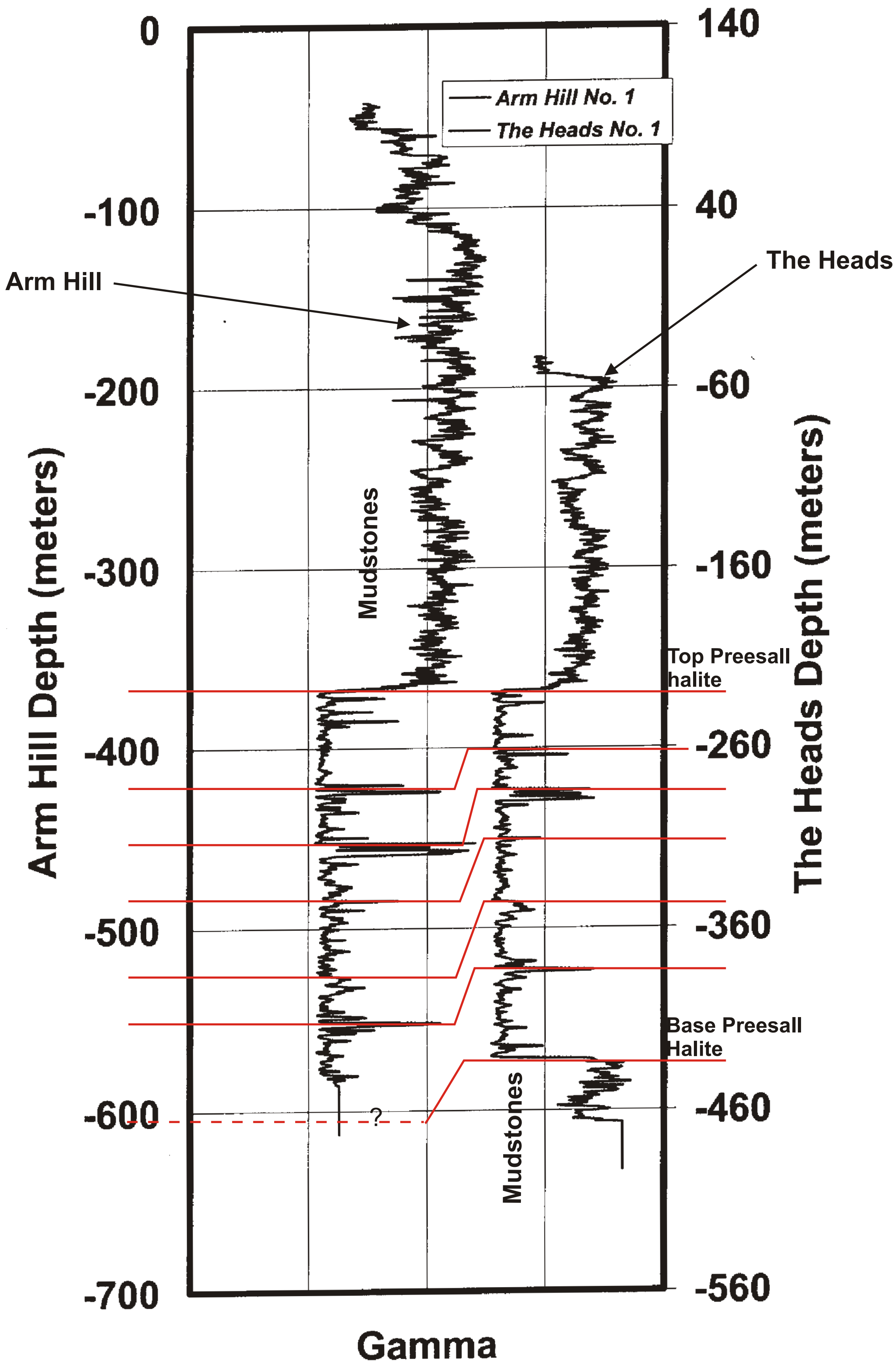


Figure 5. Gamma ray logs for the Canatxx Arm Hill and The Heads boreholes, showing halite thicknesses and correlation of internal beds based upon increased gamma values. Higher gamma values relate to mudstone (plus or minus thin anhydrite) beds.

Figure 6. Map showing the depth below ground level of the top of the Preesall Halite encountered in boreholes across the study area.

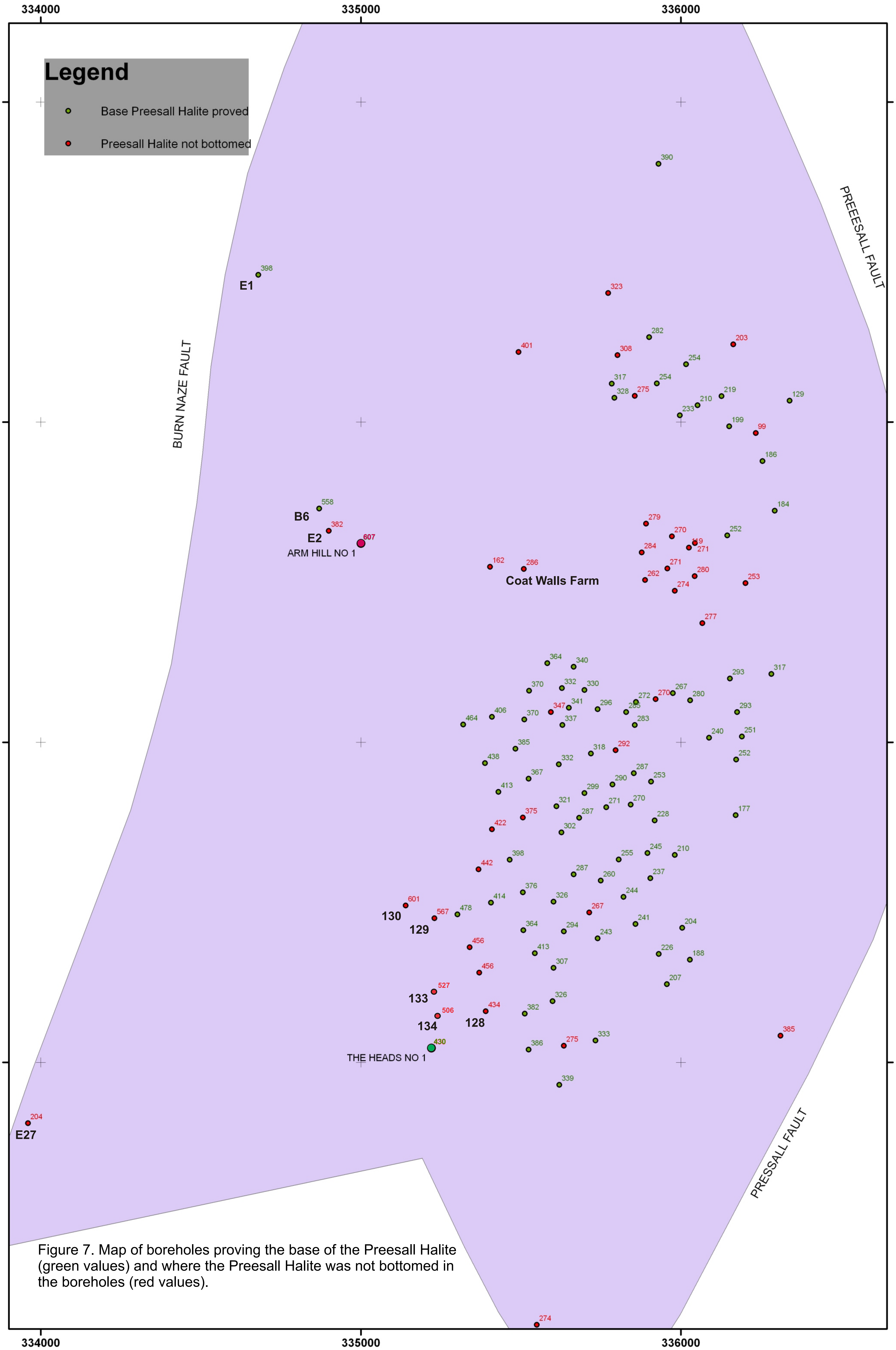


Figure 7. Map of boreholes proving the base of the Preesall Halite (green values) and where the Preesall Halite was not bottomed in the boreholes (red values).

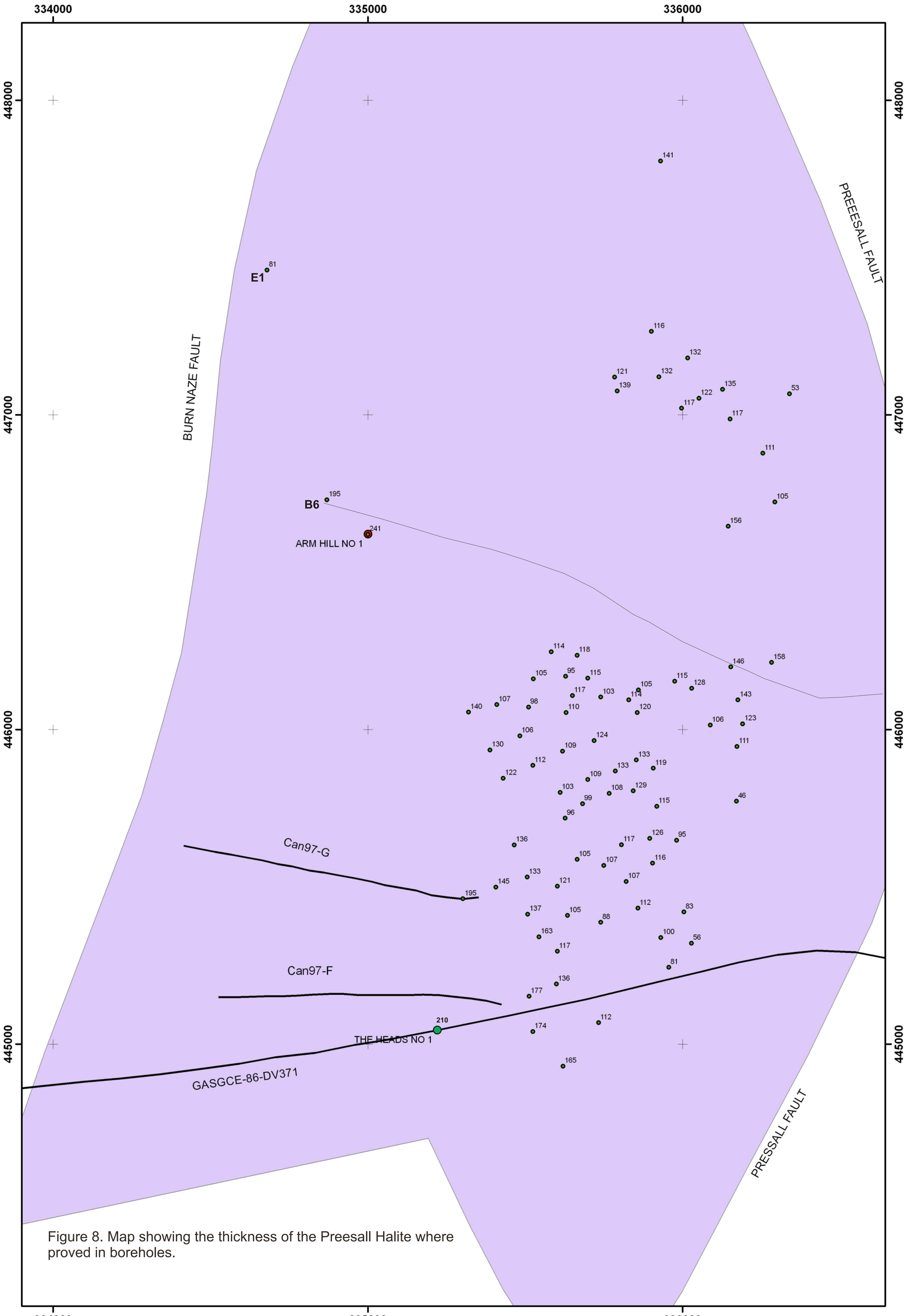


Figure 8. Map showing the thickness of the Preesall Halite where proved in boreholes.

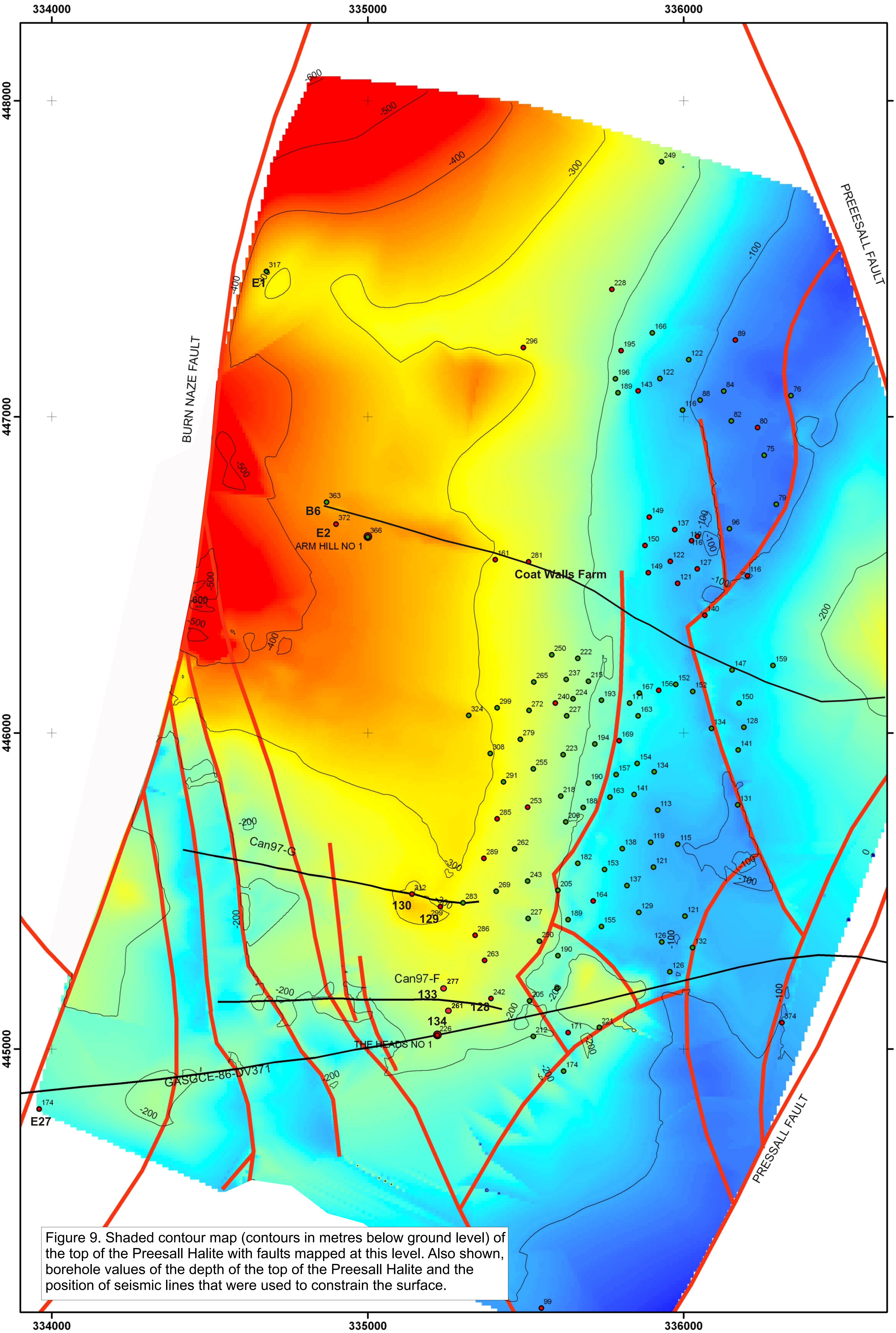


Figure 9. Shaded contour map (contours in metres below ground level) of the top of the Preesall Halite with faults mapped at this level. Also shown, borehole values of the depth of the top of the Preesall Halite and the position of seismic lines that were used to constrain the surface.

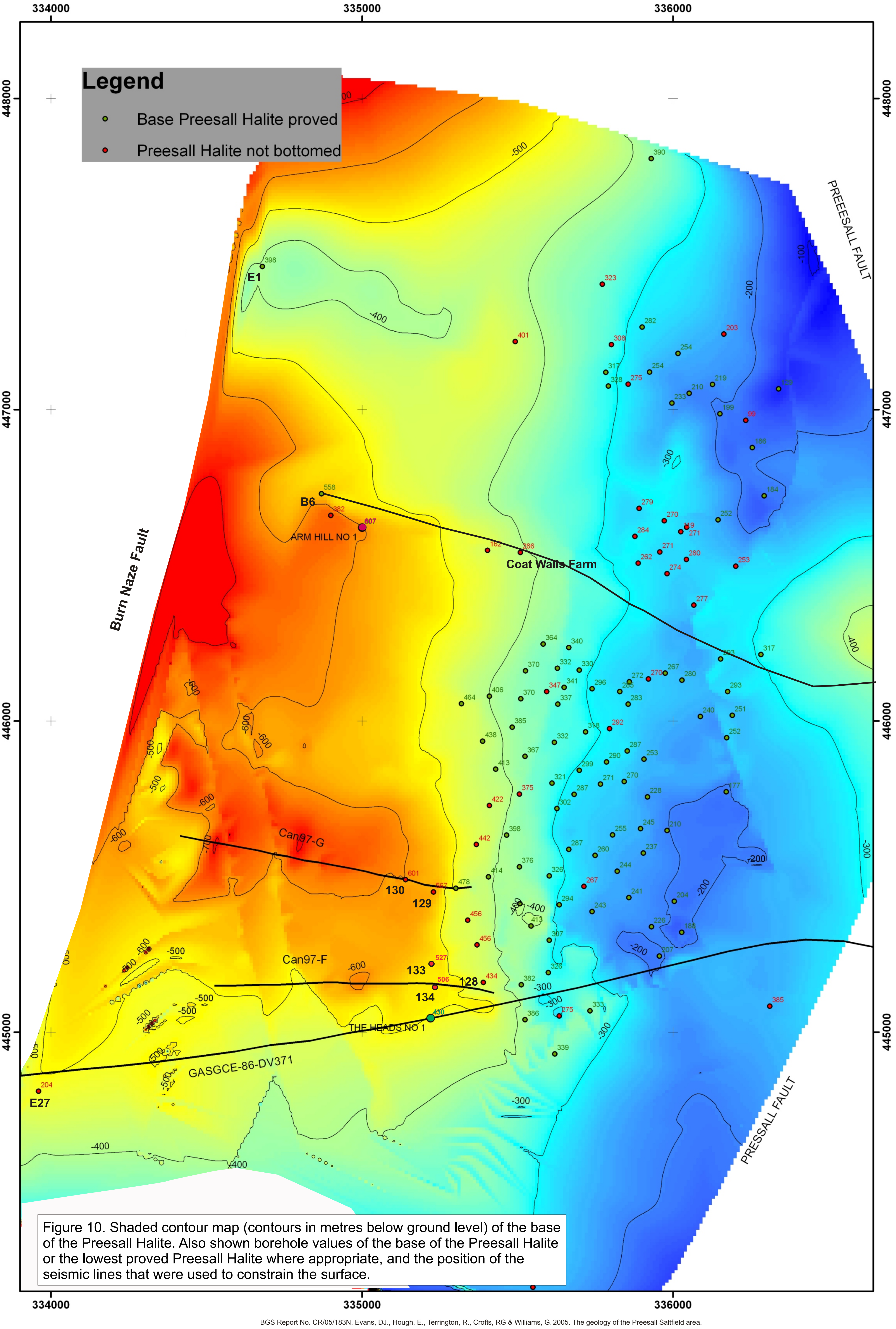


Figure 10. Shaded contour map (contours in metres below ground level) of the base of the Preesall Halite. Also shown borehole values of the base of the Preesall Halite or the lowest proved Preesall Halite where appropriate, and the position of the seismic lines that were used to constrain the surface.

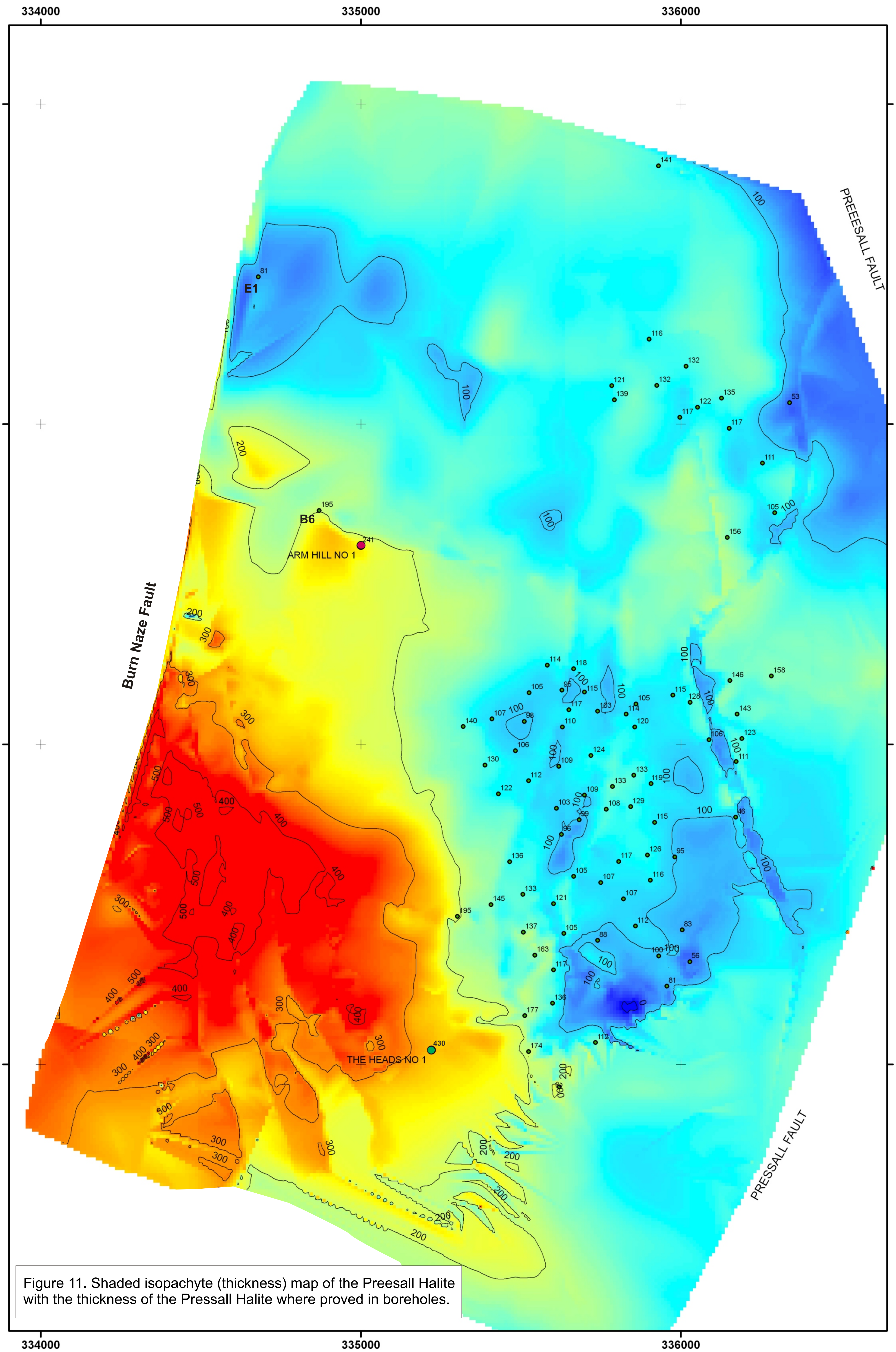


Figure 11. Shaded isopachyte (thickness) map of the Preesall Halite with the thickness of the Pressall Halite where proved in boreholes.

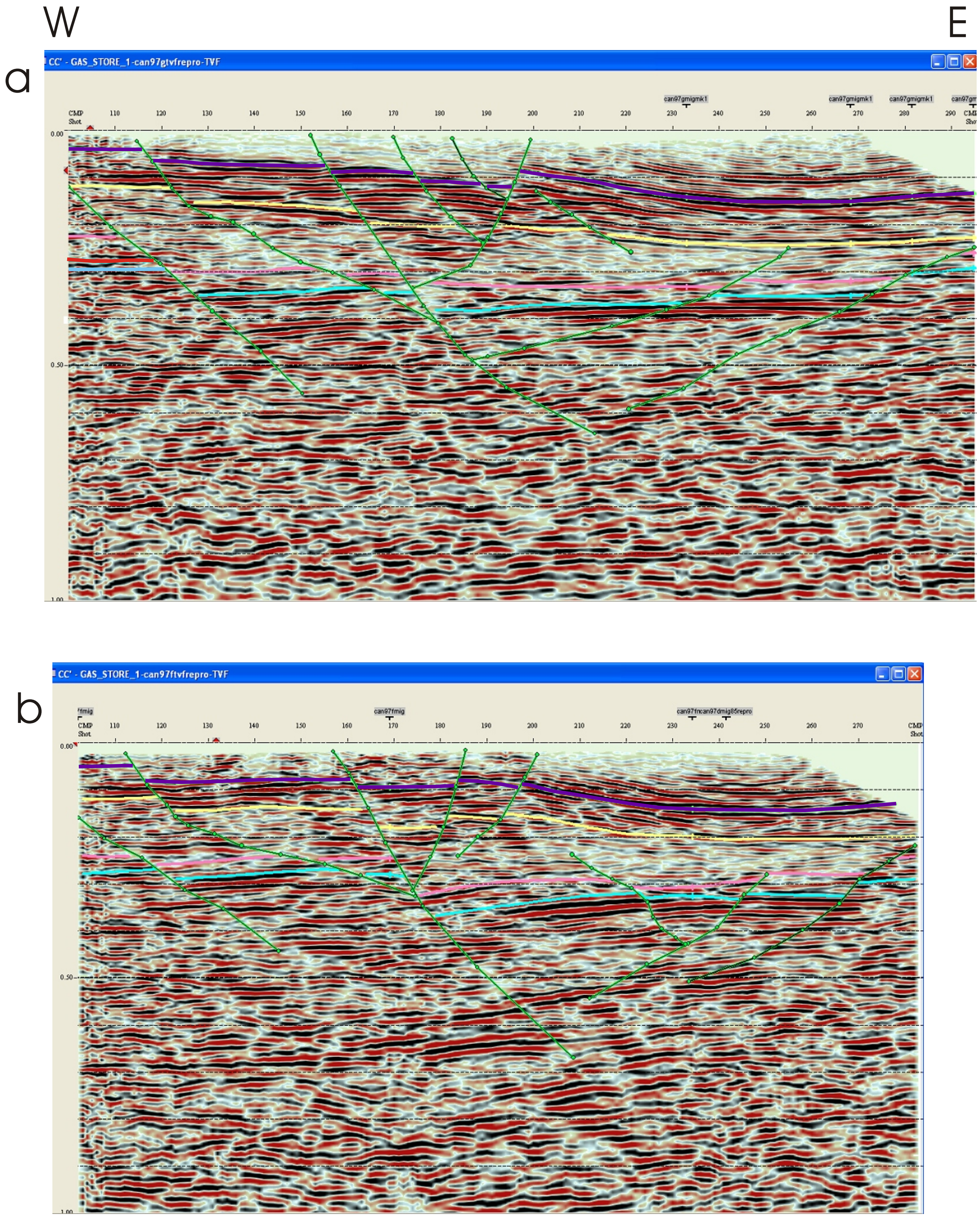


Figure 12. Interpreted 2005 reprocessed versions filtered stacks of Canatxx 1997 E-W oriented seismic lines. a) line G b) line F. Seismic lines illustrate westwards thickening of the Preesall Halite and down-east faulting in the western half of the line. Seismic picks: purple, intra Coat Walls Mudstone reflector; yellow, top Preesall Salt; pink, intra salt reflector; blue, base Preesall Halite.

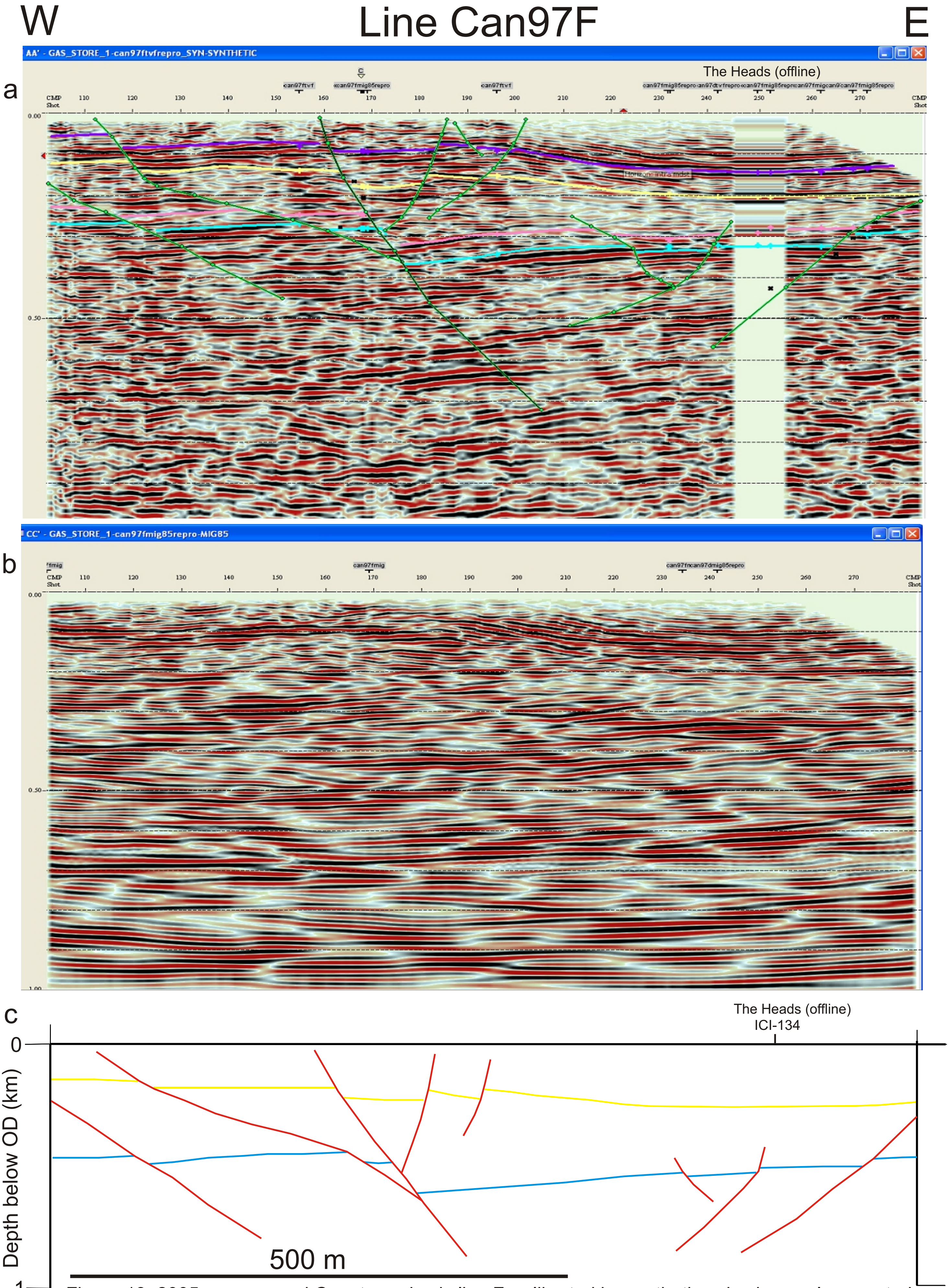


Figure 13. 2005 reprocessed Canatxx seismic line F, calibrated by synthetic seismic panel generated from sonic log data from the Heads borehole inserted. (a) interpreted filtered stack with synthetic seismic panel (b) migrated stack (100% stacking velocities) and (c) depth conversion of top and base Preesall Halite. Also ties ICI-134 borehole. Seismic picks: purple, intra Coat Walls Mudstone reflector; yellow, top Preesall Salt; pink, intra salt reflector; blue, base Preesall Halite.

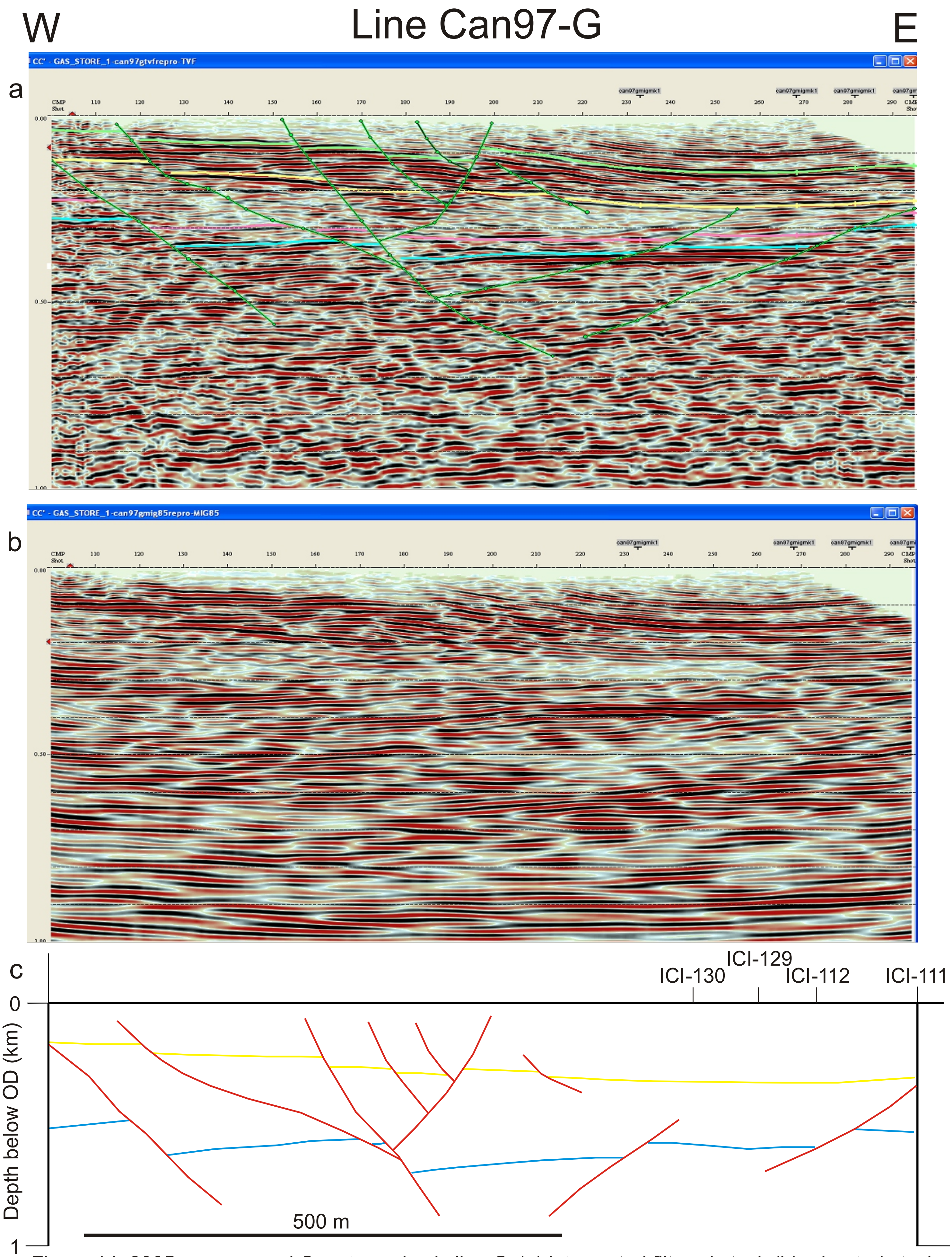


Figure 14. 2005 reprocessed Canatxx seismic line G. (a) interpreted filtered stack (b) migrated stack (100% stacking velocities) and (c) depth conversion of top and base Preesall Halite, tieing ICI-130 borehole. Seismic picks: purple, intra Coat Walls Mudstone reflector; yellow, top Preesall Salt; pink, intra salt reflector; blue, base Preesall Halite.

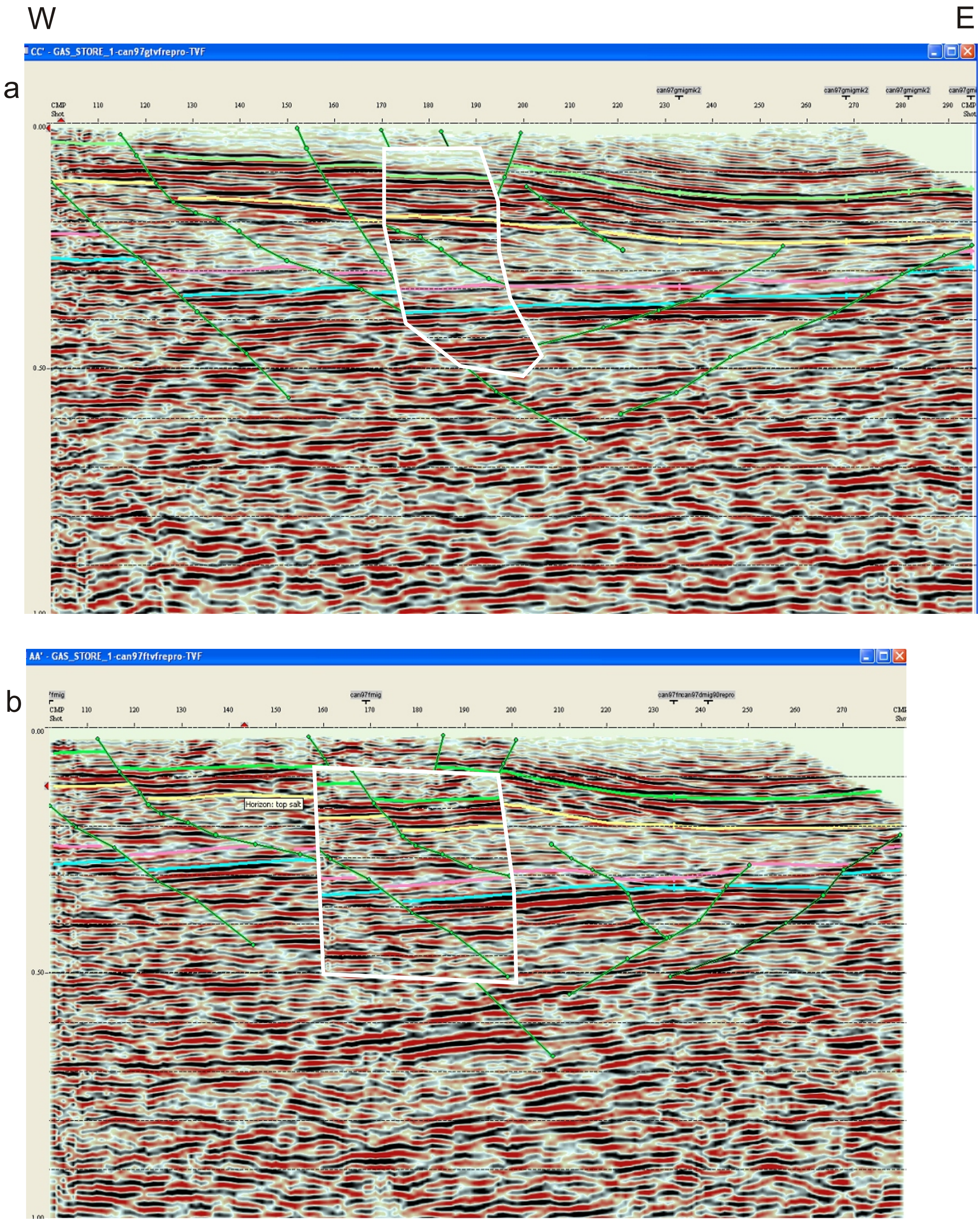
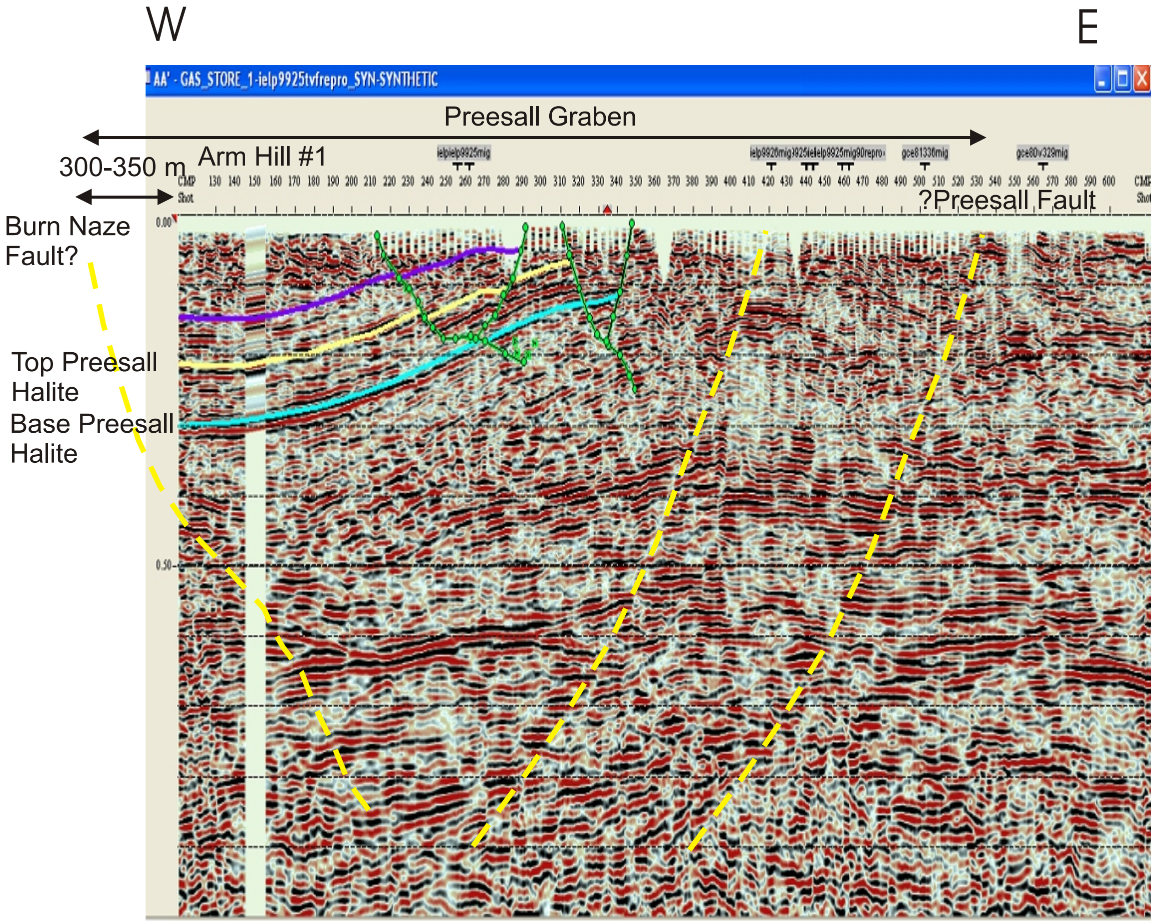


Figure 15. Correlation panels (outlined in white) for Canatxx lines G (a) and F (b). Data show panels from the western ends of the sections to illustrate the similarity with sequences to the east of the faulting and which are tied to ICI boreholes in the central area of sections and provide the evidence for extending the Preesall Halite westwards.

a



b

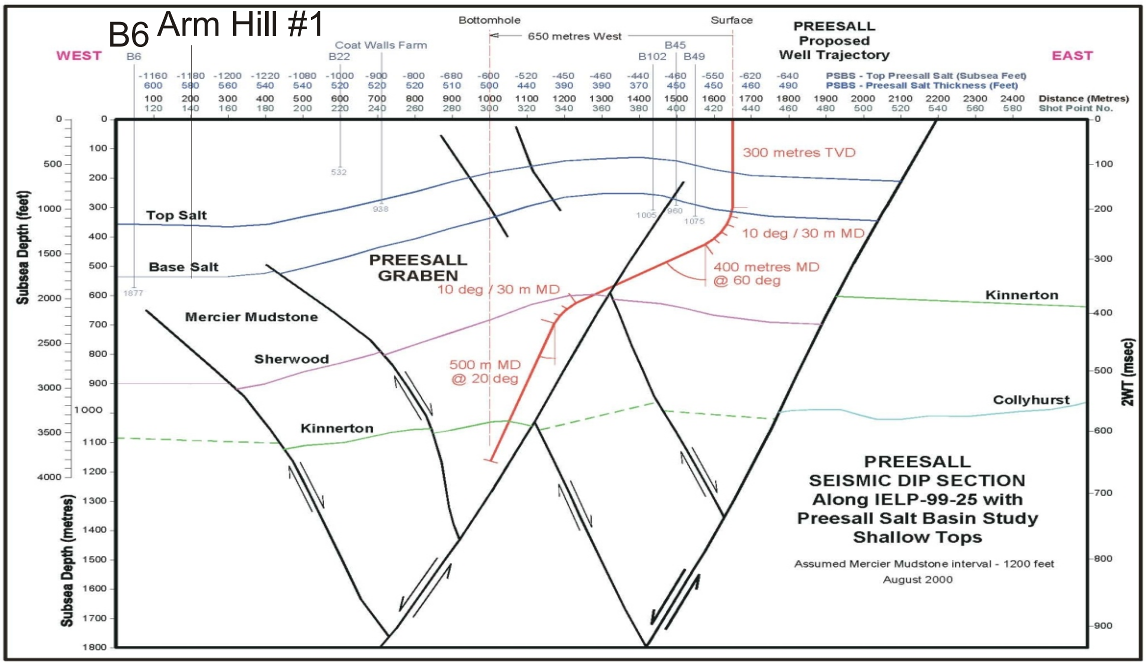


Figure 16. Seismic reflection line IELP-99-25 showing the tie to the synthetic seismic generated from Arm Hill #1and the structure of the Preesall Halite north of BNG Northing 446000 (viewed looking to the north). Sequences dip westwards towards the Burn Naze Fault with only minor apparent faulting. (a) 2005 reprocessed version (b) existing interpretation and depth conversion supplied to BGS. Seismic picks: purple intra-Coat Walls Mdst; light yellow, near top Preesall Halite; blue, near base Preesall Halite.

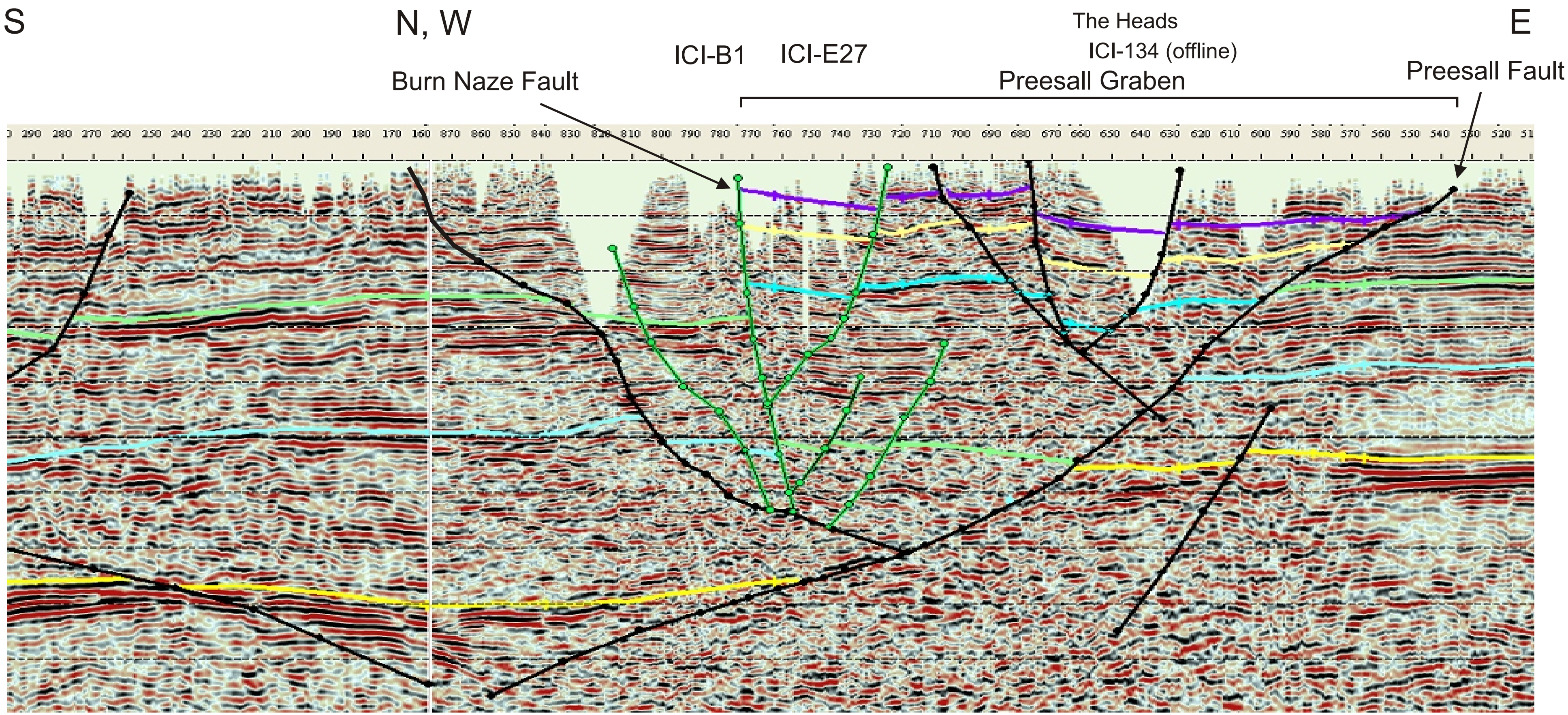


Figure 17. Interpretation of GasGCE-86-DV371seismic line (shown here as a composite with GasGCE-87-382) to illustrate the Preesall Graben and main controlling faults: the Preesall and Burn Naze faults. Thickness variations in the Triassic interval across the Preesall Fault suggest some synsedimentary movements, but lateral movement along the faults and the effects of lower halites cannot be ruled out. Note difference in structural style of the graben and the attitude of the Preesall Fault to the 1996 Daran Petroleum interpretation. Preesall Halite proved by ICI-E27 and 134 wells as indicated. ICI-B1 spudded in Thornton Mudstones beneath the Preesall Halite, proving the Burn Naze Fault between the B1 and E27 boreholes.
Seismic picks: purple intra-MMG; light yellow, near top Preesall Halite; darker blue, near base Preesall Halite; green, near base MMG; light blue, intra SSG; dark yellow, near base SSG?

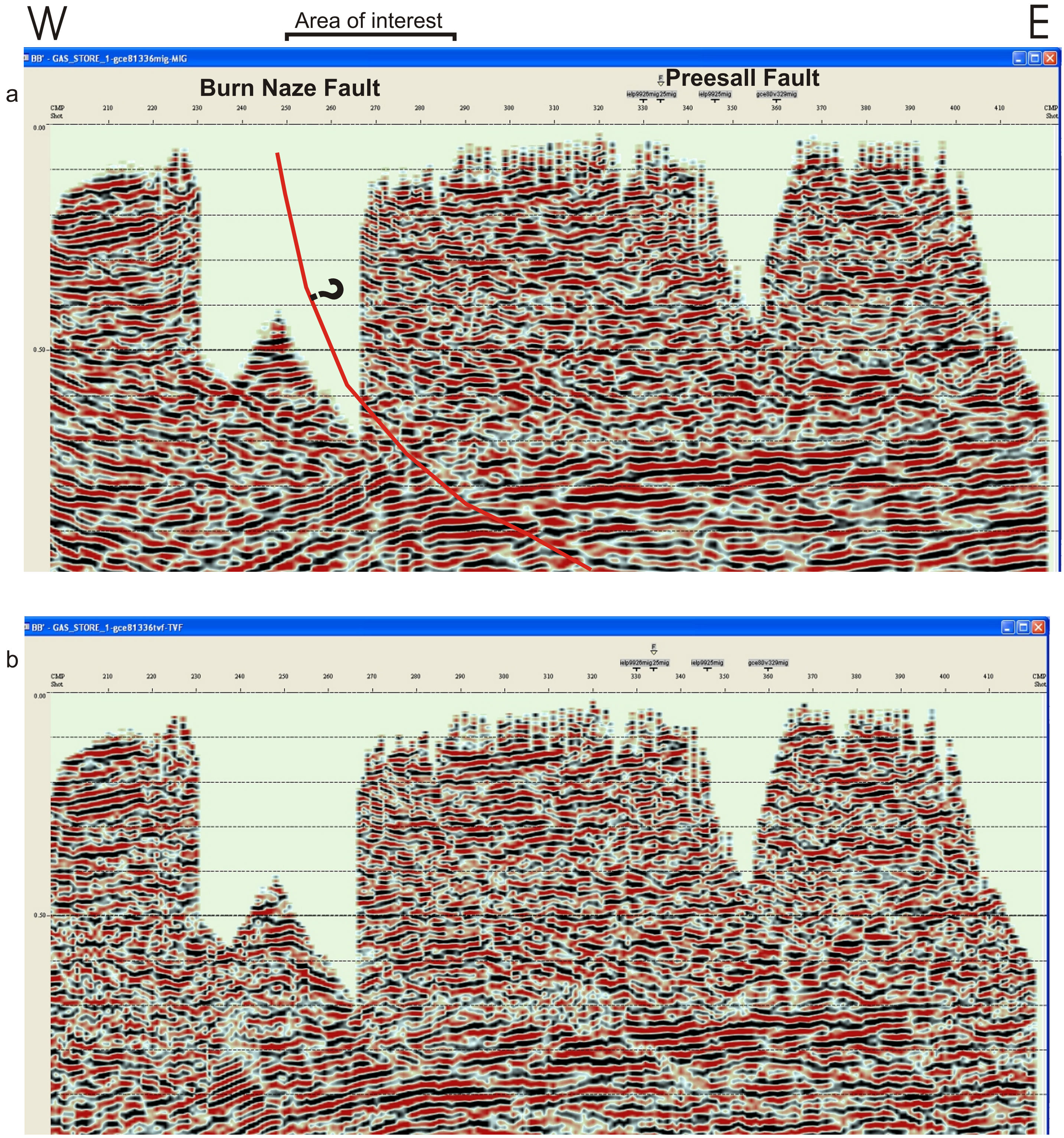
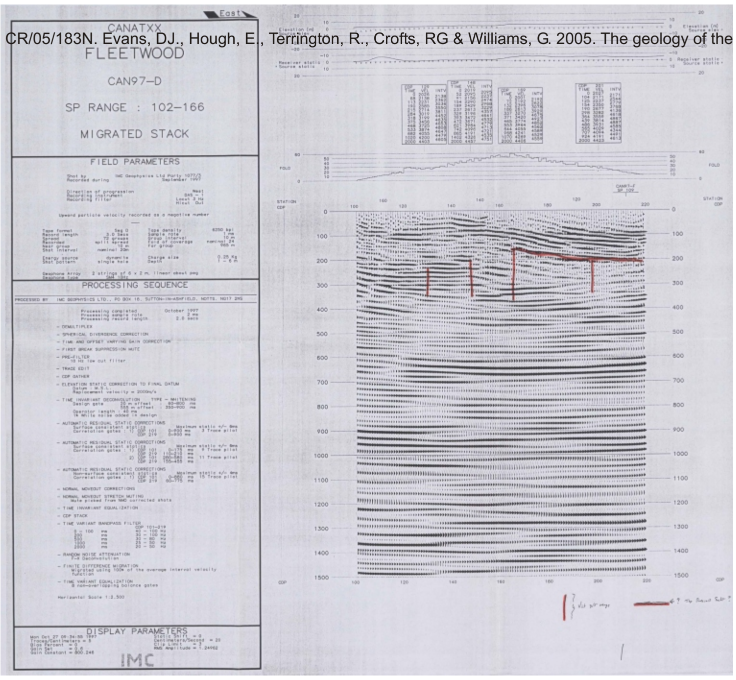
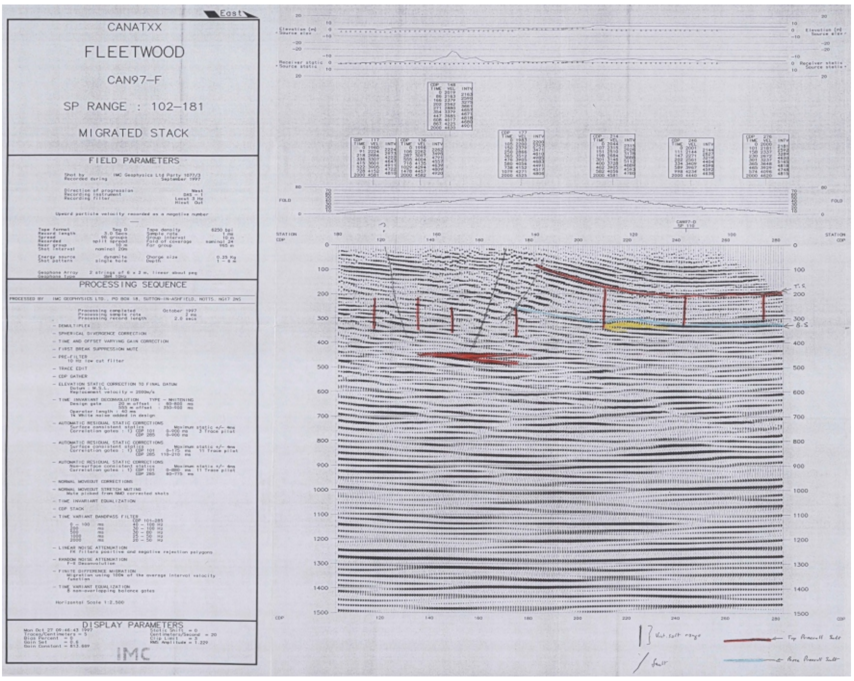


Figure 18. Reprocessed (1996) Gas Council GASGC81-336 seismic line. (a) migrated and (b) filtered stacks. Area of interest falls in the large omission zone on the western end of the line. The Burn Naze Fault as mapped by Daran Petroleum (1996) lies somewhere in this region.

Line D



Line F



Line G

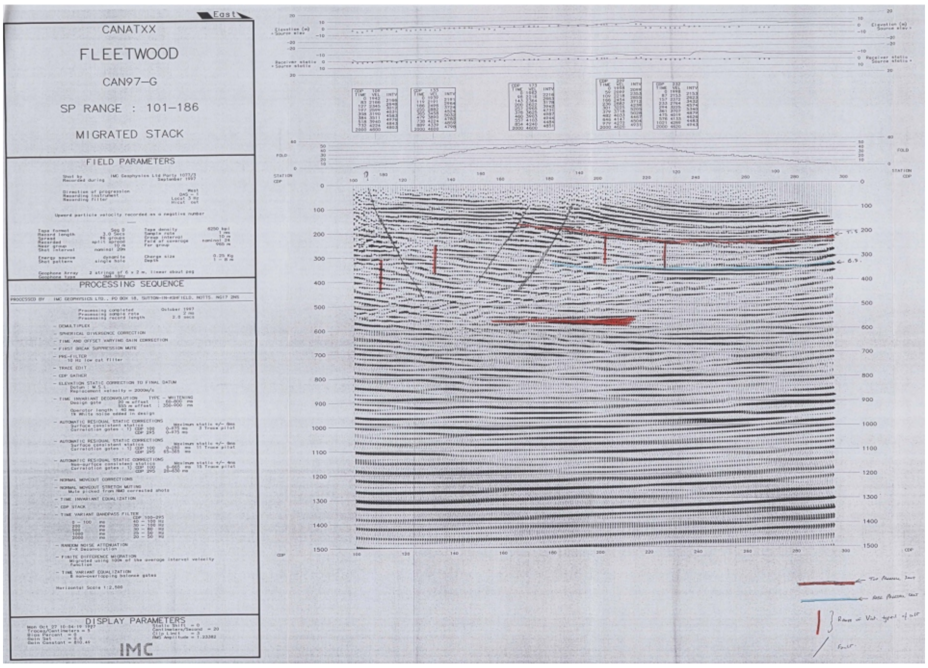


Figure 19. Canatxx data from 1997, showing original quality of processed data and with interpretations of Preesall Halite (from Jenyon, 1997). Red seismic pick is top Preesall Halite, blue seismic pick is base Preesall Halite. Vertical red bars indicate where halite is thought to be. Note how data quality in left half of all seismic lines across a fault is poor, restricting correlation of reflections.

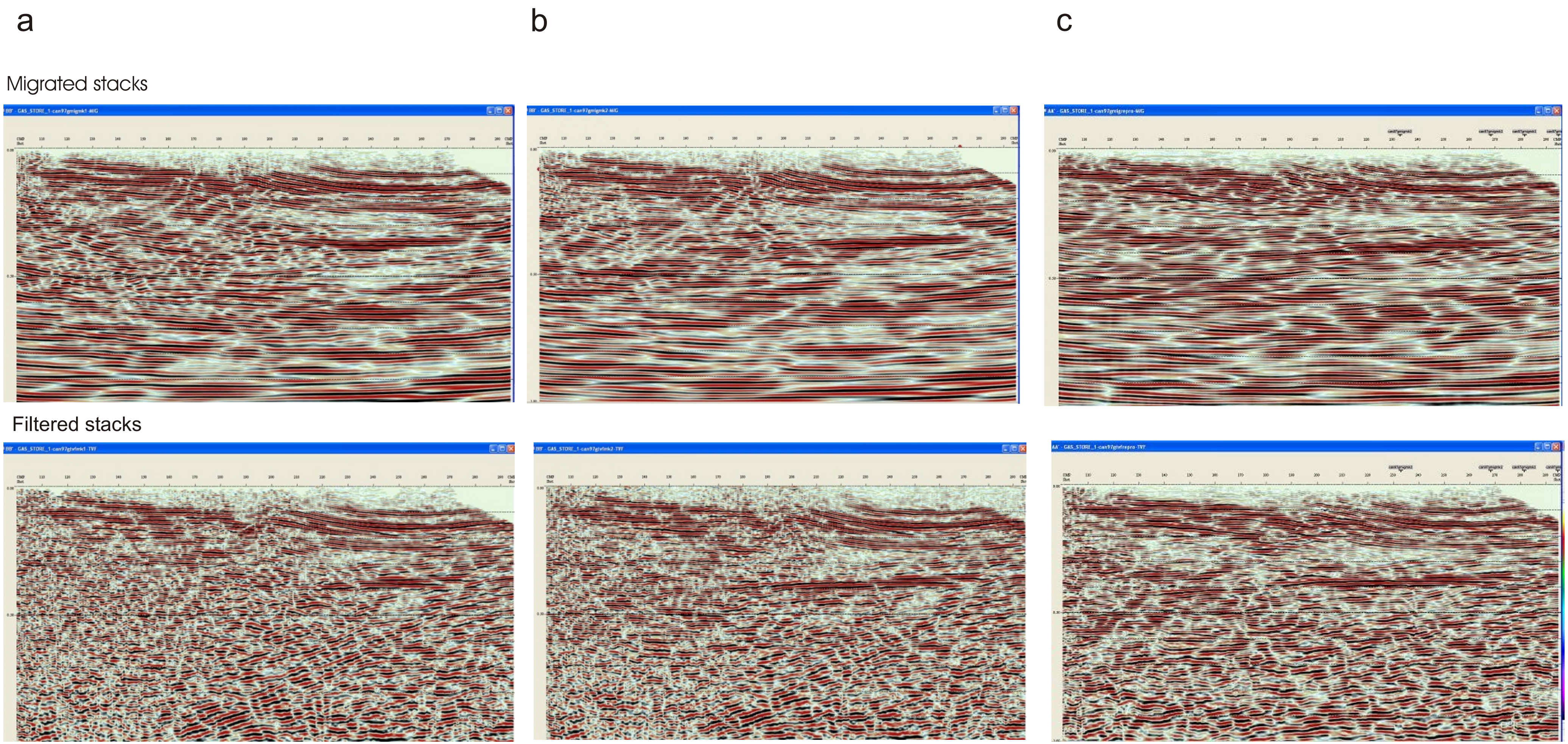


Figure 20. The filtered and migrated stack for the three processed versions of Canatxx line G. (a) original 1996 version, as used (b) the version preferred by IMC Geophysics, but not used and (c) the 2005 reprocessed version. As can be seen there is an improvement in data quality from versions (a) to (c).

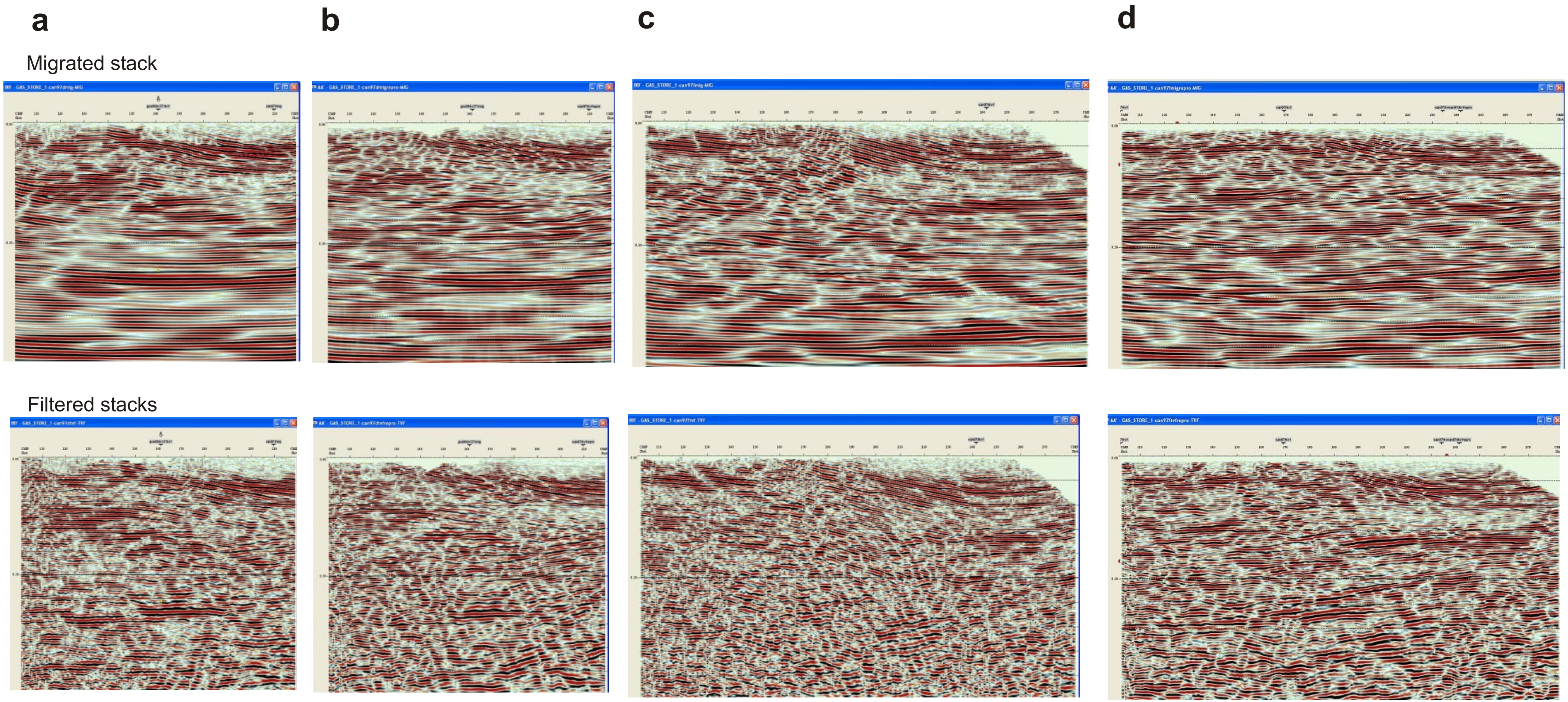
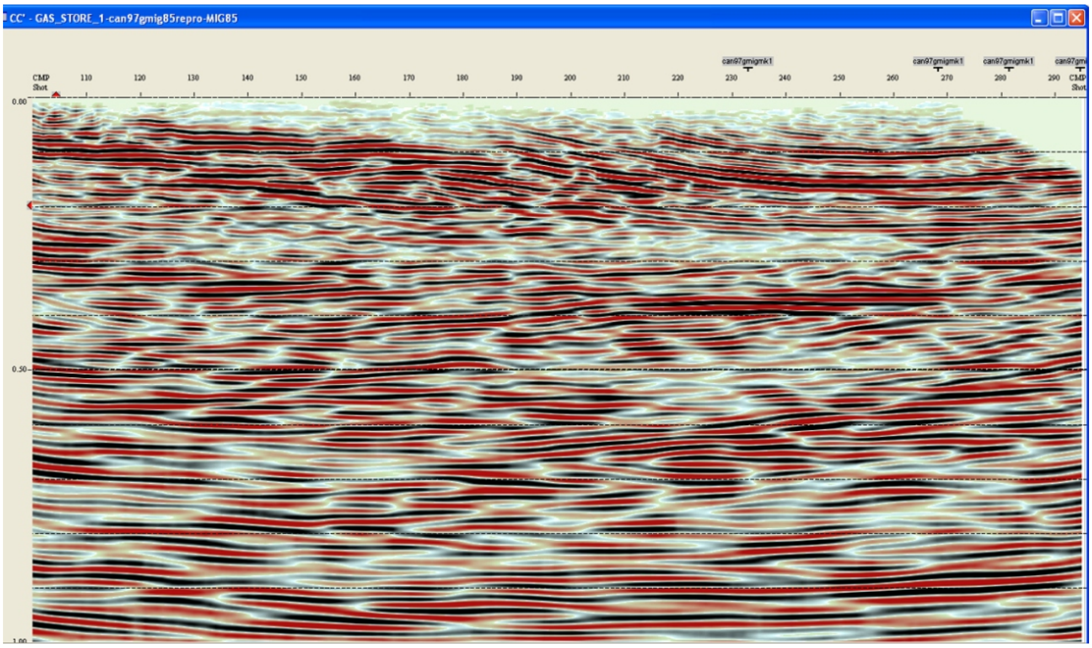
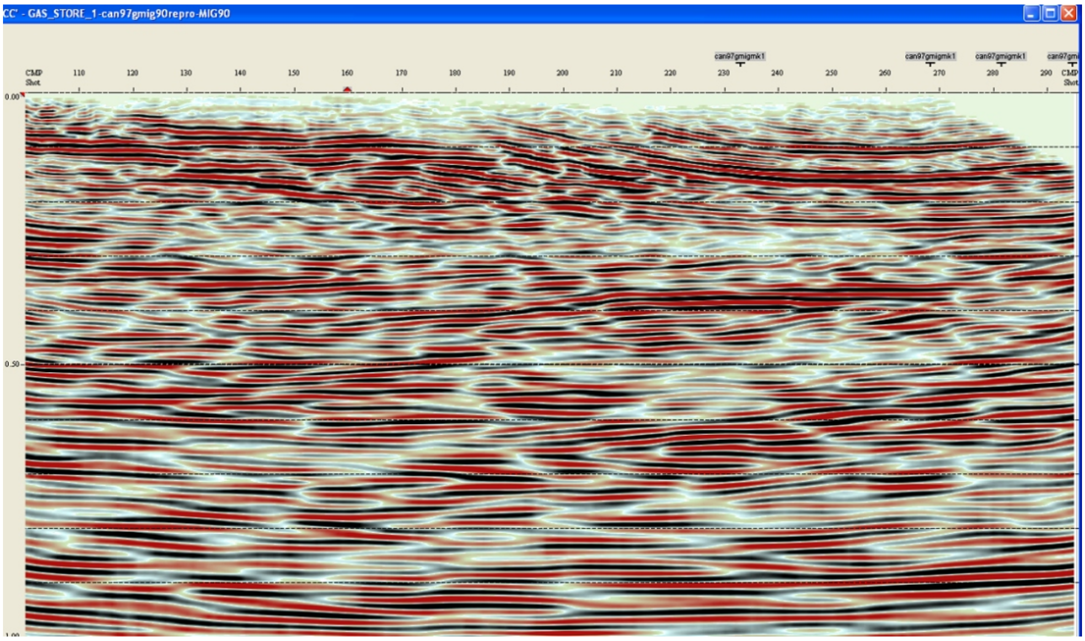


Figure 21. Original 1997 and 2005 reprocessed versions of Canatxx lines D and F, showing the improved data quality achieved during reprocessing. (a) and (b) show original an reprocessed filtered and migrated stacks of Line D. (c) and (d) show the same for Line F.

a



b



c

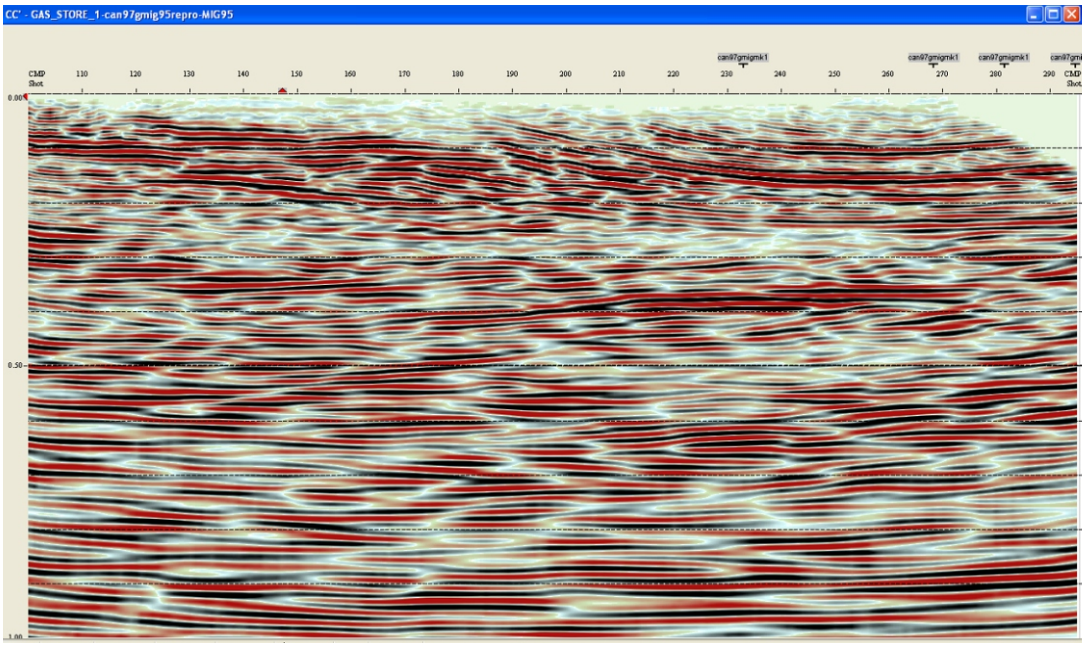


Figure 22. Plots of the 85, 90 and 95% stacking velocity migrated stacks for the 2005 reprocessed Canatxx line G. a) 85%, b) 90% and c) 95%

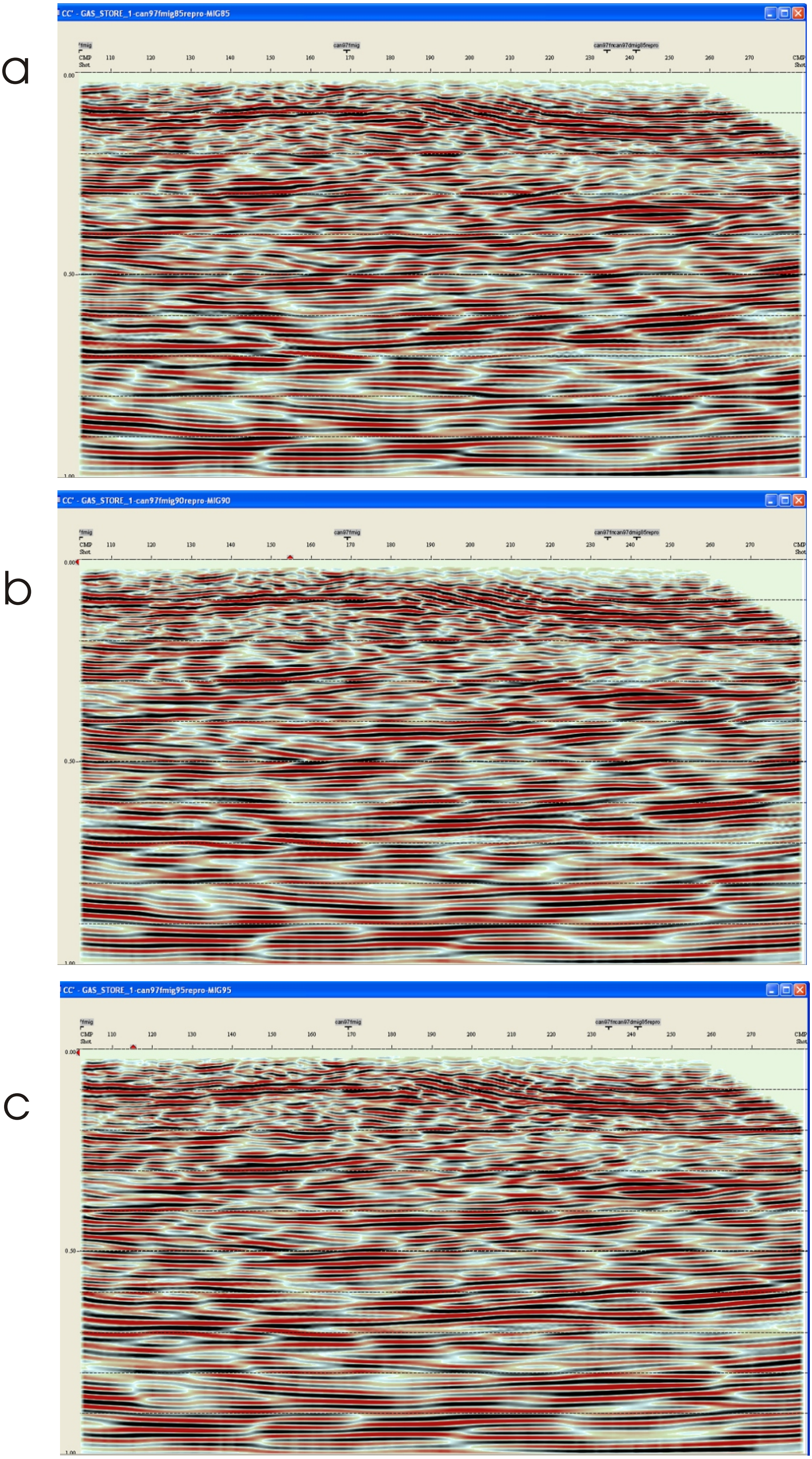


Figure 23. Plots of the 85, 90 and 95% stacking velocity migrated stacks for the 2005 reprocessed Canatxx line F. a) 85%, b) 90% and c) 95%

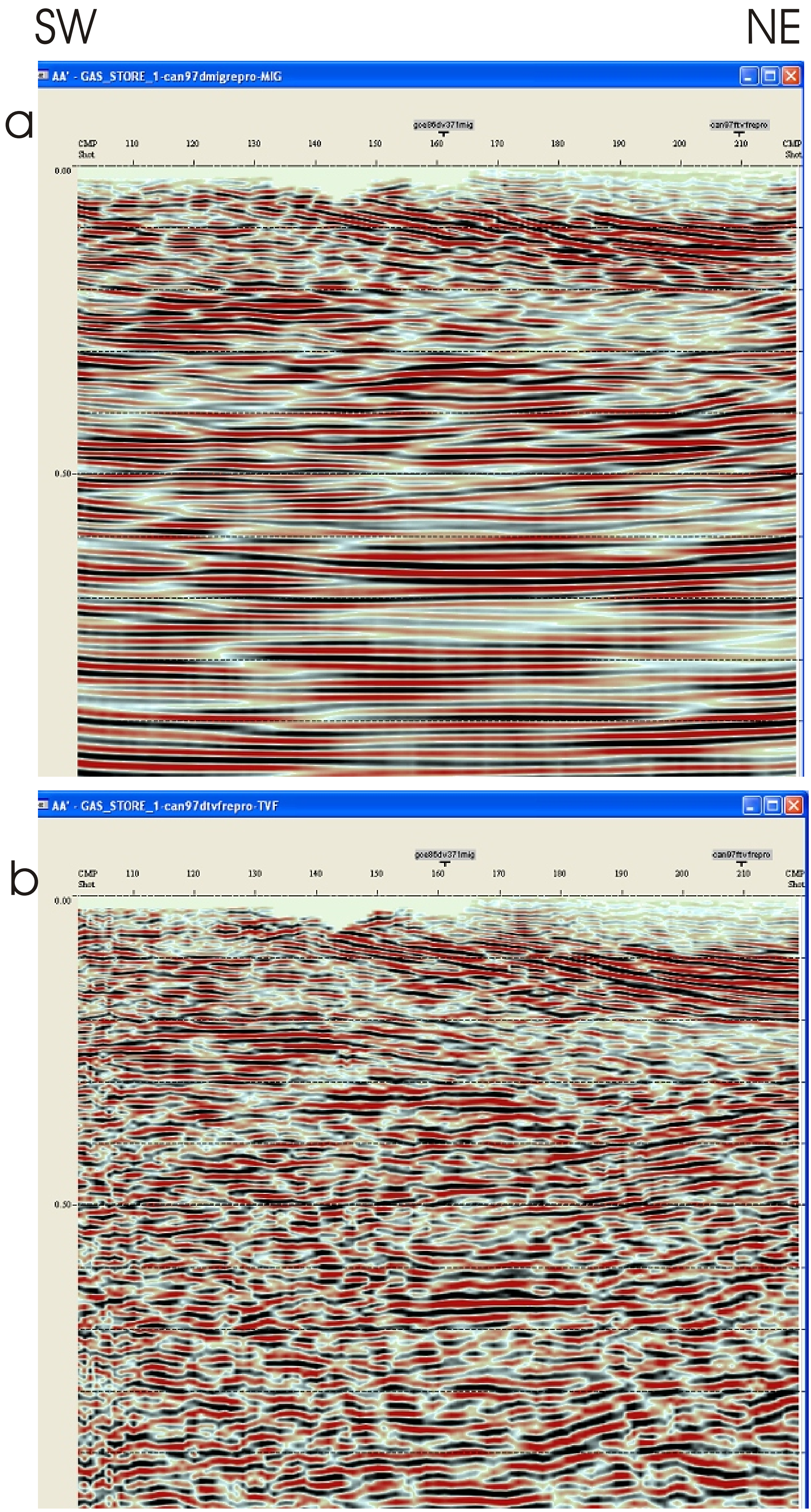


Figure 24. Reprocessed (2005) migrated (a) and filtered stacks (b) of Canatxx line D. Complex faulting apparent in central parts of the line, but line length and possibly direction do not permit reliable interpretation.

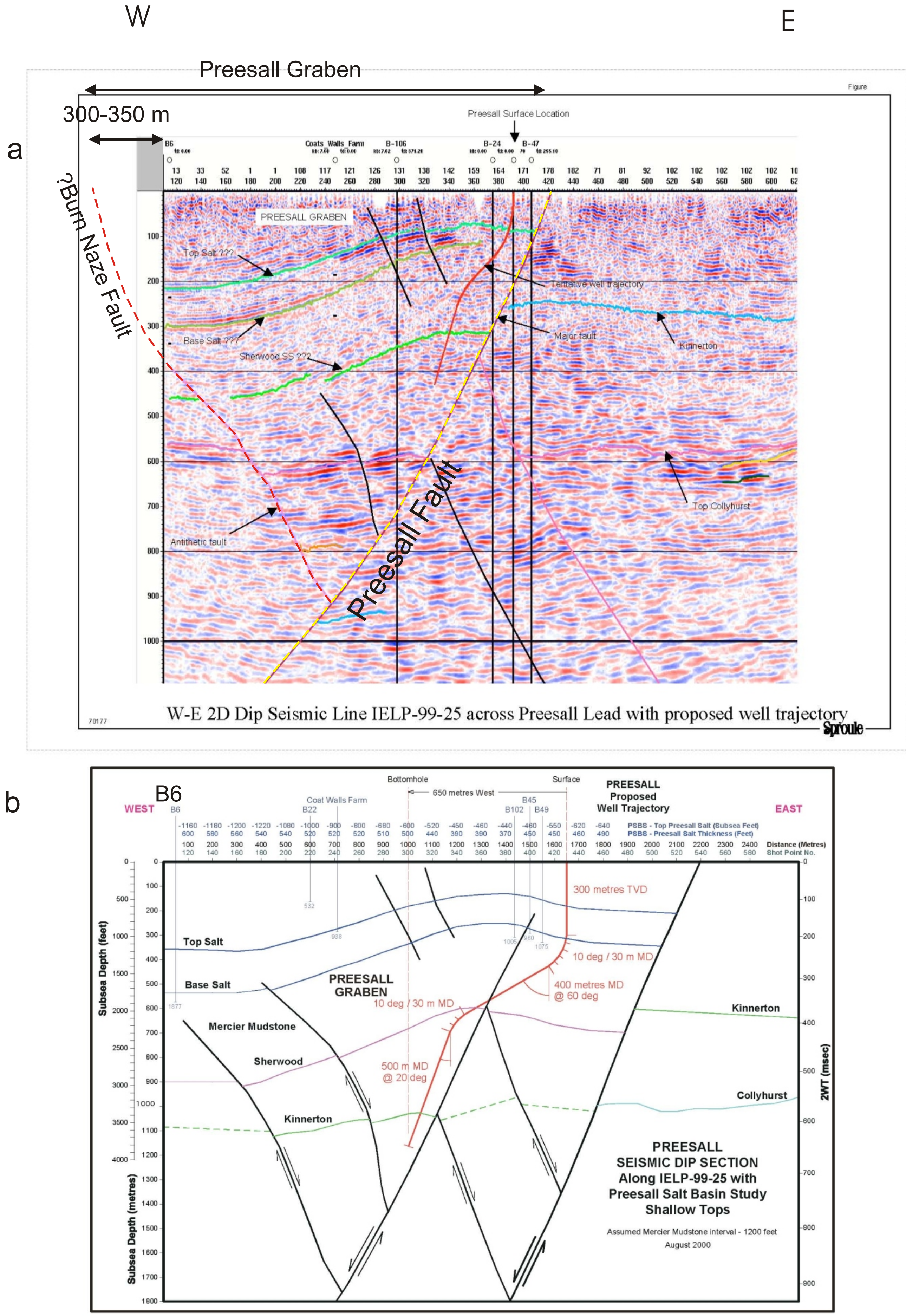


Figure 25. Seismic reflection line IELP-99-25 showing the (a) existing interpretation and (b) depth conversion supplied to BGS.structure of the Preesall Halite north of BNG Northing 446000 (viewed looking to the north). Sequences dip westwards towards the Burn Naze Fault with only minor faulting. Seismic picks tied to ICI boreholes as indicated.

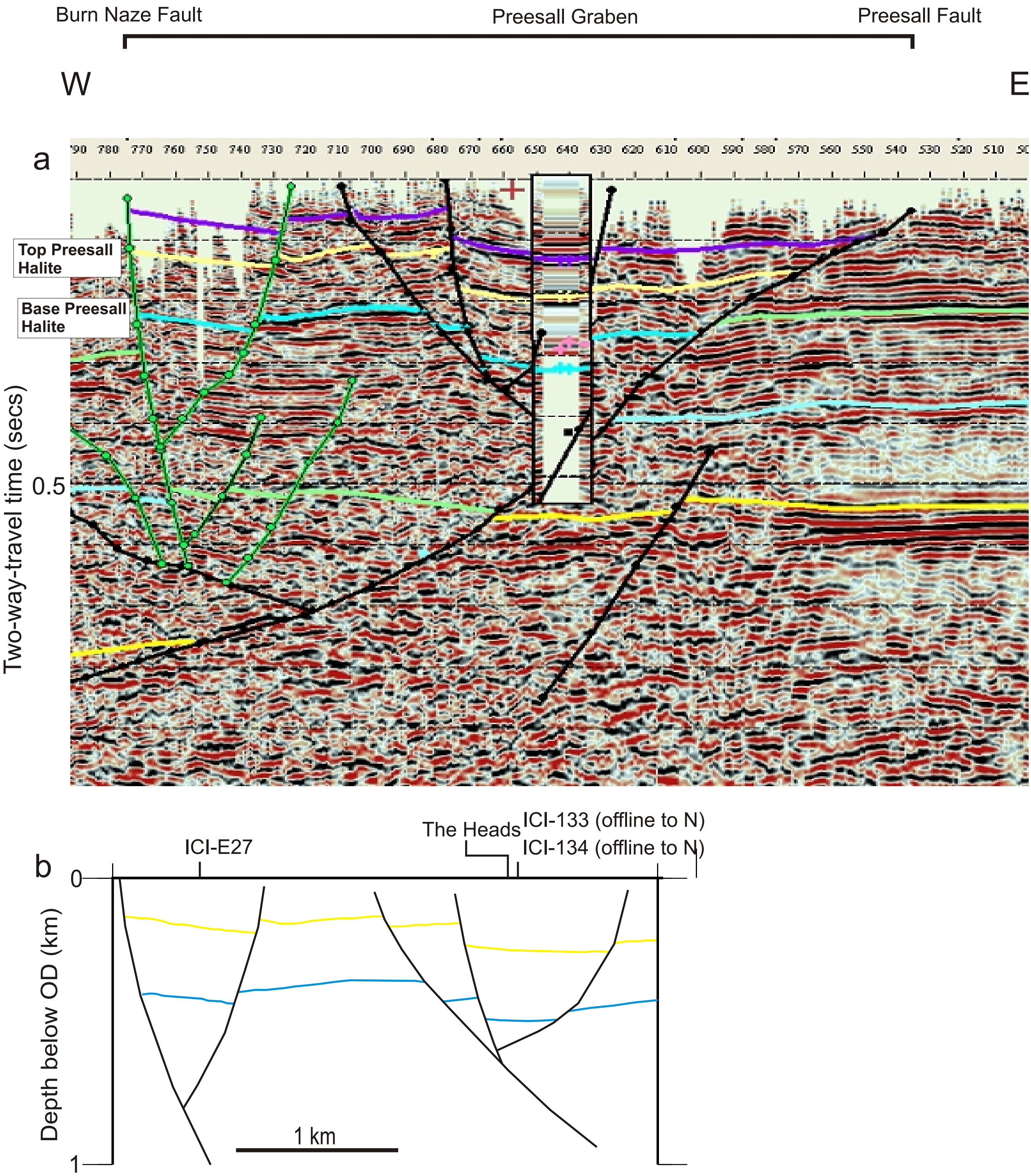
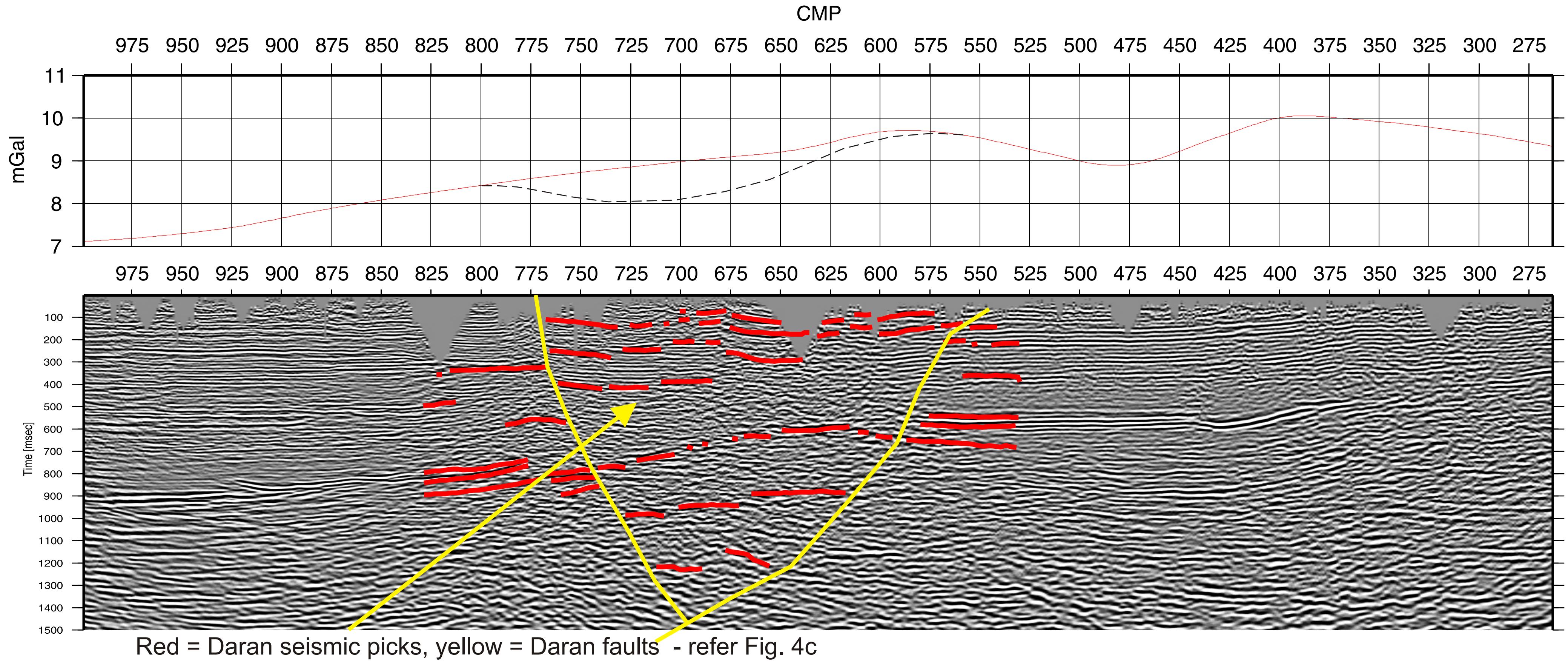


Figure 26. 2005 reprocessed GASGCE-86-DV371 seismic line showing ties to relevant boreholes. (a) interpreted migrated section with correlation panel of the Heads borehole synthetic seismic tied to Canatxx Line F (see Fig. 13) illustrating tie to top Preesall Halite (b) depth converted line drawing Data quality is poor on the eastern end, making interpretation in the shallow section unreliable.



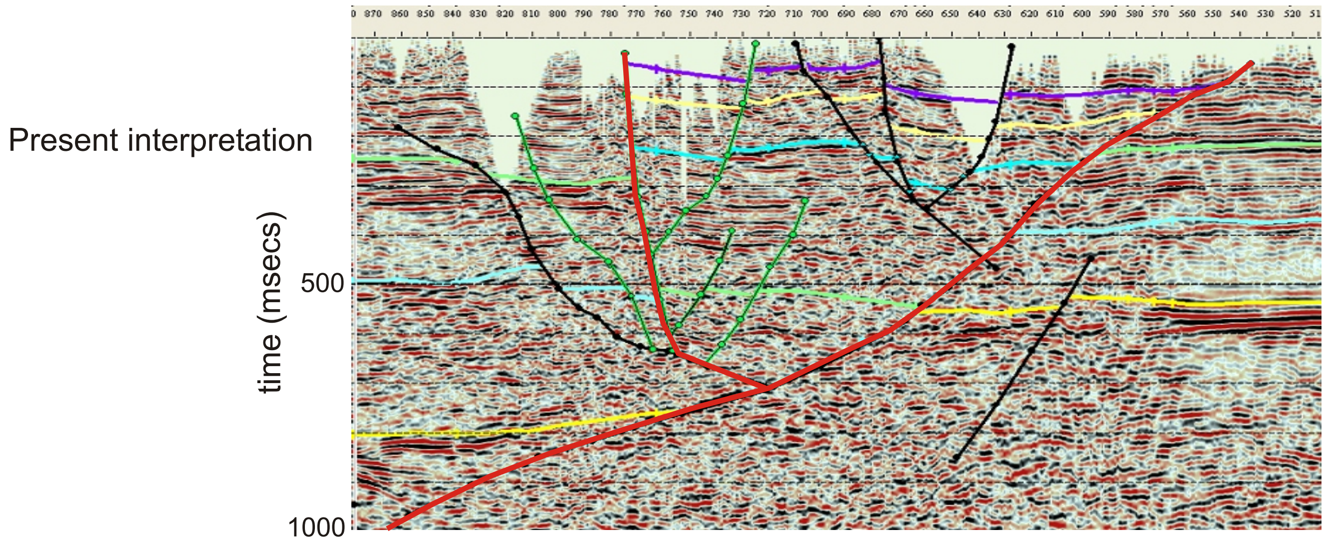


Figure 27. Comparison of the Daran 1996 interpretation of the deeper structure of the Preesall Fault and Graben and the present alternative. The Daran intepretation would introduce a thicker sequence of lower density strata that might be expected to show a gravity profile more like that dotted in black. The present interpretation of a lower angle Preesall Fault introduces higher density material further west, which would give rise to a gravity profile more like that observed, which actually increases slightly across the graben.

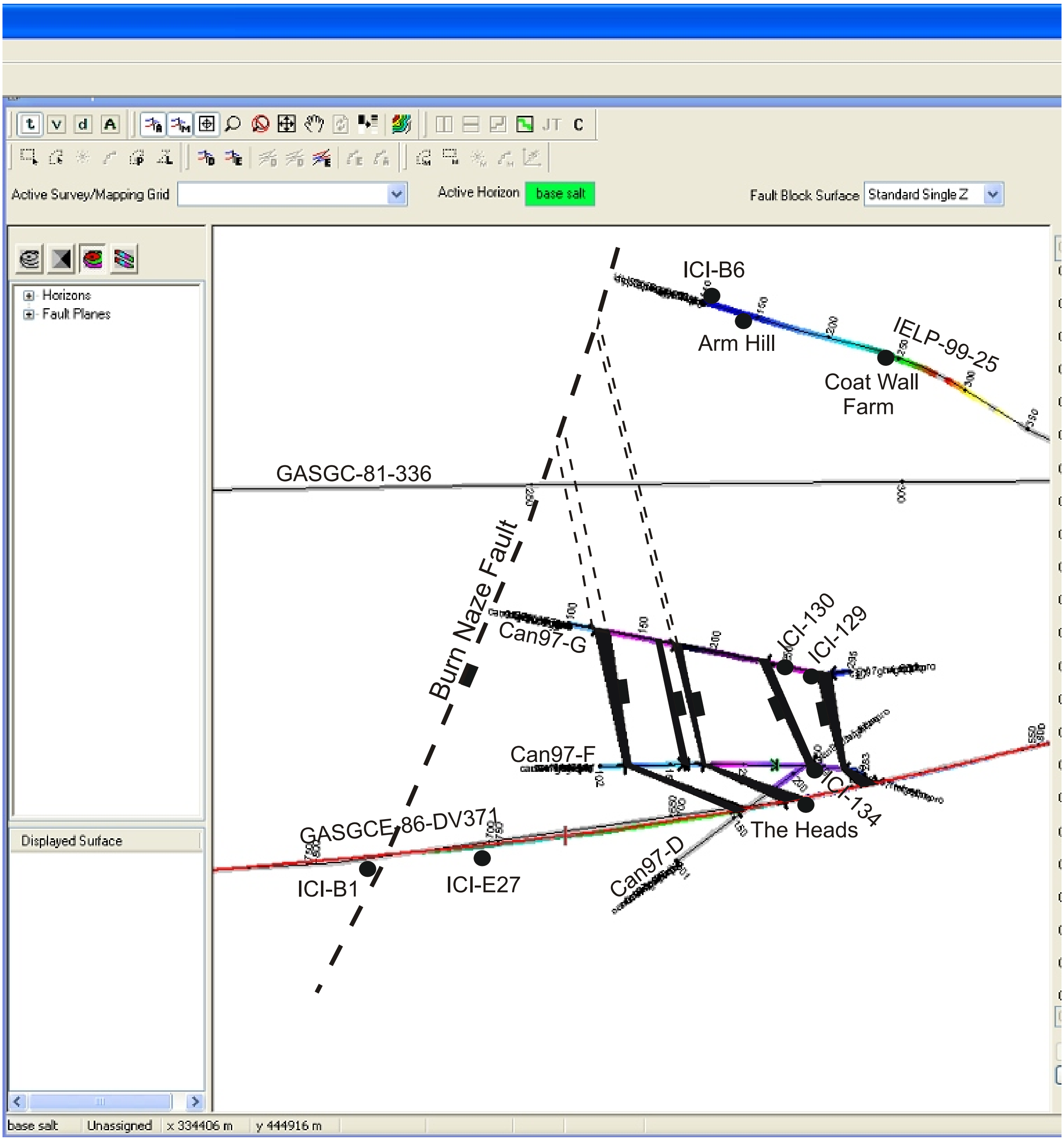


Figure 28. Apparent faulting at base Preesall Halite level.

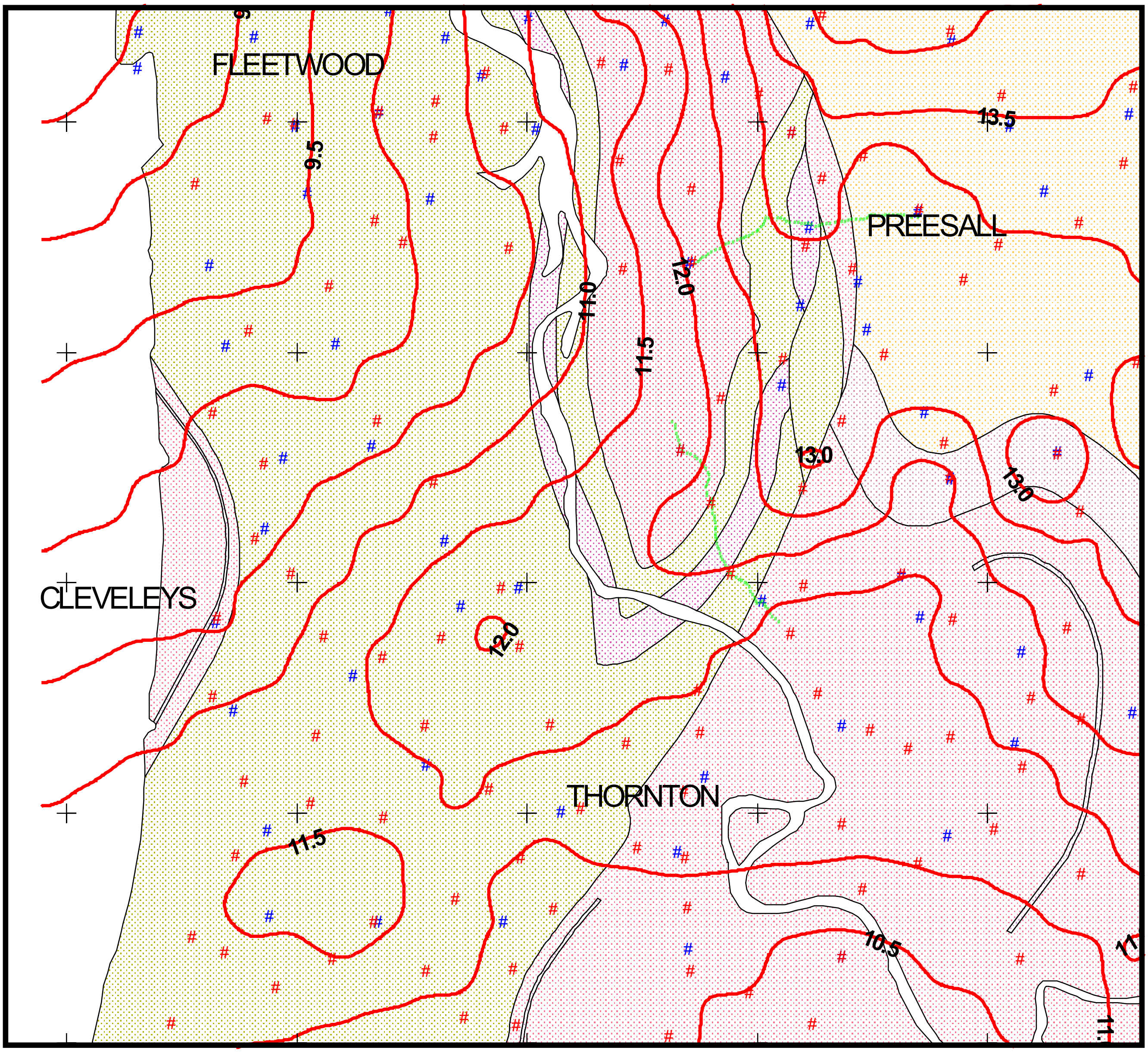


Figure 29. Bouguer gravity anomaly contours (red lines) for the Fleetwood Thornton area. Contour values reference International Gravity Formula 1930, as per Published 1:50 000 scale Blackpool geological map sheet (1975). Bouguer reduction density 2.4g/cc. Coloured shaded areas are BGS DiGMapGB-50 geology.
Red points: 1968 gravity data (used for contours).
Blue points: BGS National gravity databank digital gravity data (not used in contours).
Green points: Location of 1968 gravity traverse points

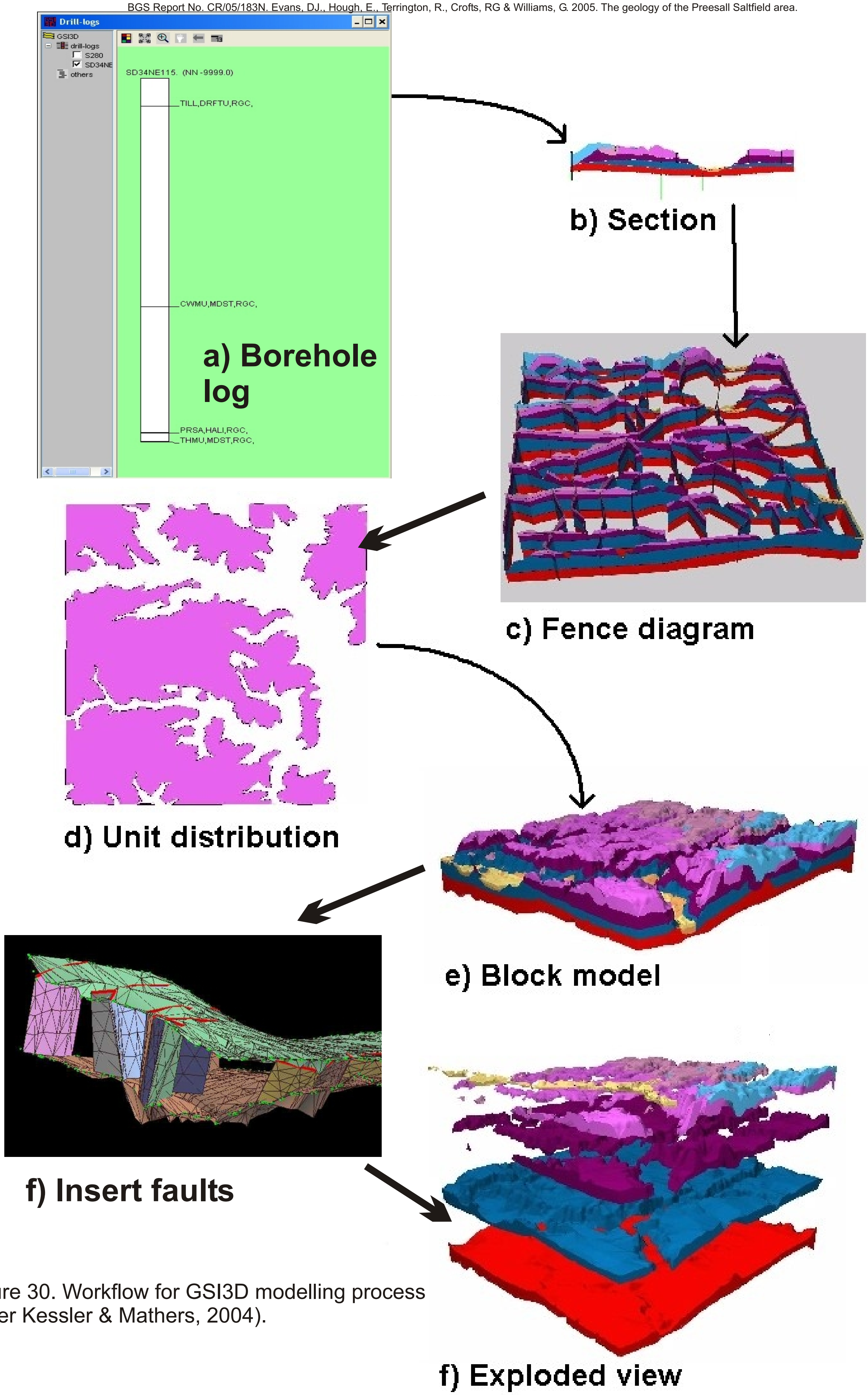


Figure 30. Workflow for GSI3D modelling process (after Kessler & Mathers, 2004).

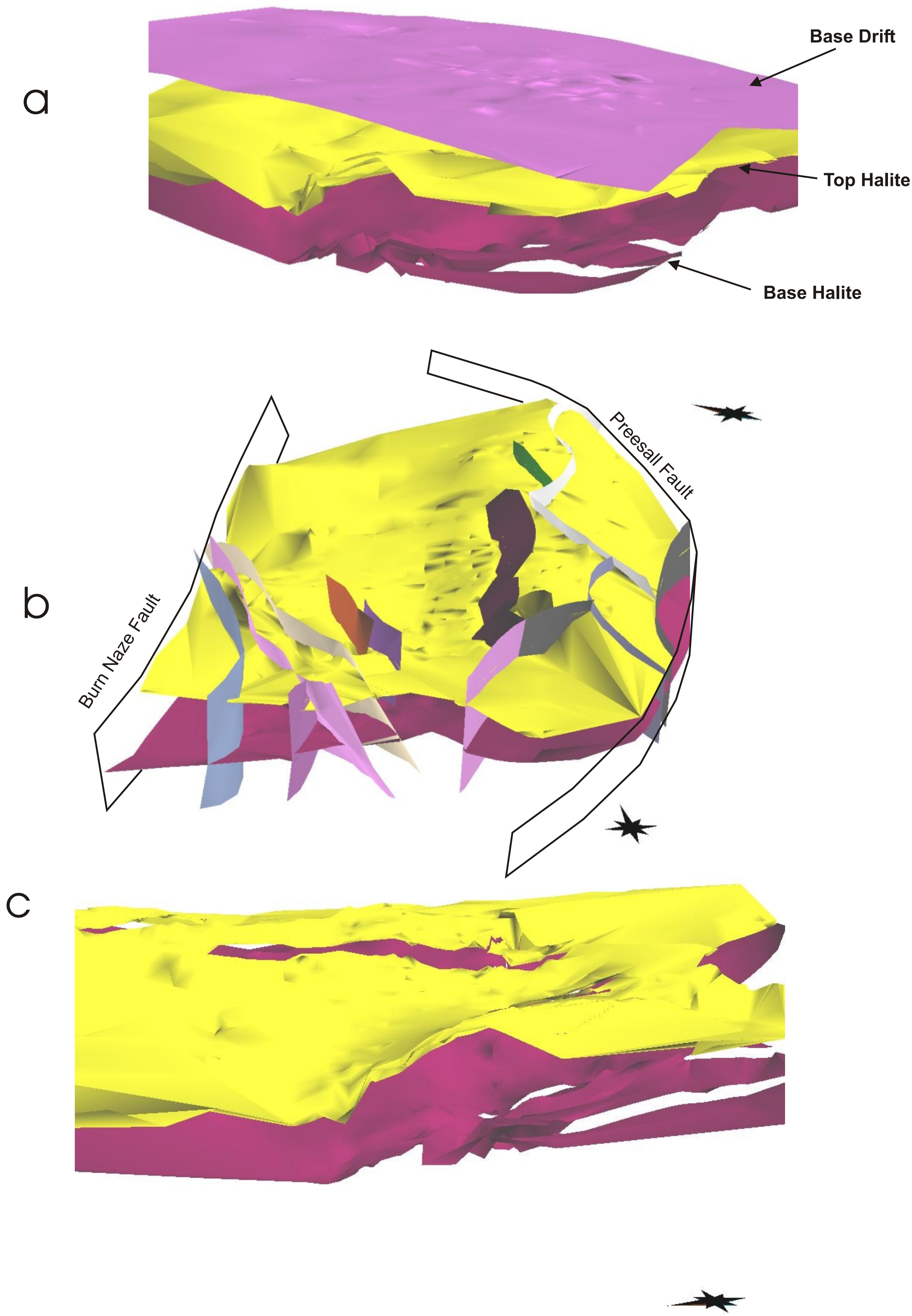


Figure 31. 3D views of the Preesall Saltfield. (a) the Drift, top and base Presall Halite surfaces, viewed looking to NE - faults not shown for clarity (b) the top and base halite with faults, viewed looking N (c) top and base halite surfaces, viewed looking ESE - faults not shown for clarity.

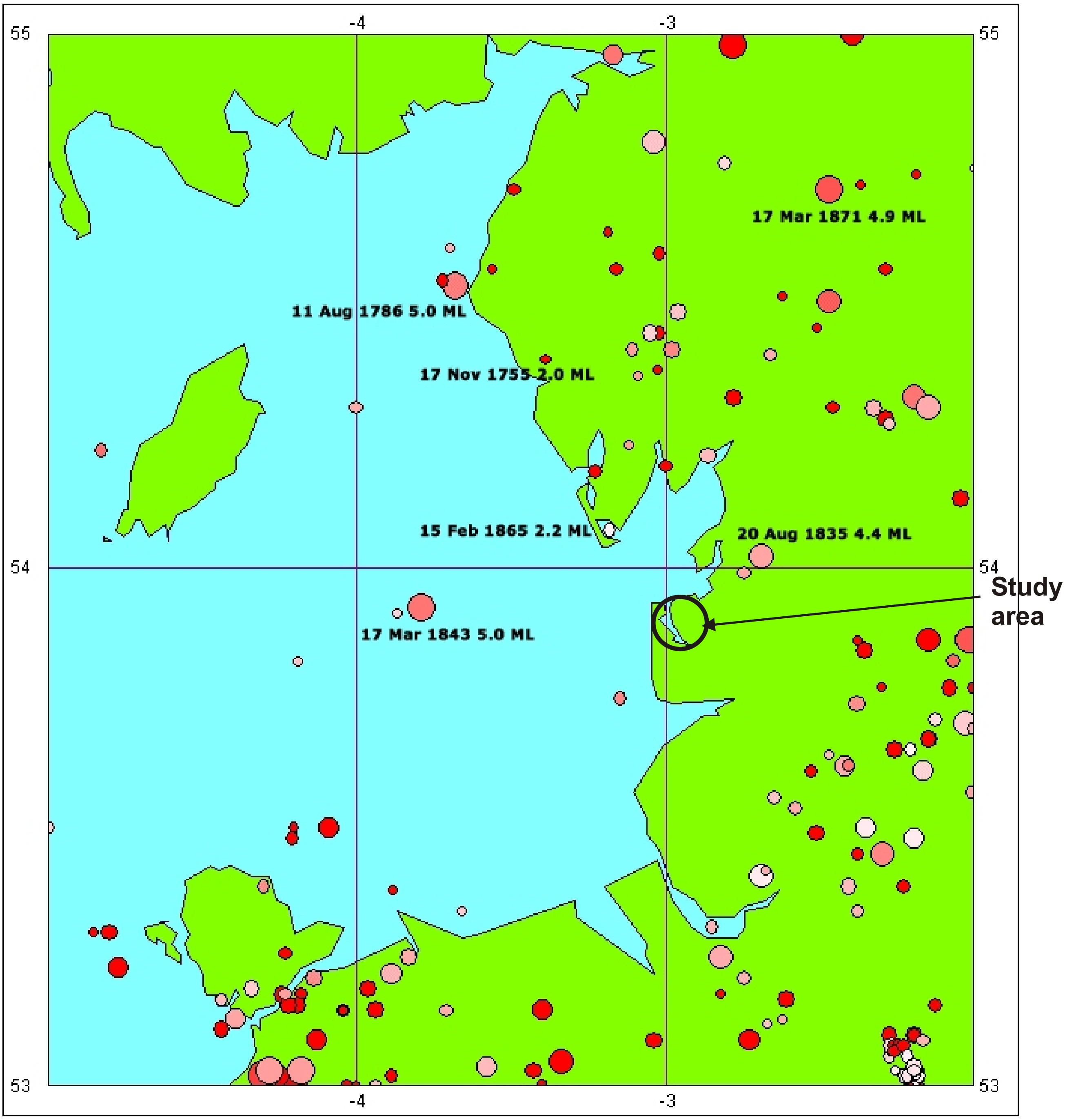


Figure 32. Regional seismicity relative to the area of interest. Symbol size is related to magnitude, and colour to depth, with shallower events being lighter (unknown depths are coloured red).