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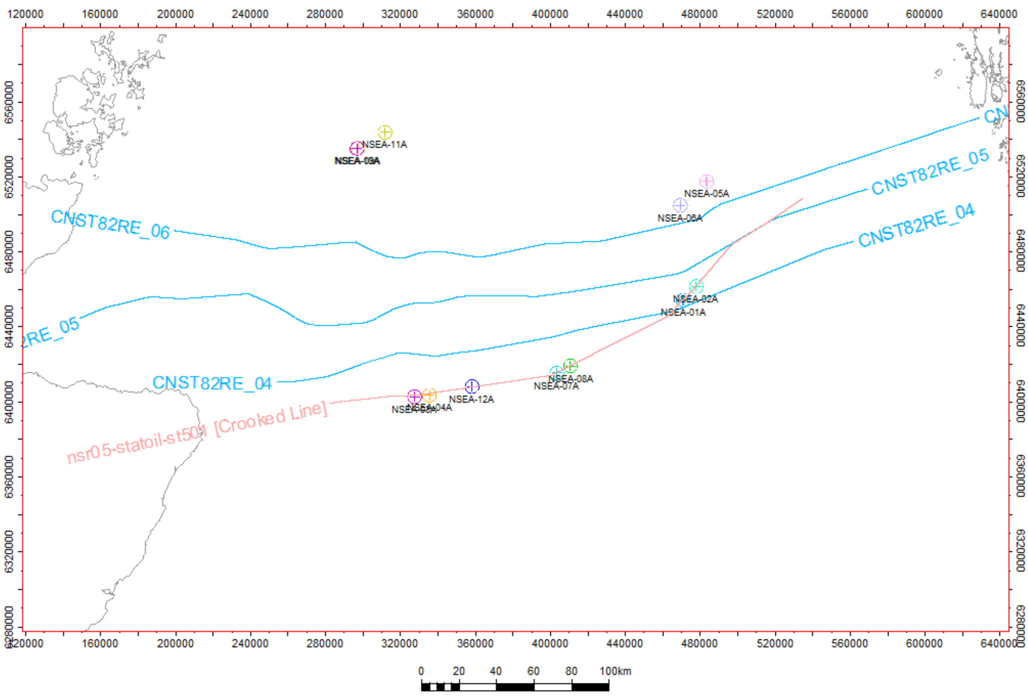
Energy and Marine Geoscience Programme

Internal Report OR/15/072



BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

INTERNAL REPORT OR/15/072

A summary of the methodology for the seismic stratigraphic interpretation for the 'GlaciStore' bid to IODP

C M A Gent[1], M A Stewart[1], D J Evans[1], R Lamb[2], J Alcalde[3,4], N Heinemann[4] and M C Akhurst[1]

[1]British Geological Survey

[2]University of Manchester

[3]University of Aberdeen

[4]University of Edinburgh

Keywords

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Front cover

The proposed IODP Drill sites in the North Sea with the trace of the main interpreted regional 2D lines.

Bibliographical reference

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British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276

email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488

email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683

email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270

Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

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

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

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

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

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

Tel 01793 411500 Fax 01793 411501

www.nerc.ac.uk

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Foreword

The report summarises the methodology used by UK CCS RC-funded, Call 1, 'North Sea aquifers' project to interpret the shallow North Sea strata that are the overburden sequence to prospective UK CO_2 storage sites. The 'North Sea aquifers' project supported the interpretation of subsurface data in the UK Central North Sea needed to underpin a bid for scientific drilling. Collaboration with a Norwegian research consortium funded by the CLIMIT programme, with participants from industry and academia, has been crucial in achieving the objective of preparation of drilling proposal.

The methodology presented here is the 'cross-border geology' component of the submission that established both the geological framework and detailed investigation for drilling sites proposed within the UK sector of the North Sea. The results of the interpretation informed the two-stage submission of the 'GlaciStore' pre-proposal and full proposal for scientific drilling submitted to the International Ocean Discovery Programme (IODP). The GlaciStore research proposes to investigate the strata that comprise the overburden sequence to operating and prospective North Sea CO_2 storage sites. The scientific objectives proposed are to: establish a depositional and chronological framework for the multiple cycles of glacial advance and retreat in the centre of the North Sea; investigate temporal changes in depositional environment and pore water geochemistry of the stratigraphic units; determine the measurable impact on geomechanical properties caused by glacial loading and unloading.

Acknowledgements

S Holloway started this worked but retired before it was fully underway and he is thanked for his advice on many aspects of the work and for gaining permission for the use of the seismic data in the interpretation.

Statoil are thanked for access to seismic survey data to inform a cross-border seismic stratigraphic interpretation of the Mid-Quaternary to Eocene sequence across the UK and Norwegian sectors of the North Sea Basin. Petroleum Geo-Services (PGS) are gratefully acknowledged for access to seismic survey data for interpretation of the shallow, sea bed to Mid-Quaternary sequence.

The preparation and submission of a pre-proposal and full proposal to IODP could not have been achieved without collaboration with the Norwegian research consortium members from SINTEF: Statoil, Lundin, IFE, University of Bergen and University of Oslo. Support for the Norwegian consortium by the CLIMIT programme is also acknowledged here.

Contents

FIGURES

TABLES

Summary

This report summarises the methodology followed for the seismic interpretation of sedimentary strata that are the overburden sequence and the Palaeogene strata that are prospective CO_2 storage formations, in the UK Central North Sea. The interpretation of selected 2D and 3D seismic reflection, well and borehole data in the UK North and Central North Sea is targeted to inform the preparation of the 'GlaciStore' proposal for scientific drilling submitted to the International Ocean Discovery Programme (IODP). Drilling sites proposed to IODP lie within the UK and Norwegian sectors of the North Sea. The methodology is described for the interpretation of seismic data for proposed sites within UK waters. The seismic interpretation was undertaken in collaboration with Norwegian members of the GlaciStore consortium.

The seismic interpretation was divided into two teams according to depth, into 'shallower and 'deeper' seismic interpretation activities, appropriate to the fields of expertise and experience of the interpreters. The 'shallower seismic' interpreters considered strata of latest Neogene and Quaternary age which were deposited during major glacial and interglacial cycles. The 'deeper seismic' interpreters considered slightly older strata of Mid Eocene to Quaternary in age. Seven potential UK drill sites were selected to address the scientific objectives in the proposal.

2D and 3D seismic, well, borehole and bathymetry data were used to map buried and open tunnel valleys and to identify any evidence for the presence of shallow gas in the 'shallower seismic' interpretation at each drill site. Only sites without any indication of shallow gas features were considered as these pose a serious hazard for drilling.

2D and 3D seismic and well datasets and existing interpretations were collated for the 'deeper seismic' interpretation. The hydrocarbon exploration well log data, which were found to be of variable quality, were used to identify and map a number of stratigraphical surfaces of Cenozoic age, and included Quaternary strata, around the grid of seismic lines. Maps from some of the key stratigraphical surfaces are presented, selected to inform the drilling proposal. A plot of acoustic velocity data was prepared to inform future conversion of the seismic interpretation to true vertical depth.

Future work, based on the seismic interpretation undertaken to underpin the drilling proposal, is identified. Features observed within the 'shallower' and 'deeper' seismic interpretations that warrant further investigation are: a chaotic zone within the Quaternary sequence; prograding units within the Eocene Horda Formation; basin centre sandstone bodies as prospective CO_2 storage strata within the Horda Formation; systematic mapping of cross-cutting, buried tunnel valleys in the Quaternary sequence from 3D seismic data.

1 Introduction

Significant oil and gas accumulations and discoveries are found in the Central to Northern North Sea in both the UK and Norwegian sectors. These are usually hosted in strata no younger than Palaeocene in age. Although the younger strata may be considered immature for oil and gas generation, the thick succession has an important role in Carbon Capture and Storage (CCS), as demonstrated by the Pliocene-aged Utsira Sands utilised by the Sleipner CCS operation (e.g. Arts et al., 2004; Chadwick et al., 2004, 2008; Bickle et al., 2007; Hermanrud et al., 2009). To be able to accurately assess and model potential storage sites, the Cenozoic mid Palaeogene to Quaternary overburden strata need to be well characterised and constrained. However, in the past the thick (locally >1000 m) heterogeneous Neogene and Quaternary succession has been regularly neglected by oil and gas companies targeting deeper reservoir horizons. The Central to Northern North Sea region is also particularly interesting and in many ways unique in that the Quaternary succession forming the cap rock to anticipated CO_2 storage horizons, comprises sequences deposited during, and as a result of, major glacial cycles.

Characterisation of the subsurface was required to inform the GlaciStore IODP proposal, not only of the target Quaternary overburden succession but also strata from the Balder Formation of Early/Mid Eocene (Palaeogene) age and younger and which contain potential CO_2 storage horizons. During the initial stages of the seismic interpretation the top of a large prograding unit originally classified as Pliocene in age (the so-called “Top Pliocene Prograding Unit”, or “TPPU”) was taken as the near-top of the Neogene succession. However, detailed seismic interpretation elsewhere to the south suggests strata giving rise to these reflections are younger than previously thought and are now classified as Quaternary in age (Head et al., 2008). The focus of the seismic interpretation was therefore re-defined, with two groups proceeding to interpret what are here termed the ‘shallower seismic’ and the ‘deeper seismic’.

1.1 PROPOSAL TO THE IODP

Drilling sites were selected to address the scientific objectives in the ‘GlaciStore’ proposal to IODP within the UK and Norwegian North Sea sectors. The scientific objectives proposed are to:

- Establish a depositional and chronological framework for the multiple cycles of glacial advance and retreat in the centre of the North Sea;
- Investigate temporal changes in depositional environment and pore water geochemistry of the stratigraphic units;
- Determine the measurable impact on geomechanical properties caused by glacial loading and unloading.

The seismic interpretations summarised here within the UK sector of the North Sea informed two phases of investigation for a pre-proposal and a full proposal submitted to the IODP. The initial site selection was presented in a pre-proposal and submitted in March 2014. The pre-proposal was reviewed and IODP invited the ‘GlaciStore’ proponents to submit a full proposal in April 2015. The subsequent detailed investigation refined understanding of the proposed sites, informed adjustment of site positions to better address the scientific objectives, where possible, or to ensure the proposed sites met with safety requirements of IODP. A total of 13 sites were investigated across the UK and Norwegian North Sea sectors. The selected sites were prioritised as only a maximum of four would be drilled should the full proposal be accepted by IODP. Detailed investigations of all the proposed sites were submitted in the full proposal, retained as contingency options to meet practical constraints during drilling, if needed.

1.2 ‘SHALLOWER SEISMIC’ INTERPRETATION

The ‘shallower seismic’ section is here defined as all strata down to the top Utsira Sands (Mio-Pliocene in age). Therefore this interpretation is of the latest Neogene and Quaternary succession in the study area, which, in this region comprises strata deposited during major glacial cycles. Areas of focus include, major horizons and sequence boundaries, surface and near-surface glacial tunnel valleys and evidence for shallow gas in either chimney form (represented on seismic reflection data as areas of poor data quality with loss of reflection continuity and amplitude), or give rise to ‘bright’ reflections, with specific interest locally around potential drill sites.

1.3 ‘DEEPER SEISMIC’ INTERPRETATION

The initial ‘deeper seismic’ interpretation was of Mid-Quaternary to top Oligocene horizons. Later interpretation follows the reclassification of the overburden succession (Head et al., 2008) with the focus of the deeper interpretation mainly on the base of the Utsira Sands (Mio-Pliocene in age) to the top Balder formation (Early/Mid-Eocene). All major seismic horizons or ‘events’ are interpreted laterally as far as possible across the regional CNST82RE survey, from the UK sector into the Norwegian sector of the Central North Sea. Particular interest is paid to a series of depositional units prograding from the UK sector to the south-east.

The aim of interpreting the deeper, mid Eocene-Quaternary section is to provide an understanding of the major structural controls on the distribution and stratigraphy of the Cenozoic overburden succession and thus potential controls on the nature and distribution of the Quaternary succession.

The ‘deeper seismic’ interpretation sets the regional structural and stratigraphical framework for the sites in the proposal for scientific drilling and as required by IODP.

2 Shallower Seismic Interpretation

Seven potential drill sites were selected for the IODP proposal, with a focus on the Quaternary (shallower) section in the Central North Sea to address the specific scientific objectives in the proposal. The potential UK sites are listed in Table 1 along with a summary of scientific objectives. Figure 1 shows the location of the potential drilling sites within the UK North Sea and the data used for selection. Additional sites, investigated by the collaborating Norwegian consortium, are included in the drilling proposal. Not all of the proposed sites are expected to be drilled.

Table 1: List of proposed IODP sites located in the UK sector of the North Sea

Site Name	Proposed Depth	Main Objective (s)
NSEA-03B	810 m	Shallow tunnel valley at 300 ms TWTT to Base Quaternary
NSEA-04A	900 m	Base Quaternary through undisturbed succession
NSEA-09B	50 m	Infill of sea bed tunnel valley
NSEA-10A	45 m	Infill of near-sea bed tunnel valley
NSEA-11B	90 m	Infill of sea bed tunnel valley and internal architecture
NSEA-13A	900 m	Base Quaternary and Early Quaternary prograding sequence
NSEA-14A	490 m	Infill of stacked, buried tunnel valleys

2.1 DATA AVAILABILITY AND QUALITY

For the interpretation of the Quaternary section, both 2D and 3D seismic data were used, alongside a number of hydrocarbon exploration, appraisal and production wells, BGS boreholes, and bathymetric information. Data information is summarised Table 2, and locations in Figure 1. The availability of some of this data, particularly the 3D seismic, is limited due to confidentiality agreements. Most of the other information was available for use within BGS by project participants.

Table 2: Data types used for site selection.

DECC, Department of Energy and Climate Change

Data Type	Owner	Details	Resolution/Information contained.	Confidentiality
2D Seismic Reflection Data	BGS	Paper records. Includes: 1985 Sparker 2D survey; 1979 Sparker 2D	Resolution dependant on individual lines: metre-scale horizontal and vertical separation possible.	Available within BGS.
3D Seismic Reflection Data	PGS	PGS 2009 Central North Sea megamerge. Digital segy data.	50 m horizontal resolution (bin size). 10-12 m vertical resolution dependant on location.	Yes, dependant on agreement with PGS.
OLEX Bathymetric dataset	OLEX* (www.olex.no)	UK OLEX map from 2011. Digital elevation (x,y,z) data.	Up to 5 m horizontal resolution dependant on line spacing. Vertical resolution: 1 m in water depths >100 m; 10 cm water depth <100 m.	Available to BGS
BGS boreholes	BGS	BGS boreholes: 81/39; 81/37; 81/13; 77/03; 77/02; 81/24.	Lithological descriptions; biostratigraphic reports; paleomagnetic information.	Available to BGS.
Commercial Well data	Various, details available from DECC website	Commercial well 'Josephine' 30/13-2. Drilled and completed Sept 1972.	Lithological descriptions; biostratigraphic reports; paleomagnetic information.	Variable, dependant on release date.

* The OLEX bathymetric database is compiled, processed and managed by the Norwegian company OLEX AS (www.olex.no). The sea-bed image is based upon voluntary contributions of echosounder data acquired primarily by commercial fishing vessels, but also including data from research vessels. The database is presented as a series of 5 m x 5 m cells with a vertical and horizontal resolution dependent on the volume and accuracy of the voluntary datasets submitted by partners. The horizontal datum is WGS84.

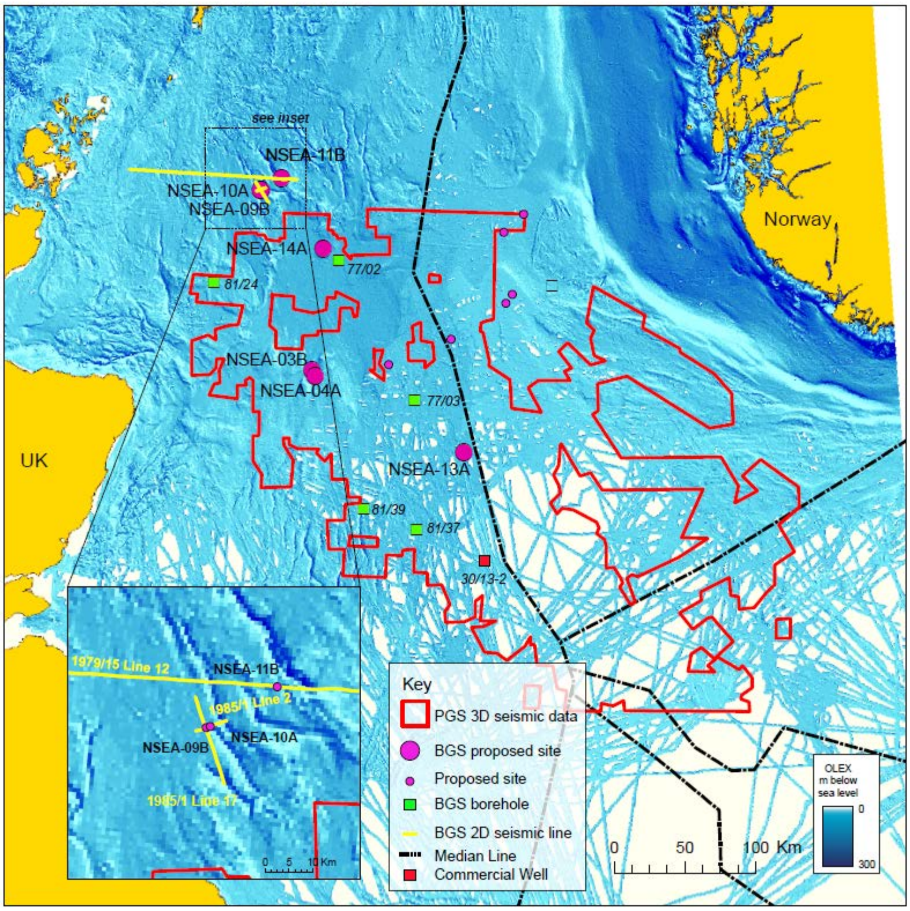


Figure 1: Location map with data used in study and proposed drill sites in the UK sector of the North Sea. Bathymetric data from the OLEX database (www.olex.no), as described for Table 2.

2.2 SELECTED DATA

Despite a wealth of commercial hydrocarbon wells in the region, many do not capture information on the top few hundred metres of sediment – the Quaternary strata of interest here. Therefore, well and borehole information used was limited to the BGS boreholes identified in Table 2, and one commercial well, 30/13-2, which was drilled in 1972 and contains some record of the Quaternary/Neogene succession. BGS acquired a number of 2D seismic reflection lines targeted at the shallower section in the 1970's and 1980's, which were utilised here to image in detail shallow glacial features at and near the sea bed. To obtain a good understanding of the regional seismic architecture and large glacial landforms, 3D seismic data is crucial. The PGS Central North Sea 2009 mega-merge 3D seismic reflection volume was obtained for the purpose of this study (for locations see Figure 1).

The rationale for data selection for each proposed drilling site in the UK sector of the North Sea (Table 1) is summarised below:

- The proposed site NSEA-13A aims to obtain 900 m of core and reach a prograding sequence of early to mid-Quaternary strata. The main supporting data for this proposed site is the 3D seismic merged data and information on magnetic reversals obtained from the 30/13-2 well and BGS boreholes. The interpretation is based on the regional seismic stratigraphic framework of the central North Sea that is part of a doctoral research project at the University of Manchester of R Lamb (in preparation). The interpretation presented here was undertaken by R Lamb for this project.
- NSEA-03B aims to penetrate a near-sea bed tunnel valley through to the base Quaternary. The proposed NSEA-04A site is 900 m deep and aims to penetrate a complete Quaternary sequence from sea bed to base Quaternary. The PGS 3D seismic

volumes were used to identify sites with good potential and the regional interpretations of key seismic surfaces of Lamb (in preparation) were used to refine site selection.

- For site NSEA-14A, the main aim is to investigate the age and fill of large, stacked buried tunnel valley systems. The main supporting data for these proposed sites is the 3D merged data provided by PGS. BGS borehole 77/09 penetrates a buried tunnel valley and was used to predict tunnel valley fill and anticipated drilling rates.
- Sites NSEA-09B, NSEA-10A and NSEA-11B aim to investigate tunnel valleys present at and near the sea bed and made use of BGS shallow 2D seismic data shot in 1979 and 1985. The 2D seismic data were collected and interpreted as paper hard copies. BGS borehole 81/39 penetrates part of the fill of a sea bed tunnel valley and was used to prognose expected succession and anticipated drilling rates.

2.3 INTERPRETATION METHOD

For all sites that made use of the PGS 3D mega-merge survey, the 3D volumes were interpreted using Petrel software. The BGS 2D lines are available only as paper records, while the commercial well data, including summary logs and associated reports were obtained from the Department of Energy and Climate Change (DECC) website. BGS borehole information was reviewed internally.

Throughout the site analysis, care was taken to avoid any indications of vertical structures or features giving rise to anomalously bright reflections within the 3D seismic data; these are considered to be indicative of shallow gas features which are a serious hazard for drilling. Shallow gas may induce blowouts on platforms, and previous instances of this hazard have been encountered in the central North Sea (i.e. the Mobil blowout at the well 22/04-b). For the proposed IODP sites, the 3D seismic was used to identify any indicators of shallow gas including: vertical disruptions in reflectors; patches of very bright reflectors; mounded bright features previously identified as gas-charged (Brooke et al., 1995); and pockmarks at sea bed which indicate vertical migration, possibly of shallow gas. Any sites which interact with such features would be considered an engineering hazard, and were therefore dismissed. For the proposed sites which aim to incorporate information on the older parts of the Quaternary, or the whole Quaternary succession (NSEA-03B; NSEA-04A; NSEA-13A), site choices were investigated on a regional understanding of the seismic architecture and selected to identify relatively undisturbed Quaternary sections. NSEA-13A aimed to capture the northernmost part of Early Quaternary prograding features, which were mapped out in detail using the PGS 3D seismic data and interpretation of key horizons from the BGS boreholes and the commercial well 30/13-2. The proposed site NSEA-03B was selected in order to penetrate a buried tunnel valley, a thick sequence of Quaternary strata, and the newly defined Base Quaternary as part of the PhD project of Lamb (in preparation) (Figure 2). The PGS 3D seismic mega-merge was used to identify a site with a well-defined valley near the middle of the basin where base Quaternary could be reached at 810 m below sea bed. The estimated Base Quaternary surface was based on a regional seismic stratigraphy of the central North Sea (Lamb et al., in preparation) which informed selection of Site NSEA-04A and interpretation of the PGS 3D mega-merge survey. The base Jaramillo magnetic reversal event is obtained from selected BGS boreholes listed in Table 2. The objective of site NSEA-04A is to penetrate a thick (900 m), relatively undisturbed Quaternary sequence.

Buried tunnel valleys are kilometre-scale features; best observed in the North Sea in horizontal time-slice within the 3D seismic data and are generally observed at two-way travel times (TWTT) between 180 ms and 500 ms. For the proposed sites which aimed (in full or in part) to capture buried tunnel valley systems, reconnaissance investigations focused on identifying sites where: tunnel valleys were present; where some indication of internal structure was present in the seismic data; where clear examples of cross-cutting, stacked, buried channels were apparent. Once a number of tunnel valleys systems were identified, potential sites were also selected as close as possible to other potential drill sites, in order to minimise drillship transit time during an IODP mission. At the proposed site NSEA-14A, two tunnel valleys are clearly observed in time-slices in the 3D seismic data at a time of 372 ms TWTT (Figure 3). A large, older valley trends NNE-SSW, and is incised by a shallower, younger E-W trending valley with a clear base. The fill characteristics of the two valleys are somewhat different within the 3D seismic data with the lower valley containing disrupted bright reflections, and the younger channel more flat-lying reflections. The proposed site will penetrate both tunnel valleys to an estimated depth of 490 m below sea bed and into the underlying strata.

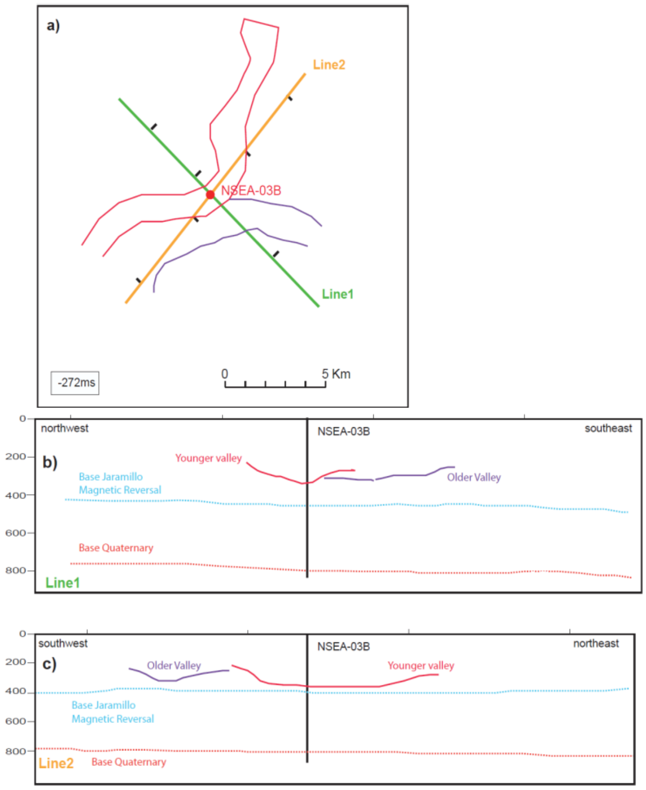


Figure 3: Proposed site NSEA-03B showing
a) outline of tunnel valleys at 272 ms TWTT
b) and c) proposed site NSEA-03B penetrating a near sea bed tunnel valley (in red) and the interpreted Base Jaramillo and Base Quaternary. Interpretations based on confidential PGS 3D seismic reflection data

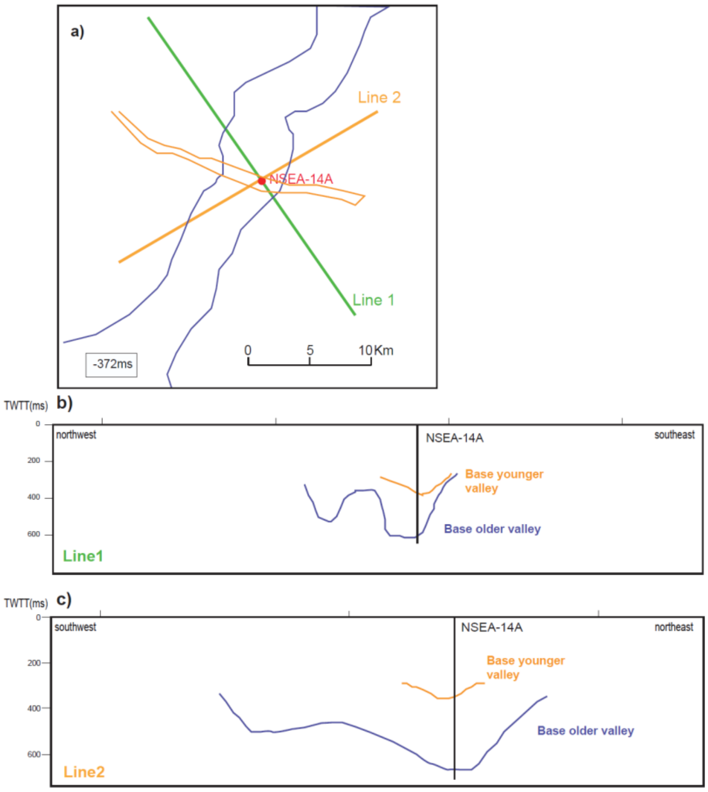


Figure 2: Proposed site NSEA-014A showing
a) outline of tunnel valleys in time-slice at 372 ms TWTT
b) and c) proposed site NSEA-14A penetrating two stacked tunnel valleys interpreted within confidential PGS 3D seismic reflection data.

To investigate the sea bed/open tunnel valleys (sites NSEA-09A; MSEA-10B; NSEA-11B), which are not imaged clearly in the 3D seismic data, BGS 2D seismic reflection data were used, in which the incisions and their fill are clearly imaged. Open and filled tunnel valleys are present in close proximity (less than 5 km) to one another (Figure 4). The extent of the tunnel valleys at sea bed were also imaged and mapped within the OLEX bathymetric database, previously identified and interpreted by Stewart (2009, 2015).

b)

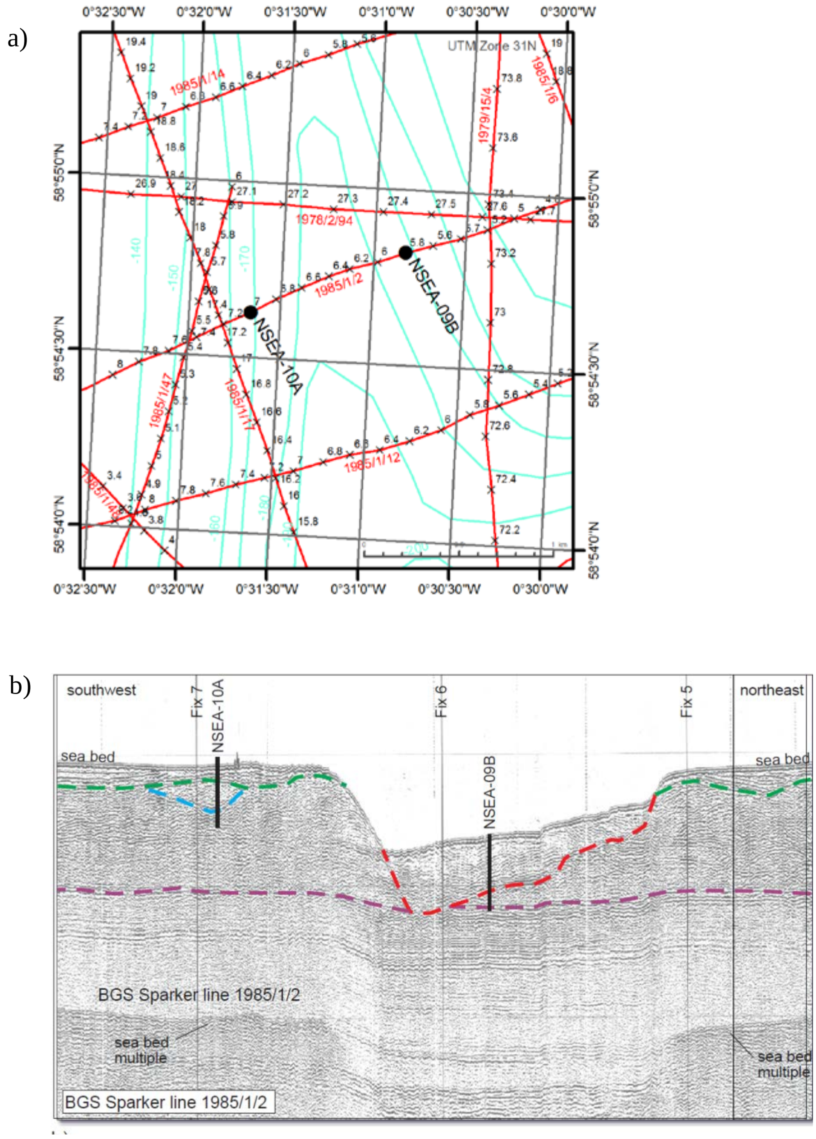


Figure 4: Proposed drill sites investigation near sea bed (NSEA-10A) and open (NSEA-09B) tunnel valleys using BGS 2D Sparker data. a) Location of proposed sites superimposed on OLEX bathymetric data b) Two potential sites and the BGS 2D line 1985/1/2.

2.4 RESULTS

An interpretation of the Quaternary stratigraphy was made based on the scientific objectives in the IODP proposal for each site. For all sites, an assessment of drilling hazards, in particular the possible presence of shallow gas, was undertaken in order to avoid any potential problems. This was carried out within the extent of the 3D seismic surveys and used to inform decisions on the sites selected below.

Figure 3 shows the interpretation for the site NSEA-03B (with the confidential 3D seismic data redacted). The large tunnel valleys identified at 272 ms TWTT have not previously been mapped in detail but are very similar in form to the features widely mapped in the region by Stewart et al. (2013). The Base Jaramillo and Base Quaternary surfaces are newly interpreted (Lamb, in preparation). The proposed site for NSEA-04A also makes use of the interpretation of Lamb (in press), placing the Base Quaternary at around 900 m below sea bed. The thick succession of relatively undisturbed strata imaged in the seismic data is considered to comprise the Aberdeen Ground Formation (Stoker et al. 2011).

Site proposal preparatory work at NSEA-13A included identification of a series of units prograding from the southeast, which Lamb (in press) interpreted regionally using the PGS 3D mega-merge data. The top of the prograding unit was mapped regionally, as well as its major internal units. The lack of well data to provide ages or borehole correlations for these units highlights the need for scientific drilling in this region.

Seismic reflection data around the NSEA-14A site (Figure 2) also imaged tunnel valleys not previously mapped in detail, and provides clear evidence of cross-cutting tunnel valleys previously described by Stewart et al. (2013).

At sites NSEA-09B, 10A and 11B, the BGS 2D seismic lines revealed tunnel valleys in close proximity at and near sea bed (Figure 4). The age relationships between these features remain uncertain – in the current stratigraphy they are considered to be related to the last glacial maximum (Stoker et al., 2011). This raises questions from a depositional process point of view regarding why some tunnel valleys were filled and others are open.

3 Deeper Seismic Interpretation

The interpretation of the deeper part of the succession investigated was undertaken using Petrel software. Initial interpretation of fine-scale seismic packages and first-pass sequence stratigraphic interpretation of three selected lines was undertaken on paper records and digitised in the graphic design software package CorelDraw.

3.1 AVAILABLE DATA AND ITS ORIGINS

For the interpretation of the Mid Eocene-Quaternary section, the project had access to a large volume of data covering the central and northern North Sea area. Both 2D and 3D seismic reflection data were available, alongside a number of hydrocarbon exploration and production wells. However, due to time constraints, the volume of 3D data and identified miss-ties between 2D and 3D datasets, it was agreed that the focus of the deeper seismic interpretation should be on seismic lines from the regional CNST82RE 2D survey and the Statoil NSR05-statoil-st501 line ('crooked line').

The vast majority of the data were contained within a large project file derived from a Geographix interpretation project. These data included seismic reflection SEG-Y files, well headers and traces, geophysical well logs, well tops and velocity data (Table 3). There were also some existing seismic 'picks' that provided a useful framework from which to extend the current interpretation.

There were 426 wells loaded to the project, including 261 wells from the Norwegian sector. Of the wells available, 84 had no depth values, only coordinates and 50 wells were loaded in Two Way Travel Time (TWTT), mostly located in UK quadrants 15 and 16 and Norwegian quadrants 15, 16 and 17. UK-sector wells were most likely to have been acquired as released wells. The origin of Norwegian sector well data is unknown, although is most likely as a result of previous projects associated with the Sleipner facility.

Table 3: File origins for data used (excluding seismic data)

File Name	Created	Last Modified	Contents and Origin
TIME-DEPTH.xls	15/10/1996	16/08/2007	Created for Sleipner Project, it contains checkshot values for Norwegian and UK sector wells. Norwegian data most likely supplied by Statoil in 1996. UK data origin unknown (likely from old Wellog data). Also a global velocity curve has been calculated using the checkshot values.
Time Depth Pairs from Query3.xls	24/02/2014	29/04/2014	One-way travel time (OWTT) and two-way travel time (TWTT) values for Formation Tops in wells across the CNS and NNS, 9934 formation tops recorded (including sea bed). Recent nomenclature has been assigned to old wells in column 'LithoStratUpper_NEW' by Sam Holloway. Values (TWTT and Formation Tops) derived from composite logs with both marked on. File created from a DTI Access database.
cut down time depth pairs fewer columns.xls	24/02/2014	27/05/2014	As above but with 2 fewer columns and empty rows separating each well entry. Wells with only one time-depth pair for an unknown formation top (no nomenclature) have been removed.
Sleipner_SACS2.pet	13/08/2007	13/11/2014	Master project with large volumes of data loaded over the CNS/NNS in UK and Norwegian sectors (wells, seismic, checkshots, formation tops). Probably created by importing a Geographix Sleipner Project into Petrel. Contains all 2D surveys of use and 3D Mega merge. Also contains several interpretations of 2D lines by D Evans (from Feb-May 2014).
Utsira_Picks	--	13/11/2014	Picks of the Top and Base Utsira Sand, most likely from Sleipner Geographix Project. Points converted to lines (surfaces) and exported.

3.2 DATA QUALITY

3.2.1 Seismic Reflection Data

The quality of the seismic reflection data available was taken into consideration. Ideally, a good quality seismic line would be processed to a useful depth, eliminating as many sea floor multiples as possible whilst retaining the shallower events. Furthermore, as this study is being undertaken across the width of the North Sea, it should have been shot and recorded at a suitable station spacing to image medium- to large-scale features (kilometres to tens of kilometres) on a regional scale. A summary of the available seismic reflection surveys is provided in Table 4. As can be seen (Table 4), the CNST82RE 2D survey and the Statoil NSR05-statoil-st501 lines have Common Depth Point (CDP) spacing of 12.5 m which is most suitable for the purposes of this project.

Table 4: Available seismic reflection data

Survey	Type	CDP spacing (m)	No. Lines/Cubes	Comments
CNST82	2D survey	12.5	22 Lines	Survey over the Central North Sea
NNST84	2D survey	25.0	18 Lines	Survey over the Northern North Sea
NVGT88	2D survey	12.5	24 Lines	Survey over the North Viking Graben (Norwegian Sector)
VGST89	2D survey	12.5	9 Lines (17 sections)	Survey over the Viking Graben
CNST86	2D survey	25.0	26 Lines (95 sections)	Survey over the Central North Sea (most coverage in UK sector). Formed of many short 2D sections of line.
NSR05	2D survey	12.5	1 Line	Statoil line across the Central North Sea. Cropped to 2000 ms TWTT. Also known as the ‘crooked line’
PGS MEGA SURVEY	3D survey compilation	12.5	28 Cubes	Coverage over the UK sector of the Central North Sea

3.2.2 Geophysical Well Log Quality

There were a number of wells with loaded geophysical logs in Petrel. The geophysical logs used were compared to the composite logs to verify the curves, namely the gamma ray and sonic curves. Some of the logs were run over sections of the well with casing and casing shoes set within the zones of interest. These may be from surface to a certain depth or sections set in deeper parts of the borehole that may have been prone to breakouts or deterioration and they disrupt the geophysical logging. They are generally recognised by subdued log responses or straight line gaps between two logging runs. Due to the straight line nature of the geophysical log curves especially in casing shoes, they were easily recognisable, verified by cross-referencing the composite log with the disrupted sections of the geophysical logs and consciously omitted.

3.3 SELECTED DATA

The seismic survey which showed the greatest regional coverage whilst also comprising whole lines, rather than numerous segments was the regional CNST82RE survey. The CNST82RE survey is used because it has fair to good quality data across the area of interest and E-W lines run close to parallel to the Statoil NSR05-Statoil-st501 (‘crooked line’) line. The previous interpretations are also a good starting point from which interpretations could be extended with a good degree of confidence into the rest of the regional survey. The 3D cubes were tested but due to their limited regional extent (per cube) and identified miss-ties between 2D and 3D data, producing several regional 2D interpretations across multiple seismic cubes would have been impractical in the given time of the project. Surveys NNST84 and NVGT88 were considered to cover areas too far to the north, VGST89 is not of regional extent as well as being split into multiple sections for one line. CNST86 covers mainly the UK sector with a few more regional lines but some lines are also cut into much smaller segments (kilometres scale), which is unusable for a regional interpretation. To make the short lines more useful, they would have had to have been merged, which wasn't deemed necessary as the CNST82RE was already seen as suitable for a regional interpretation.

The well data loaded into Petrel, are from vertical or near vertical hydrocarbon exploration, appraisal and production wells, the majority have gamma ray and sonic logs. Using, if available, velocity data (e.g. time-depth pairs - see section 3.5.2), enabled some of the wells to be displayed in TWTT. However, the majority of the wells were not converted into TWTT because many were outside of the area of interest (Quadrants 15-16 and Norwegian Quadrants N 15, 16, 17). Where possible, composite logs were also used to verify the geophysical well logs, although much of the Eocene and younger units, particularly in the Quaternary were not well subdivided or absent.

In addition, the CNST82RE line 04 contains a 20 kilometre section where the navigation data was disrupted; there was also a similar smaller 2.3 kilometre zone of distortion on line CNST82RE-05.

3.4 INTERPRETATION METHOD

The CNST82RE-04 line was interpreted by Drs G Kirby and S Holloway in 2003 for the CO_2 NGCAS (Next Generation Capture and Storage Project) as it is in the vicinity of the Forties structure (20 kilometres to the north) and used to model migration of CO_2 injected into the Forties Sandstone in 2D. This interpretation provided a useful guide and starting point for interpretation of the remainder of the CNST82RE survey, although the ages of the strata representing the shallower reflections have subsequently been revised.

There was a slight (1-2 wavelets) discrepancy between the seismic reflection data and the corresponding geological logs and interpreted formation tops in the well data. This could be due to a number of reasons, e.g. inaccuracies in the velocity data, or the borehole being offline. Therefore, when interpreting the seismic data, the loaded formation top data was used as a guide rather than as rigid tie-in points.

The interpretation was initially undertaken for the major reflection events in the shallower sections, including the Mid Quaternary down to, roughly, the Oligocene section. However, after starting the interpretation it was agreed to divide the activity into a shallower and deeper interpretation, appropriate to the fields of expertise and experience of the interpreters. For the 'deeper seismic' interpretation, and the window of interest shifted to deeper strata, including any major reflection events from the Top Utsira Sand (or equivalent) down to the Top Balder Formation (or equivalent) (Figure 5).

The general interpretation workflow steps were to identify any major horizons, using the loaded formation tops as a guide, and extrapolating them across several lines: both East-West and North-South. Once these packages had been identified then the interpretation was further refined, highlighting more discrete events or sequences. Using published literature and the formation top information, these units were assigned possible ages or to lithostratigraphical units (e.g. Top Horda Unit, Top Mid-Miocene Unconformity) and described by their seismic reflection character. What these minor events or internal boundaries correspond to, on a local regional or global scale, has not been investigated in this study.

3.5 RESULTS

3.5.1 The Interpretation

Several of the surfaces (reflections) were interpreted over the majority of the survey and some of the more subtle boundaries were also interpreted over a large area. However, the majority of the more subtle boundaries and packages were interpreted only in detail on three of the regional lines (CNST82RE- 04, 05 and 06). A summary of the interpretation is given in Table 5.

Table 5: Selected interpreted horizons and their areal extent

Survey	Interpretation Extent	Lines Interpreted	Comments
Top 'Chaotic' Zone	Regional	6	Quaternary feature
Top and Base Utsira Sands	Regional	7	
Mid Miocene Unconformity	Regional	13	Unconformity is very subtle in places
Near Top Polygonal Faulting	Regional	6	
Top Intra-Eocene 'Quiet' Zone	Regional	13	
Eocene Prograding surfaces	Local	4	Complicated prograding sequence
Internal Eocene Intra-'Quiet' Surface	Local	4	
Top Horda 'Noisy' Zone	Regional	13	Possibly Top Horda Formation
Top Balder Formation	Regional	16	Base of interpretation

During the earlier phases of the interpretation, horizons subsequently incorporated in the 'shallower seismic' interpretation (Section 2) were included; Figure 5a shows an interpretation including the shallower features. Of note is the aerially restricted Chaotic Zone within what is now classified as the Quaternary succession. This sedimentary package was mappable on a number of lines and shows some features which could be interpreted as shelf channel erosion and basin floor deposition. After initial interpretation, the shallower part of the sequence was reassigned (Section 2). Interpretation then highlighted units at greater depth, initially, the strongest reflectors were picked, subsequently, any interior reflectors or minor packages were identified. The stratigraphical intervals that are the focus of the interpretation are:

- The Base Utsira to Mid Miocene Unconformity (MMU)
- The MMU to the Top Eocene
- The Mid Eocene prograding units and basin interactions

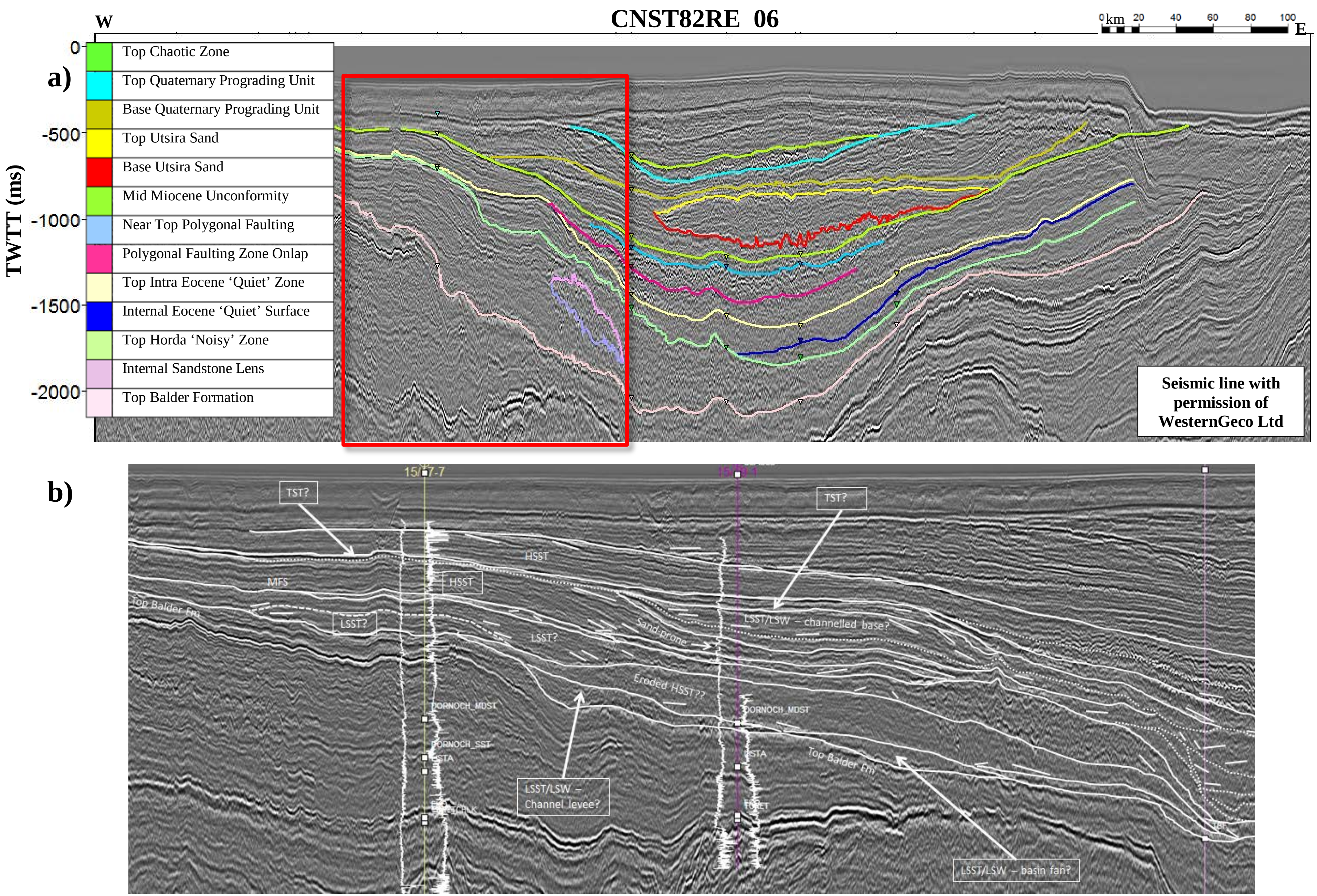
A preliminary sequence stratigraphic interpretation of the western part of seismic line CNST82RE-06 (inset in Figure 5a) from CDP 4397 to 8198 was undertaken, as much as could be achieved within project resources. The interpretation (Figure 5b) sets the sequence stratigraphic and depositional framework for scientific drilling sites within the UK sector of the North Sea and the method followed and terminology used is that of Vail (1987) and was applied to the horizons identified in Table 5. The preliminary sequence stratigraphic interpretation is not constrained by palaeontological data, and data from wells 15/17-7 and 15/19-1 was used as a guide rather than certain formation boundaries. CNST82RE-06 (inset in Figure 5a) from CDP 4397 to 8198 was undertaken, as much as could be achieved within project resources. The interpretation (Figure 5b) sets the sequence stratigraphic and depositional framework for scientific drilling sites within the UK sector of the North Sea and the method followed and terminology used is that of Vail (1987) and was applied to the horizons identified in Table 5. The preliminary sequence stratigraphic interpretation is not constrained by palaeontological data, and

data from wells 15/17-7 and 15/19-1 was used as a guide rather than certain formation boundaries.

Figure 5: Interpretations of line CNST82RE 06 on different scales (on following page)
a) Interpretation including major horizons from Top Balder to recent. Vertical exaggeration x50. Red box highlights Figure b.
b) Fine-scale interpretation of south-easterly prograding Eocene sediments with possible system tracts annotated. Vertical exaggeration x15. (wells 15/17-7 (left) and 15/19-1 (right) gamma and sonic curves displayed)

Seismic line with permission of WesternGeco Ltd

Annotations follow terminology of Vail (1987): Highstand Systems Tract, HSST; Lowstand Systems Tract, LSST; Lowstand Wedge, LSW; Marine Flooding Surface, MFS; Transgressive Systems Tract, TST.


a)
W
CNST82RE 06
0 km 20 40 60 80 100
E
TWTT (ms)
0
-500
-1000
-1500
-2000
Top Chaotic Zone
Top Quaternary Prograding Unit
Base Quaternary Prograding Unit
Top Utsira Sand
Base Utsira Sand
Mid Miocene Unconformity
Near Top Polygonal Faulting
Polygonal Faulting Zone Onlap
Top Intra Eocene 'Quiet' Zone
Internal Eocene 'Quiet' Surface
Top Horda 'Noisy' Zone
Internal Sandstone Lens
Top Balder Formation
Seismic line with permission of WesternGeco Ltd
b)
15/17-7
TST?
TST?
HSST
MFS
HSST
Top Balder Fm
LSST?
LSST?
Sand prone
LSST/LSW – channelled base?
Eroded HSST??
DORNOCH_MDST
DORNOCH_SST
DORNOCH_MDST
LSST/LSW – Channel levee?
Top Balder Fm
LSST/LSW – basin fan?

The same prograding units were reviewed by all ‘deeper seismic’ interpreters to determine confidence in the pick and to assess against possible noise in the 2D seismic reflection data. As a result, more likely or more ‘real’ events were chosen for further work. Some of the more obvious horizons were mapped over a larger regional scale, whereas interpretation of the finer-scale, lower-order boundaries was restricted for the most part to lines 04, 05 and 06 (Figure 5b). The restriction to three lines is to allow for an interpretation which would highlight the complexity of the sedimentation and lateral continuity of sequences that may be encountered in any appraisal of a storage site.

3.5.2 Velocity Analyses

Velocity data from previously compiled spreadsheets (Table 3 and Section 3.1) and well checkshot files for 13 wells in close proximity to the regional lines was interpreted and plotted to create a ‘regional’ velocity curve (Figure 6). The interpretation and subsequent maps (Figure 7) were all produced in the time domain, however, the depth conversion was not completed so all work has remained in TWTT.

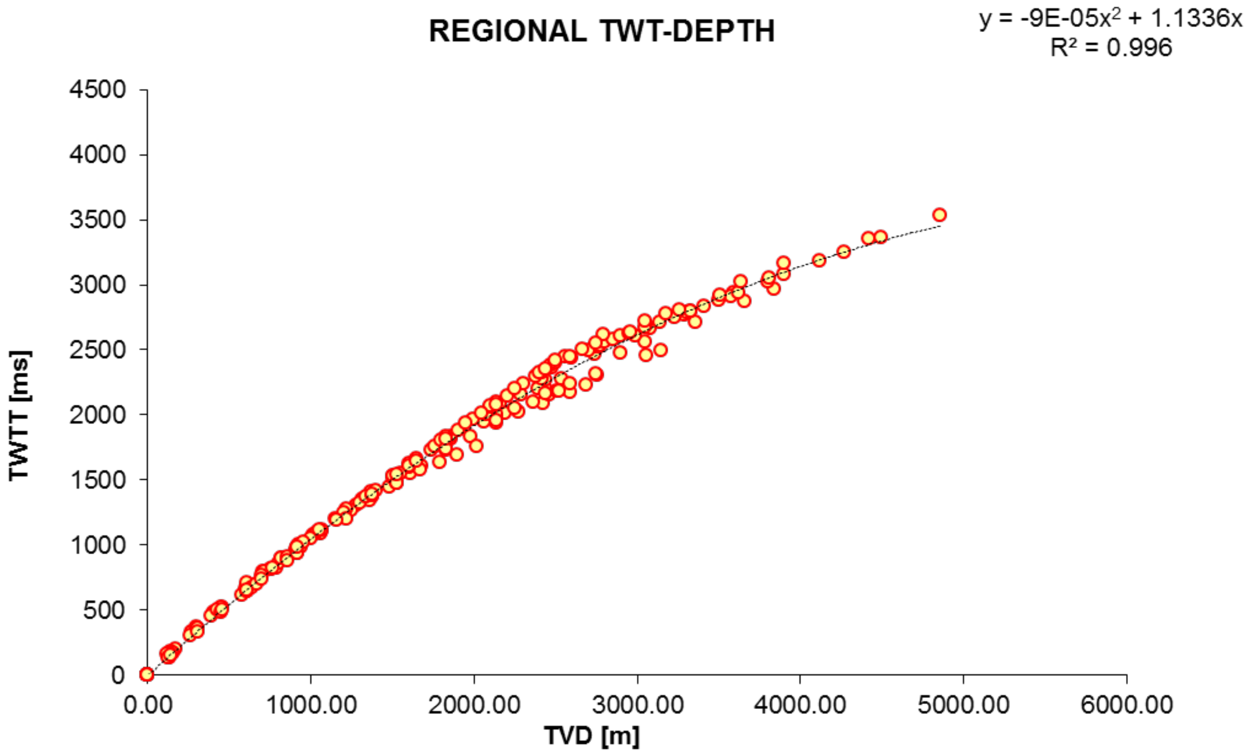


Figure 6: A velocity curve calculated from Two Way Travel Time (ms) and True Vertical Depth (m) for selected wells in close proximity to the CNST82RE lines interpreted

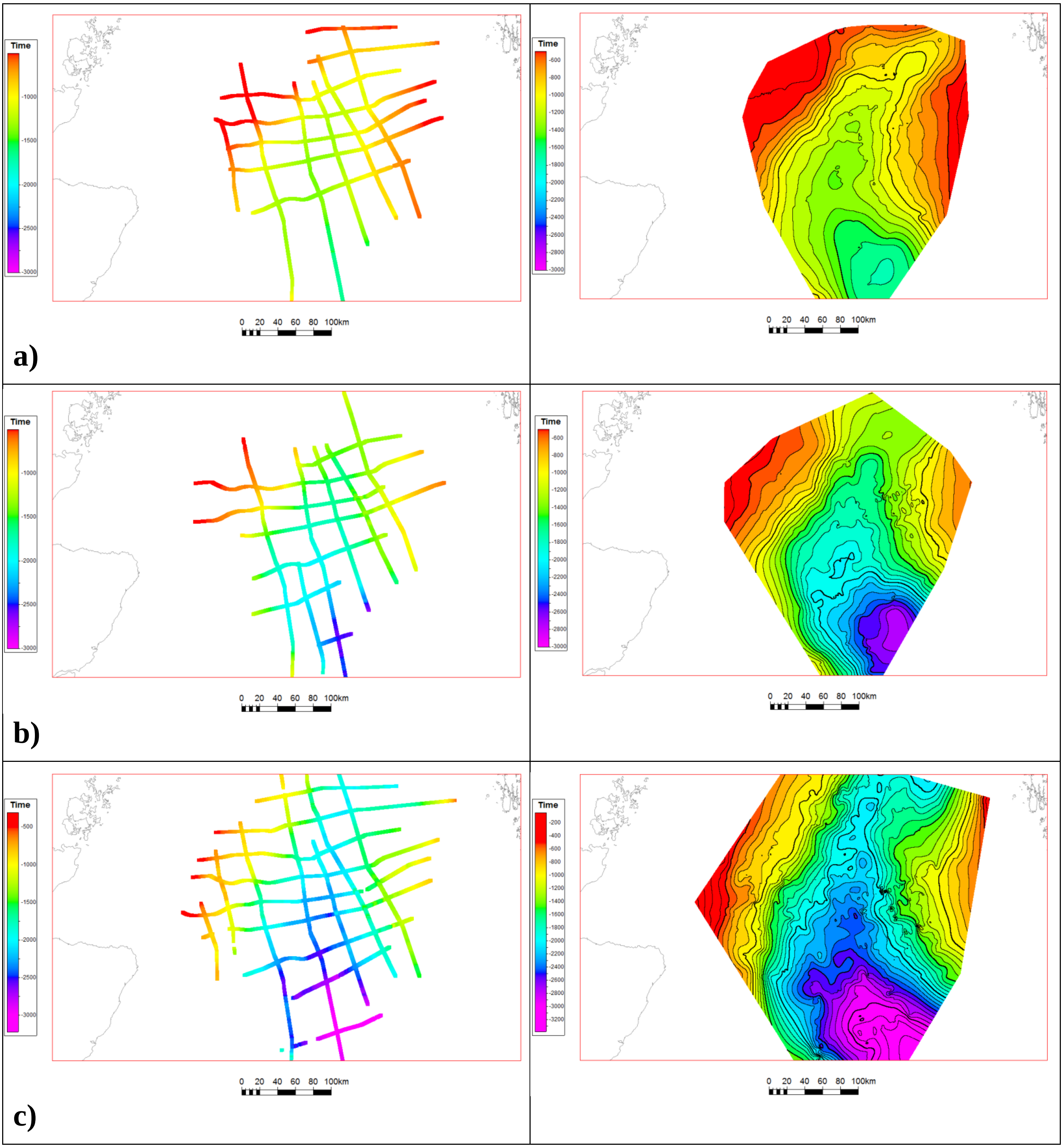


Figure 7: Regional interpretations and subsequent surfaces of three horizons. a) Near Mid-Miocene Unconformity. b) Top intra-Horda 'quiet' zone. c). Top Balder Formation. Maps are in Two Way Travel Time (ms) and provide a surface based on a widely spaced interpretation

4 Interesting Features/Further Work

4.1 THE QUATERNARY 'CHAOTIC ZONE'

In the early interpretations before the two 'shallower' and 'deeper' seismic working groups were defined, the chaotic zone was interpreted and presented to GlaciStore consortium members. As a result of a brief (due to time constraints) literature search it appears that this zone hadn't been noted before. The 'chaotic zone', as the name suggests is a seismic package of discontinuous and variable amplitude reflections developed above the basinward toe region of a large prograding unit. What this unit represents needs more investigation, but it potentially shows shelf erosion and basin deposition in mass flow events as basin-centre fill. It may have already been interpreted and reported previously, so a more substantial literature search would be required.

4.2 INTERPRETING THE EOCENE EVENTS

Further work could be carried out on interpreting the eastward prograding units within the Horda Formation in the UK sector. Mapping these features in 3D seismic volumes and their correlation with relevant well data would provide a better understanding of the type of system tracts observed (highstand, lowstand etc), and potentially with a good interpretation the different phases of deposition and flooding, could be correlated with both global sea level change and Shetland Platform uplift events. Understanding these events and subsequent deposits could be useful for characterising the overburden both for sealing lithologies and for potential deeper porous sandstone bodies for CCS storage sites. Perhaps also some of the parasequences identified within the Horda Formation could be targeted as storage sites (e.g. as secondary targets) or as important potential migration pathways.

4.3 THE GRID SANDSTONES

The Grid Sandstones (Horda Formation) are Mid Eocene to Early Oligocene sandstones, described in Knox and Holloway (1992) as submarine fan deposits in the lower part and dominantly shelf deposits in the upper part, consisting of fine to medium grained sandstones with a 'blocky' wireline log signature. These sandstones seem to occur towards the basin centre (eastern margin of the prograding units), clearly visible in the geophysical well logs and seismically definable within the mudstones of the basin centre Horda Formation. However, after a literature search, they seem to be poorly mapped. Further work may find and map these features in 3D seismic, following a similar methodology to that outlined in Kilhams et al. (2011), who successfully mapped a similar older feature in the Tay Sandstone in close proximity to the Forties field (further south than the area of interest for this study). Defining these features could be useful in assessing primary or secondary storage sites which, if not considered for storage, could provide migration pathways within the overburden from any deeper storage sites.

4.4 MAPPING TUNNEL VALLEYS

There is scope for further systematic mapping of buried tunnel valleys within the areas surrounding the potential IODP sites using the PGS 3D seismic data. Cross-cutting between tunnel valleys is apparent and it should be possible to map out the tunnel valleys and their overprinting in a way similar to that described in Stewart and Lonergan (2011).

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