Peterhead CCS Project

Doc Title: Seismic Interpretation Report

Doc No.: **PCCS-05-PT-ZG-0580-00002**

Date of issue: **22/05/2015**

Revision: **K03**

DECC Ref: **11.106**

Knowledge Cat: **KKD - Subsurface**

KEYWORDS

Goldeneye, CO_2, Captain Sandstone, Overburden, Aquifer, Seismic, Interpretation, Processing, Depth Conversion.

Produced by Shell U.K. Limited

ECCN: EAR 99 Deminimus

IMPORTANT NOTICE

Information provided further to UK CCS Commercialisation Programme (the **Competition**)

The information set out herein (the **Information**) has been prepared by Shell U.K. Limited and its sub-contractors (the **Consortium**) solely for the Department for Energy and Climate Change in connection with the Competition. The Information does not amount to advice on CCS technology or any CCS engineering, commercial, financial, regulatory, legal or other solutions on which any reliance should be placed. Accordingly, no member of the Consortium makes (and the UK Government does not make) any representation, warranty or undertaking, express or implied as to the accuracy, adequacy or completeness of any of the Information and no reliance may be placed on the Information. In so far as permitted by law, no member of the Consortium or any company in the same group as any member of the Consortium or their respective officers, employees or agents accepts (and the UK Government does not accept) any responsibility or liability of any kind, whether for negligence or any other reason, for any damage or loss arising from any use of or any reliance placed on the Information or any subsequent communication of the Information. Each person to whom the Information is made available must make their own independent assessment of the Information after making such investigation and taking professional technical, engineering, commercial, regulatory, financial, legal or other advice, as they deem necessary.

Table of Contents

List of Tables

List of Figures

Executive Summary

This report documents the geophysical work carried out to characterise the Goldeneye CCS (Carbon Capture and Storage) storage complex in support of assessing the storage capacity of the reservoir and the identification of any potential leak paths to the surface. The work is based on the most recent seismic survey covering the Goldeneye field area, the East Ettrick Survey, which was acquired in 1997 and reprocessed in 2001 as Pre Stack Depth Migration (PreSDM) to improve the imaging of the subsurface. The report explains the rationale for the identification and interpretation of key seismic events (horizons) and discontinuities (faults) from the sea floor to, at depth, Upper Jurassic rocks.

Twenty horizons were interpreted across the PreSDM seismic volume including the top reservoir, termed the Top Captain Sandstone. As the interpretation was carried out in the time domain, conversion to depth was then performed using a 7-layer velocity model. The result showed the reservoir to be a domal structure whose internal layers pinch out northwards against a structural high. The overlying seal, composed of the Upper Valhall and Rødby Shales and the Lower Chalk, follows the same domal structure and is mapped as continuous across and beyond the reservoir extent. Successively shallower intervals include both secondary seals (the Lista and Dornoch Mudstones) and secondary storage horizons (the Upper Chalk, Mey/Balmoral and Dornoch Sandstones): they are gently tilted, shallowing to the north and the west.

Faults have been interpreted with three main focuses. Below the Captain reservoir, predominantly E-W faults at the Base Cretaceous Unconformity helped define the field geometry. At the level of the reservoir and its immediate seal faults were assessed for reservoir compartmentalisation and seal continuity: they are again E-W, discontinuous, and with offsets significantly less than the reservoir or the seal thickness. Above the reservoir and seal, faults were assessed for possible linkages to the surface. NW-SE faults are seen in the Chalk and rarely in the Mey sandstones. These faults are not connected to those at reservoir level and do not extend to the shallower layers.

Particular attention was paid to acoustically-significant features in the overburden above the Goldeneye reservoir. These features complicate interpretation at depth: seafloor pockmarks, subglacial channels, palaeo-seafloor piercements and coals. These cause local artefacts in the seismic data such as striping and apparent faulting, and were carefully assessed by proprietary high-definition reprocessing ("HiDef") of the seismic volume. This allowed improved separation of artefact from true signal and confirmed that there were no through-going fault or fluid escape structures in the area.

The regional Captain Sandstone aquifer was also mapped for some 180 miles east-west across four adjacent seismic datasets including the Goldeneye PreSDM volume. Four geological horizons were interpreted: the top Rødby (seal), top and base Captain Sandstone and the base Cretaceous. The regional depth conversion was carried out using a single velocity layer to top Chalk and well-derived average velocity maps to top and base reservoir. The aquifer is characterised as a long E-W trending ribbon that shallows progressively eastwards.

The seismic interpretation summarised above provides evidence that there are no features indicating leakage from the reservoir and no features that could be considered likely to impair the ability to store CO_2 in Goldeneye. The seismic horizons and faults have been used as input data to create three static model suites covering the Goldeneye Field itself, the overburden above the Goldeneye Field, and the regional aquifer of the Captain Sandstone. These suites are described in the document KKD 11.108 "Peterhead CCS Project Static Model Reports". They were used as the input to dynamic and geomechanical models that were needed to further assess the storage and containment capacity of the complex, the repressurisation behaviour of the Captain Aquifer and possible interactions with other users of the Captain Sandstone.

1. Introduction

This report forms part of the subsurface documentation in support of the Peterhead CCS Project. It compiles the geophysical data, methods and interpretation results which were used to create the framework for static and dynamic models of the Goldeneye field, the overburden and the regional aquifer, and for geomechanical modelling. The geophysical data is largely based on wells and seismic surveys which were acquired during the exploration and development phases of the Goldeneye field and of the broader Captain Sandstone Fairway.

The report summarises the regional geological setting, followed by a review of the data available for the work. The data processing is then addressed, followed by the successive steps involved in seismic interpretation to arrive at a valid horizon-fault framework in depth. This includes description of each horizon addressed. Special attention is paid to overburden features that produce artefacts on underlying layers and the use of high-definition reprocessing to identify these. Finally, seismic interpretation of the regional Captain Sandstone aquifer is addressed.

The geophysical work for the Peterhead Project is specifically aimed at providing a structural framework – the geological horizons and faults – for the area. The data does not lend itself to the recognition of fluid contacts, static or dynamic reservoir properties, or the differentiation of depositional facies.

This report is an update of the previously-released geophysical evaluation report for the Longannet CCS project to incorporate work not available at that time: the use of a proprietary high-definition reprocessing step to assess overburden artefacts. The section on overburden artefacts has also been expanded to describe these issues more fully. Finally, the opportunity has been taken to correct minor inconsistencies where found.

2. Geological Setting and Data Availability

2.1. Regional Geology

The regional studies related to the Goldeneye accumulation encompass the Inner and Outer Moray Firth regions of the UKCS (United Kingdom Continental Shelf) Central North Sea. The area is dominated by the Halibut Horst, a feature that remained emergent throughout most of the Jurassic and Lower Cretaceous periods. The Goldeneye Field is situated south of the horst on the northern edge of the South Halibut Basin: the field is a gas condensate accumulation with a thin oil rim. The main reservoir is formed by the Early Cretaceous-aged Captain Sandstone Unit, a turbidite sandstone with good reservoir properties. Goldeneye was discovered in 1996 by Shell/Esso well 14/29a-3, which encountered a gas column of 92 m. In the following years three appraisal wells were drilled: 1998 Amerada 20/4b-6 (South), 1999 Shell/Esso 14/29a-5 (South-East) and 2000 Amerada 20/4b-7 (South-West). In 2004 five development wells were drilled (see Figure 6-4).

2.1.1. Geological Setting

The shelf edge depositional setting of the Lower Cretaceous (latest Aptian–earliest Albian) resulted in ribbon-like deposition of the Captain sands extending along the southern margins of the Halibut Horst (Blocks 13/23, 13/24, 13/29 and 13/30) and the South Halibut Shelf (Blocks 14/26, 14/27, 14/28, 14/29, 14/30, 15/26, 21/1). The deposition of the Captain sands continues along the southern margins of the Renee Ridge through the Glenn discovery and towards the Britannia Field area (Blocks 21/2, 21/3, 21/4 and 21/5) (Figure 2-1). The system is termed the "Captain Fairway".

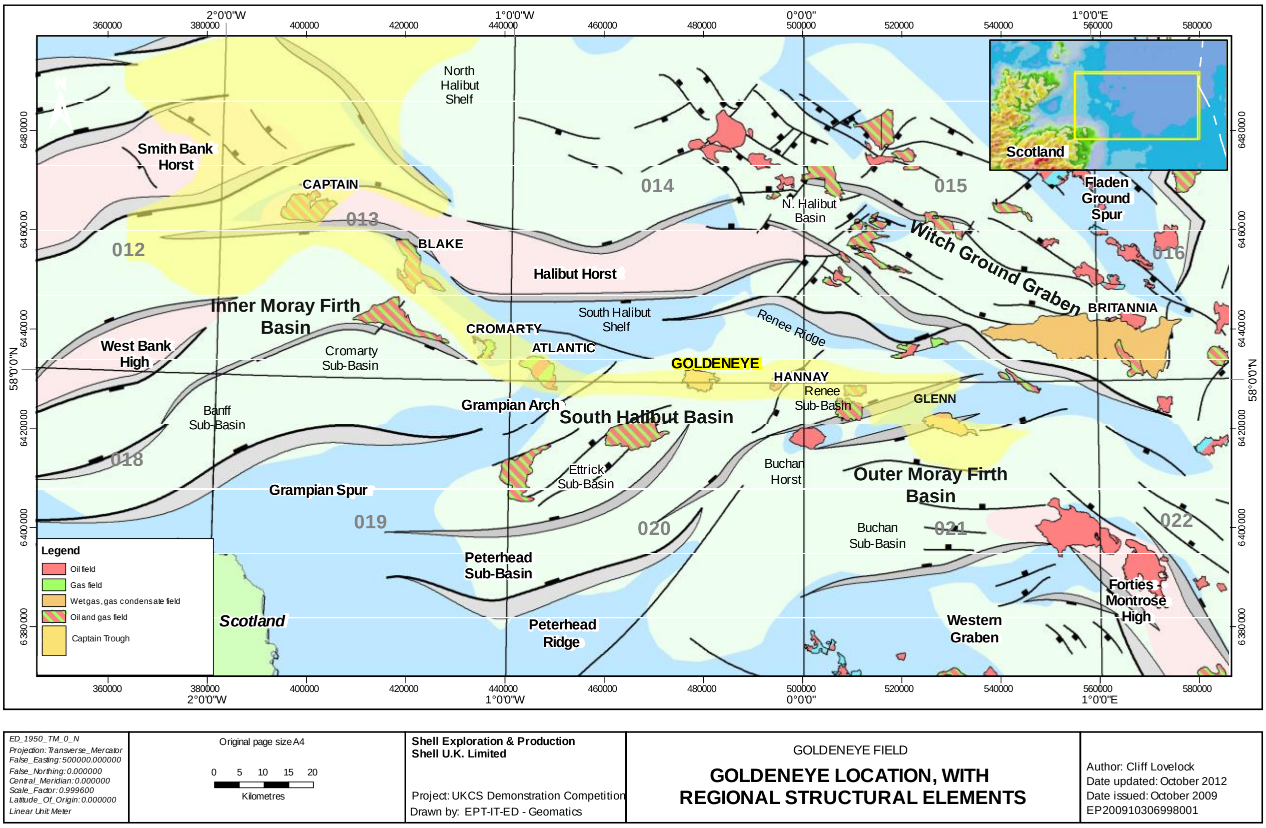

Figure 2-1: Distribution of Captain Sandstones across outer Moray Firth: Captain Fairway highlighted in yellow; basinal areas in pale green

2.1.2. Structural History

The Goldeneye Field is located at the confluence of an E-W (East-West) fault system defined by the Halibut Horst, and a SW-NE (Southwest – Northeast) system in the South Halibut Basin. The Captain fairway west of Goldeneye is also influenced by SW-NE faults of the Smith Bank Horst and Inner Moray Firth Basin and to the east by a NE-SE system related to the Witch Ground Graben (Figure 2-1).

Formation of the Moray Firth rift system began in the Permian and continued through to the Jurassic when the main features seen today became established. An unconformity at Base Jurassic heralded the initiation of tectonism whilst Late Jurassic (Late Cimmerian) rifting resulted in the development of a series of tilted fault blocks and associated half-grabens [1]. The imprint of older lineaments is apparent: the north-easterly orientation of the Inner Moray Firth and South Halibut Basins is mainly aligned to Caledonian basement faults whilst the east-west orientation of the Halibut Horst is attributed to alignment with Hercynian extensional trends [2].

A regional unconformity at Base Cretaceous is followed by early Cretaceous subsidence with minor compression, and Lower Cretaceous sediments passively infilled the pre-existing deep-water basin, on lapping the Jurassic against the main structural highs. There was also a fundamental change in the tectonic regime at Aptian-Albian level related to the Austrian tectonic event [3], which significantly is the period when the Captain sands were deposited. During this time there was a diminution of the influence of basin subsidence and the start of greater control on the basin form by a mild N-S compressive regime reactivating the Halibut Horst and other local structural highs. Post-rift basin infill continued with the Chalk which draped the residual Lower Cretaceous topography and onlapped across the Halibut Horst.

A major change in structural regime and sedimentation occurred in the Early Tertiary due to ca.1km of uplift of the Inner Moray Firth, Scottish Highlands and the East Shetland Platform areas resulting in a regional eastward tilting of the area, uplifting the Chalk and Lower Cretaceous to allow partial erosion and exposure at surface in the Inner Moray Firth. During this period large quantities of clastics were deposited in the Outer Moray Firth and Central Graben areas. There was also a continuation of the mild north-south compressive regime which warped the top chalk surface and funnelled the sands west-east through the basin.

2.1.3. Regional Stratigraphy

The regional stratigraphic column for the Outer Moray Firth is shown in Figure 2-2. At the top it is a Quaternary and Tertiary cover of interbedded sands, shales, claystones and lignites, broadly thickening towards the east. In the Quaternary, Pleistocene glacial channels of dominantly NW-SE orientation were cut across the sea floor and infilled with sediments of different acoustic properties that create artefacts in underlying layers. The upper Tertiary Nordland and Westray Groups are mud-dominated intervals whilst the lower Tertiary Moray and Montrose Groups are sandier with a large variability in sand/shale ratios. Sand appears more abundant towards the east. Coals are present in the Moray Group, which cause velocity anomalies and initiate artefacts into the underlying reflectors.

Rapid sedimentation in the Lower Tertiary resulted in elevated pore pressures and diapir-like palaeo-seafloor piercement features that terminate within the Tertiary section.

Below the Tertiary clastics is a chalk section of fairly uniform thickness: the Upper Cretaceous Chalk is the oldest formation to be deposited over the entire Halibut Horst. Prior to this the Halibut Horst area is believed to have been emergent. The Chalk itself has an irregular top surface due to later uplift and erosion.

Emergence and erosion of the Halibut Horst, and storage of resultant clastic sediments on both the north and south Halibut shelfal areas, is believed to have contributed significantly to turbidite deposition through the Lower Cretaceous and Jurassic in the Outer Moray Firth. This sand deposition took place in a punctuated way against a background deposition of hemipelagic shales, marls and occasional limestones in basins and sub-basins of variable thickness.

The Lower Cretaceous Captain Sandstones of Albian–Aptian age are generally more sand rich and massive than the underlying Ryazanian-Barremian sands. The latter appear (from log signatures and seismic expression) to be of more classical low density fan-type turbidites as opposed to the massive, blocky, sandy debrite/high density turbidites of the Captain Sandstones. A regional unconformity defines the base of Cretaceous sedimentation.

Good reservoir quality turbidite sands are also found within the Upper Jurassic Kimmeridge Clay Formation. Underlying the Kimmeridge Formation, Upper/Middle Jurassic paralic sediments were deposited (e.g. Heather/Pentland Formations) above the Base Jurassic unconformity.

Below the Jurassic section lie Triassic silts and shales of the Smith Bank Formation, the Permian Zechstein and Rotliegend Formations and the deeper sand rich clastics of Carboniferous and Devonian age. Below the Devonian sediments, basement granites are thought to form the core of the Halibut Horst.

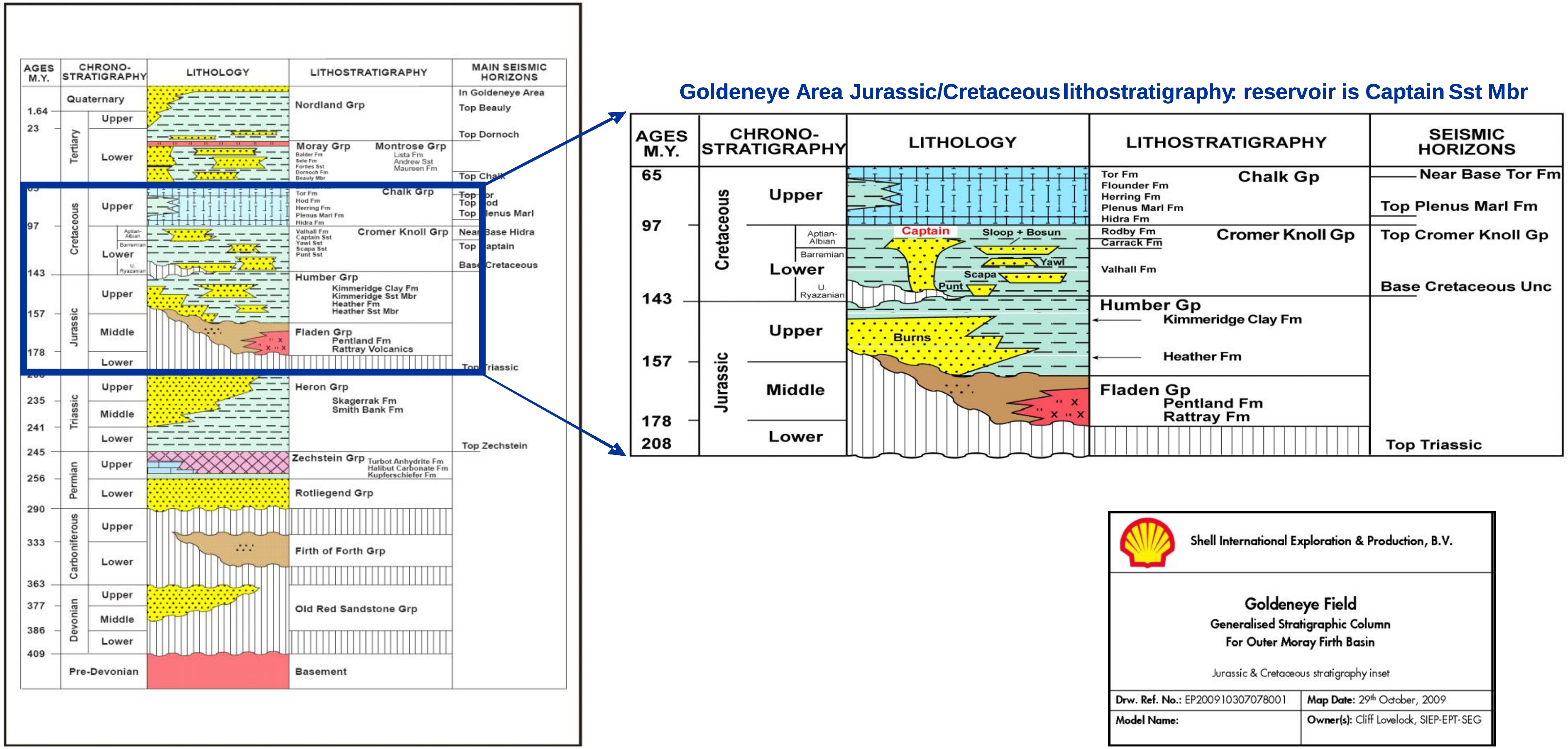

Figure 2-2: Generalised stratigraphy of the Goldeneye area

2.2. Charge History

Geochemical analysis of oil and gas samples from fields and accumulations along the Captain fairway lead to the interpretation of a multi-staged charge history for the Goldeneye structure (Figure 2-3).

- **Stage Ia**: A palaeo oil-water contact is recognised at 8385 ft (2555 m) TVDSS in well 14/29a-3, indicating that the Goldeneye structure was initially filled with oil. This oil charge, from a 'kitchen' between the Goldeneye and Ettrick fields, may have occurred as early as 120-80 Ma ago. The early charge preserved the original high permeability in the upper part of the reservoir.
- **Stage Ib**: Subsequent to this, oil charge continued from the deeper parts of the kitchens in the Ettrick Sub-basin, gradually filling the remaining column down to around 8780 ft (2676 m) TVDSS.
- **Stage IIa**: After the Goldeneye structure was completely filled with oil, it was tilted, resulting in a reduction of the vertical relief of the paleo-accumulation and allowing oil to spill. The most likely timing of that event is at the beginning of the Tertiary, around 60-55 Ma, when regional eastward tilting occurred and the basin deepened significantly.
- **Stage IIb**: As a result of the regional E-W tilting of the South Halibut Basin, which includes the Goldeneye structure, large amounts of gas were released from the deep Fisher Bank Basin kitchen in the east. The released gas then could enter and migrate through the eastward dipping Captain fairway. On its way through the Captain fairway, the gas flushed existing oil accumulations leaving completely gas filled structures in Glenn, Hoylake, Goldeneye and Cromarty. With flushing happening around 50-60 Ma, most of the flushed oil probably leaked to the surface and was lost from the system. Some of it may also have migrated into shallow traps, resulting in the shallow heavy oil accumulations which are known to exist in this area.

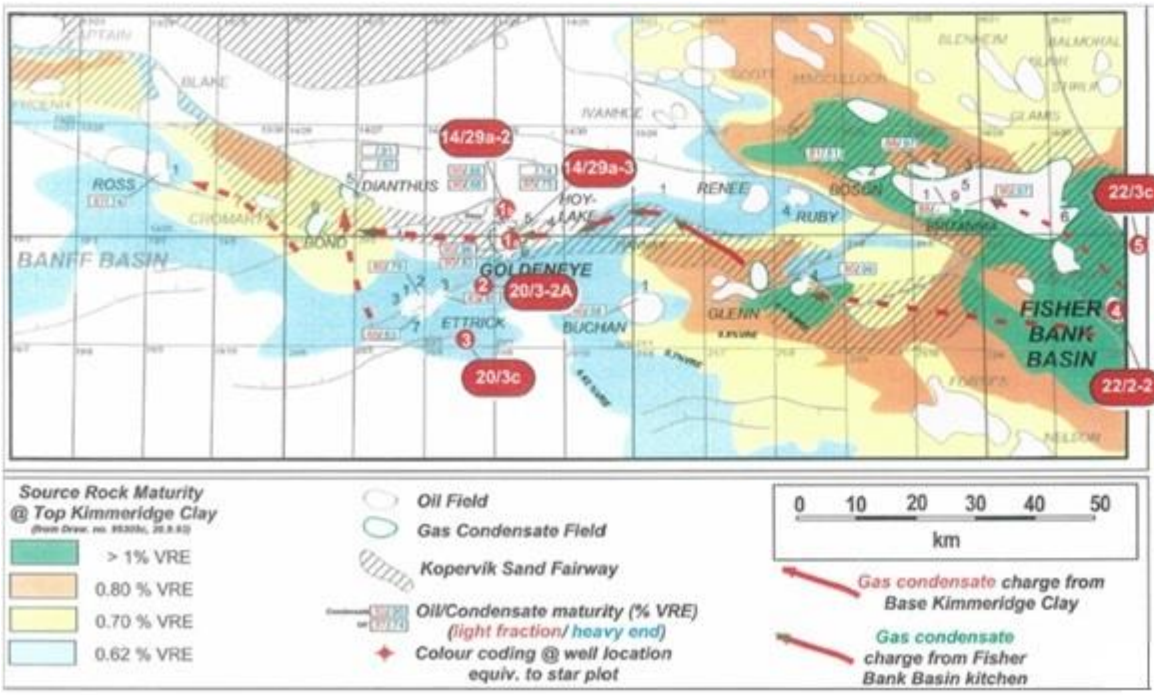

Figure 2-3 Hydrocarbon source areas for the Captain Fairway reservoirs

- **Stage IIIa**: Due to continuous and substantial burial during the Tertiary (thickness of Tertiary >4500 ft [1370 m]), pressure increased and gas was compressed. In this way, space in the trap was created for some oil to accumulate below the gas condensate column. If gas flushing from the Fisher Bank Basin had continued during this period, no additional trapping volume would have been preserved and we would not find an oil rim today. Thus, gas migration from the Fisher Bank Basin must have stopped almost completely soon after the oil was flushed out of the Goldeneye structure. Faulting in the Glenn area may have caused this.

- **Stage IIIb**: Due to the presence of shale barriers below the GOC, oil is not homogeneously distributed below the gas, but compartmentalised. In the north of the Goldeneye accumulation (l4/29a-3) where Captain sands scour directly into the Kimmeridge Clay, the local kitchen expels oil at very low maturity (<0.7%VR/E). In the south (20/4b-6), charge is mainly coming from the deeper and more mature kitchens of the Buchan and Ettrick area. In the east (14/29a-5) oil may have spilled directly from Hoylake. It is important to mention that maturity differences are limited to the heavy fraction (C30 range). The light ends of Goldeneye oil samples are relatively well mixed with the overlying gas phase, indicating that the oil and gas is in direct contact across the accumulation.

Geochemical analysis and basin modelling results imply therefore that the aquifer to the Goldeneye field is continuous in the east, all the way to a fault zone in the vicinity of the Glenn accumulation (UKCS Block 21/2). It is harder to estimate the extent of the western aquifer from the available geochemical data, but would appear to extend at least as far as the Atlantic field. From dynamic simulation and history match, as well as informal discussions with other operators in the area, it seems that there is continuous pressure communication from Goldeneye to beyond the Atlantic field – as far as the Blake field, across the Grampian Arch in UKCS Block 13/24.

3. Seismic Data Availability

Several seismic datasets were available that cover the South Halibut Trough, including 2D regional lines, the 1994 Greater Ettrick Regional 3D, the 1997 East Ettrick 3D, the 2001 Goldeneye PreSDM 3D and the 2001 Blake 3D (see Figure 3-1). The Goldeneye Field itself is covered by several vintages of 3D seismic (Figure 3-2). Shell acquired the Greater Ettrick Regional 3D Survey, a low-fold (20) quad-quad reconnaissance 3D survey in 1992, which was subsequently reprocessed in 1994. The Goldeneye discovery well 14/29a-3 was drilled on this dataset. Data quality is moderate to poor at target level. Following the discovery, a target oriented 230 km^2 high-fold (96) seismic dataset the East Ettrick 3D Survey was acquired in 1997 which was centred on the Goldeneye Field and covered parts of Blocks 14/28b, 14/29a, 14/30a,b,c, 20/3b, 20/4b and 20/5c. This 3D survey was used for the Field Development Planning for the Goldeneye Field.

Despite extensive efforts during the (re-)processing of the 1997 3D seismic data, seismic data quality still remained only moderate around the target level due to the laterally variable shallow coal layers. In order to address these data quality issues a full 3D Pre-Stack Depth Migration (PreSDM) was carried out in 2001. This PreSDM dataset provided significant improvements in reflector continuity and resolution, and in fault plane definition. The PreSDM seismic cube was used to identify the development well locations prior to the start of development drilling in 2003.

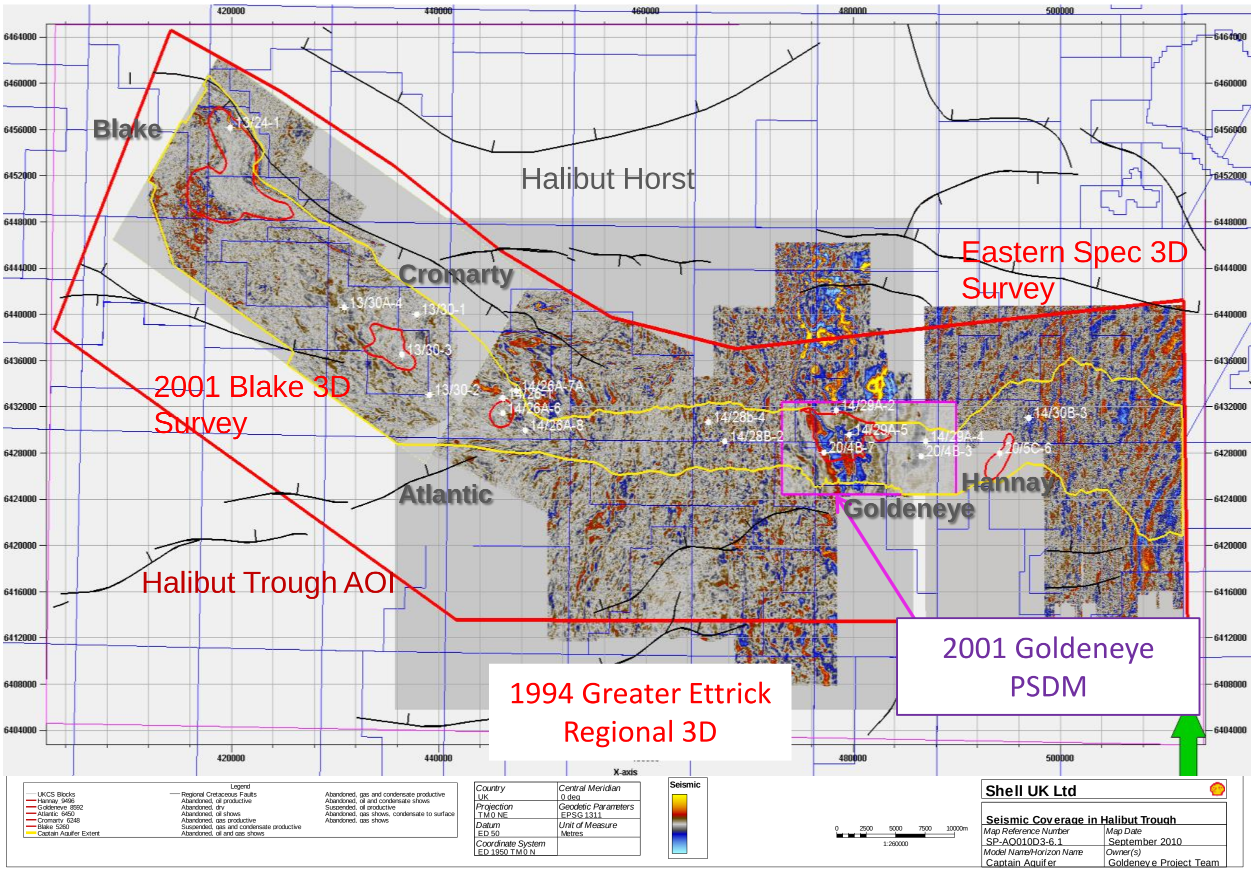

Figure 3-1: Regional seismic coverage in Halibut Trough

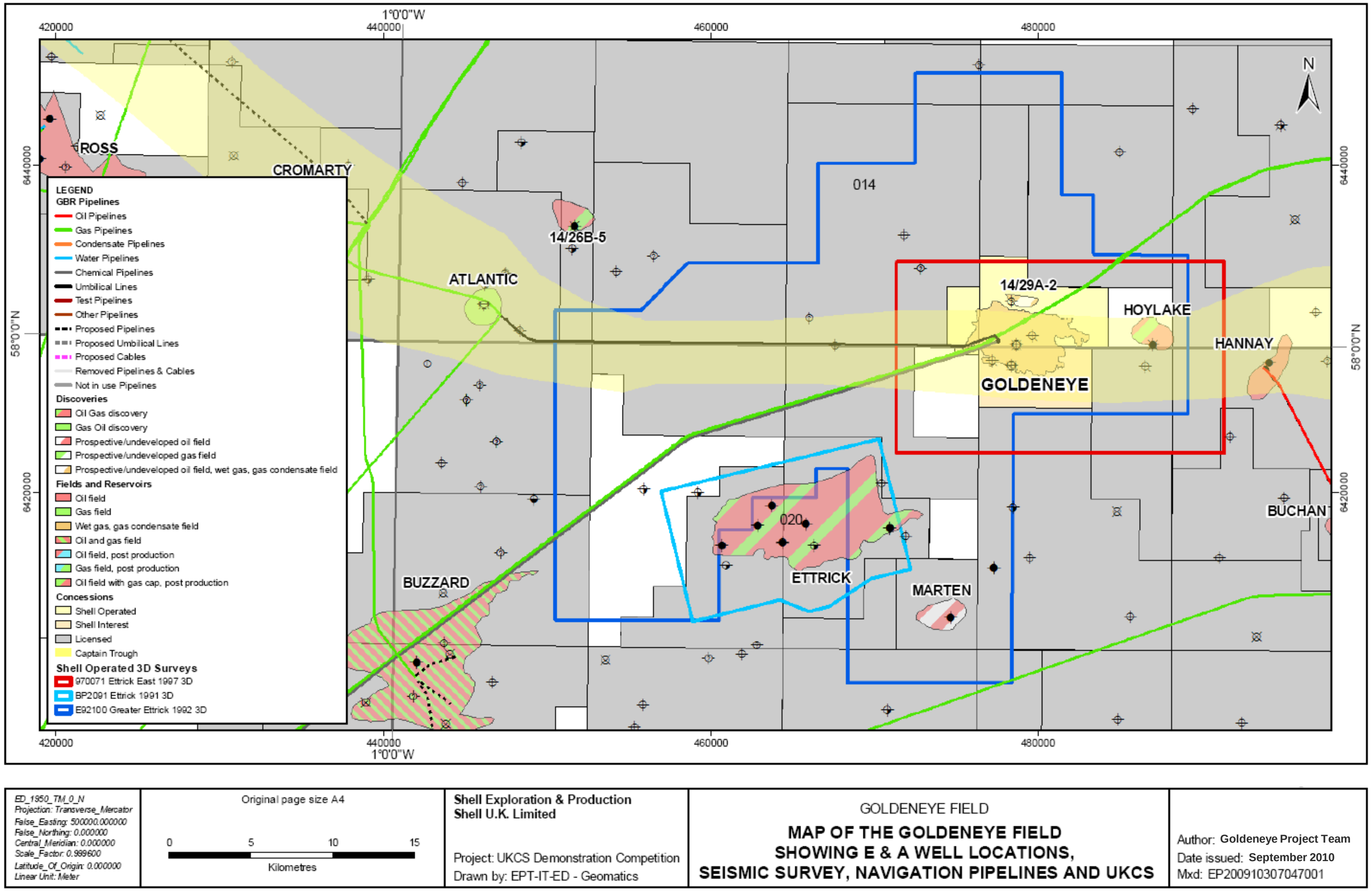

Figure 3-2: 3D seismic surveys available over the Goldeneye Field

Seismic interpretation of the Captain Sandstone is generally difficult due to problems in imaging the reservoir itself because of the poor impedance contrast at top reservoir between the Captain Sandstones and the overlying Rødby shales. The seismic image quality at reservoir level is also reduced due to the effect of the overlying lithology. The overburden includes glacial channels, stacked, laterally varying, low-velocity coal layers and a thick high-velocity Chalk section. The glacial channels and coal layers are responsible for buried statics (move-out distortion), and amplitude effects due to focussing of energy and absorption losses. The Chalk layer causes marked ray bending which is exacerbated by the high degree of rugosity exhibited by the Top Chalk. In addition, the seismic data are contaminated with water-bottom multiples and strong long-period multiples generated by the coal and chalk interfaces.

Figure 3-3 shows a regional seismic line running approximately west to east in the Outer Moray Firth (post-stack time migrated data). This regional line shows that data quality deteriorates below a single coal layer and that degradation is more severe below stacked coal layers. The number of coal layers above the Goldeneye Field varies from one to four. The regional line also shows an increase in the relief of the Top Chalk interface in the vicinity of the field. The Captain Sandstones dip about one to two degrees from West to East.

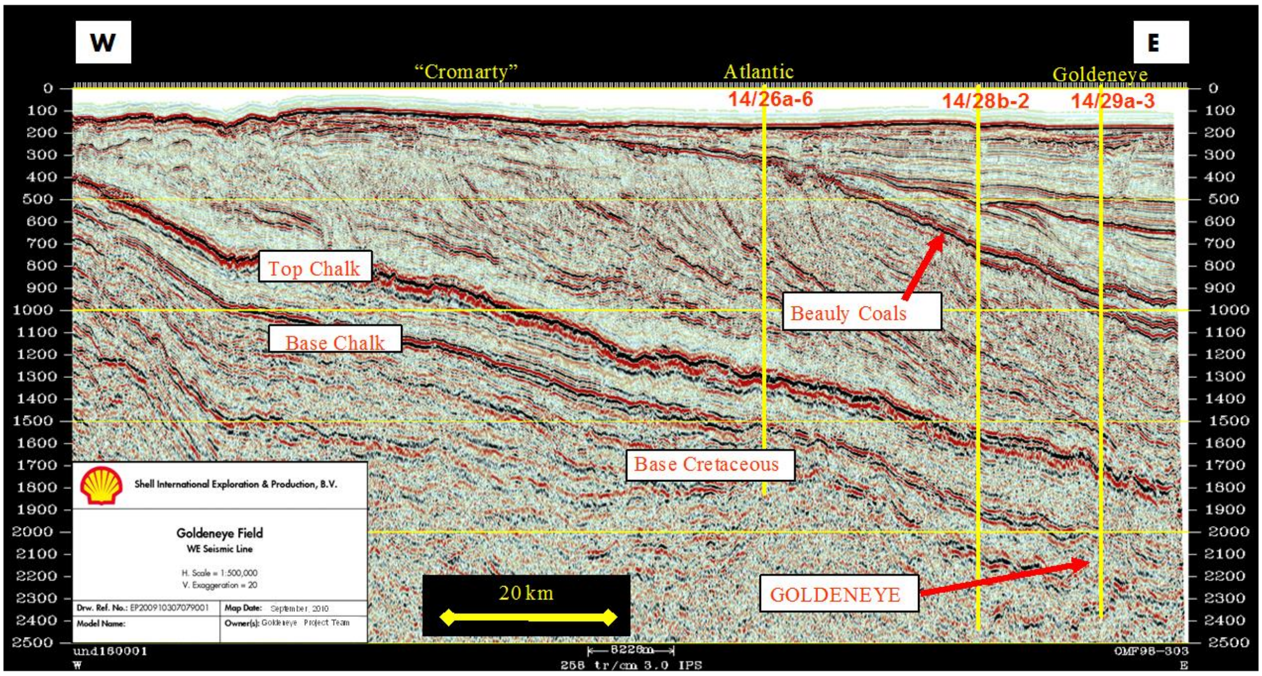

Figure 3-3: Regional W-E Seismic Line along Halibut Trough.

Note: *Display is in TWT (Two-Way Time). The Goldeneye Field is located to the right of the display at around 2100 ms (2530 m).*

The polarity convention for these seismic data is that a hard kick increase in acoustic impedance is displayed as a negative number, shown as a red loop in all displays and figures in this report.

4. Seismic Processing

The seismic processing applied to the two main seismic surveys (three seismic volumes) used in this study is detailed below. The Goldeneye Static Field Model and the Goldeneye Overburden Model were both constructed from interpretations based on the 2001 PreSDM seismic data, whilst the Aquifer Static Model was constructed from interpretations that also use the Blake and Eastern Spec surveys.

4.1. 1994 3D Greater Ettrick Regional Survey

A 20-fold 3D dataset was acquired in 1992 with a Quad/Quad set-up using 3 km streamers. The dataset was reprocessed in 1994. Data quality, temporal resolution and Signal-to-Noise ratio is poor at target level, and direct mapping of the top reservoir is difficult.

4.2. 1997 3D East Ettrick Survey

From July to September 1997 a target orientated 234km^2 3D seismic survey was acquired by Western Geophysical using one airgun source and six streamers. The survey was centred on the Goldeneye Field and covered parts of Blocks 14/28a, 14/28b, 14/29a, 14/30a, 14/30b, 14/30c, 20/3b, 20/4b and 20/5c. The Captain reservoir was not well-imaged by previous 2D and 3D seismic data, and so the survey acquisition parameters were designed to maximise resolution of the target interval between 2.0–2.5s TWT. Key acquisition parameters are given in Table 4-1 below.

Table 4-1: Acquisition Parameters

Acquisition Parameter	Data
Survey size (full-fold)	234 km^2
Streamer length	3600 m
Record length	6 s
Fold	96
Bin size	6.25 m x 18.75 m
Near offset	125 m
Sample interval	2 ms
Sail-line direction	E-W

Data processing was carried out in 1997 and 1998 by CGG, subsequently reprocessed by Veritas in 2000/2001 in preparation for PreSDM (Pre-stack depth migration, see next section). Processing parameters are summarised below:

- Reformat from SEGD to in house.
- Apply zero phase conversion filter (designed according to Shell method 3).
- Merge navigation and seismic.
- Spherical Divergence to be T squared.
- First break mute to be: Near offset 0.0 seconds, Far offset 3.1 seconds.
- Swell noise attenuation, 5 Hz 18 dB/Octave low cut filter, F/K filter ±12 ms per trace applied from 3.25 seconds (to be applied to all lines).
- Q compensation of 136 with reference frequency 175 Hz.
- K-filter with 0.33 Nyquist cut. AGC wrap.

- Tau-p de-convolution: Transform ± 750p's.
  Design: near offset 500-4100, far offset 700-4600 ms.

Mute:	Rayparm	Time Time, ms	Velocity, ms
	-750	2,000	1333
	-500	3,000	2000
	-200	6,000	5000
	200	6,000	5000
	500	3,000	2000
	750	2,000	1333

  Operator length 360ms + 60ms gap length.

- XT DBS: Design: Near offset 500 – 4500 ms, far offset 3500 – 5900 ms
  240 ms operator + 48 ms gap length.
- SCAC design windows to be near 1800-3800, far 3200-4500.
- SCAC 500 x 500 smoothing filter.
- Sort to 2D cdp gathers.
- NMO using smoothed 90% of velocity field (5 point spatial and temporal filter).
- AGC.
- Radon Demultiple: forward transform –800 to +1800 ms
  notch removed 0 to +1800 ms
- AGC removed.
- NMO removed.
- NMO using 100% of smoothed velocity field.
- AGC.
- Anti-alias K-filter.
- AGC removed.
- Drop alternate traces.
- Re-apply first break mute.
- Remove spherical divergence correction.

Additionally, Shell proprietary noise suppression software was applied (SOF-filtering) followed by spectral whitening. However, seismic data quality still remained only moderate around the target level. The reflectivity data was inverted to acoustic impedance to better understand the extent of the Captain sands and the distribution of reservoir parameters. This was a Jason model-driven constrained sparse-spike inversion. As the data quality did not allow simultaneous AVO inversion, a mid-angle stack was inverted to elastic impedance. Additionally, semblance volumes were created from all data sets to support the interpretation of faults and stratigraphic pinch-outs.

A number of projects were instigated on the Goldeneye data (test reprocessing 1997-streamer data, OBC-reprocessing, Rock Properties Analysis, AVO-modelling, etc.) in order to better understand the factors determining the poor seismic data quality over the field, but the primary factor is the lack of acoustic impedance contrast at Top Captain Sandstone.

4.3. 2001 3D Pre-Stack Depth Migration (PreSDM)

The dedicated 1997 3D East Ettrick seismic survey was adequate to delineate the field and to proceed with field development planning. However, in order to reduce risks (associated with structural uncertainty, the degree of reservoir compartmentalisation and uncertainty associated with the stratigraphic pinch-out in the north of the field) and to optimise well positioning, the Goldeneye PreSDM project was undertaken with the aim to deliver a substantial improvement in the seismic image at reservoir level.

The data were reprocessed from field tapes in 2001. Other important processing steps were:

- Resample 2 ms to 4 ms.
- Tau-P deconvolution to attenuate water-bottom multiples.
- Data depopulation to 48 fold in an 18.75 m x 18.75 m bin.
- Radon demultiple to attenuate long period multiples.

The PreSDM project plan was based on re-processing of input seismic data, construction of an initial velocity model and two stacklamp (image gather) runs to update the model. The main steps were:

- Build initial velocity model, without coal bodies.
- Use the initial model to migrate the high density input seismic data set (with reduced maximum offset and reduced maximum TWT) on a coarse grid; update the shallow section of the model; incorporate coal bodies in the model as a gridded layer.
- Use the updated, hybrid model to migrate a depopulated data set (dropping alternate shots) on a coarser grid and update the deeper part of the model.
- Optimise migration parameters using 3D-in-2D-out tests.
- Migrate four key lines (3D-in-2D-out) to assess value of PreSDM (volume migration tollgate).
- Volume migration and post-migration processing.

Post-migration processing involved residual moveout (RMO) correction, attenuation of multiples, residual gain application, random noise attenuation, K filtering in cross-line direction, mild amplitude deabsorption, bandpass filtering, and the generation of angle stacks (angle of incidence ranges 0-11°, 12-22°, and 23-33°).

The inclusion of the shallow coal bodies as a gridded layer (see Figure 4-1) reduced the overburden imprints at reservoir level but probably influenced imaging to a lesser extent.

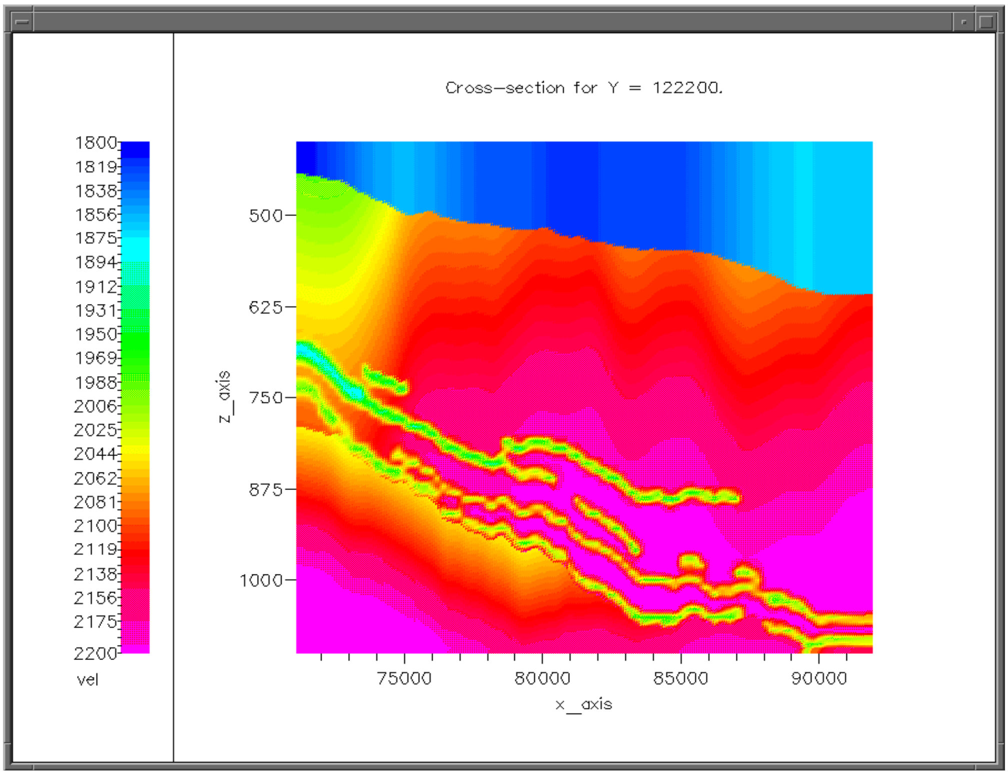

Figure 4-1: Gridded coal bodies in the final velocity model (coordinates in m; velocity in m/s)

The PreSDM volume showed a marked improvement in continuity, resolution and fault definition. Figure 4-2 shows a comparison of PosSTM (1999) and PreSDM (2001) data. On the latter dataset the Plenus Marl and Top Captain (2100 ms) are more easily mapped and fault definition on the Top Zechstein is improved.

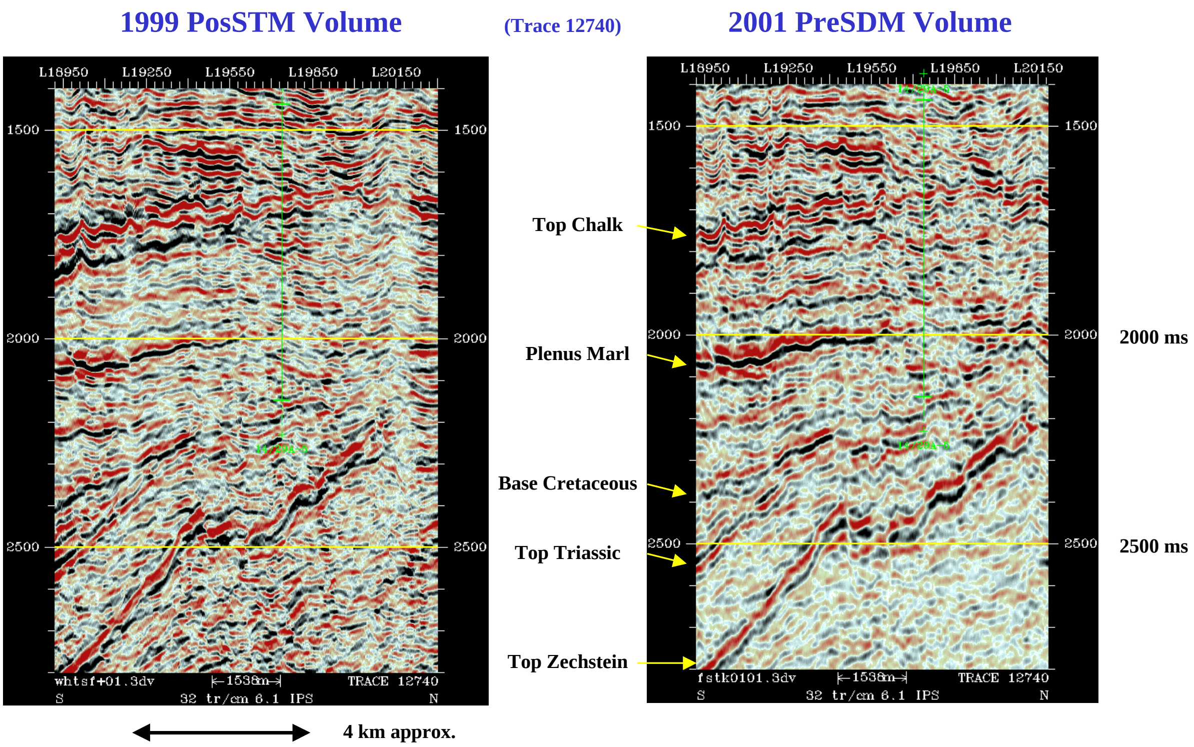

Figure 4-2: Comparison of PosSTM (1999) and PreSDM (2001) volumes

4.4. 2010 HiDef processing

The East Ettrick survey was subjected to High Definition Processing in 2010 to allow better images of shallow seismic features and overburden artefacts. The reprocessed area covers that of the PreSDM dataset, about 140 km^2, and focuses on the first 1,000 m below mudline. The approach makes use of the near offset data only and outputs the data on a fine output bin grid, which is typically 6.25 m by 6.25 m. The workflow required a high quality pre-processing sequence, especially in terms of noise and multiple attenuation. Therefore a number of (near) offsets were used in the final (PreSTM) stack in order to reduce remnant multiples and improve the general signal to noise ratio. A comparison between PreSDM and HiDef results at the level of the Eocene Beauly Formation is shown in

Figure 4-3: Comparison of 2001 PreSDM and 2010 HiDef data

. It should be noted that the sharper imaging at this level and a number of palaeo-seafloor piercement structures not resolvable on the PreSDM. The resultant volume post-dated the main horizon interpretation and was used to address shallow overburden questions only.

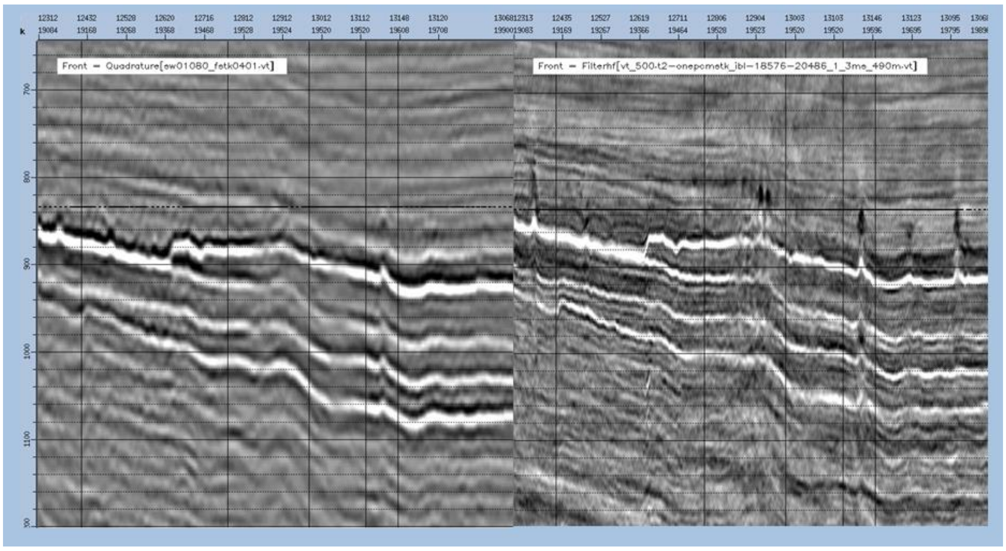

Figure 4-3: Comparison of 2001 PreSDM and 2010 HiDef data

5. Seismic-to-Well Ties

Seismic-to-well ties were generated to create a synthetic seismic trace from the P-impedance log and a zero-phase wavelet. This was primarily focused at reservoir level to ensure accurate picking of the internal reservoir units. All synthetics were bulk shifted so that the integrated time matched the synthetic response at the Top Plenus Marl horizon – the nearest consistent tie point above the Top Captain. At shallower levels, the Top Horda was another important tie point, a strong peak (soft kick) marking a decrease in acoustic impedance.

Figure 5-1 shows the synthetic for the type well (well 14/29a-3) for this interpretation. The top of the Captain Sandstone reservoir in this well corresponds to a zero crossing at 2034 ms. Figure 5-2 shows the well tie for the 14/29A-2 well which lies just north of the field where the Captain Sandstone has pinched out and the Rødby Formation lies directly on the pre-Captain Scapa Formation.

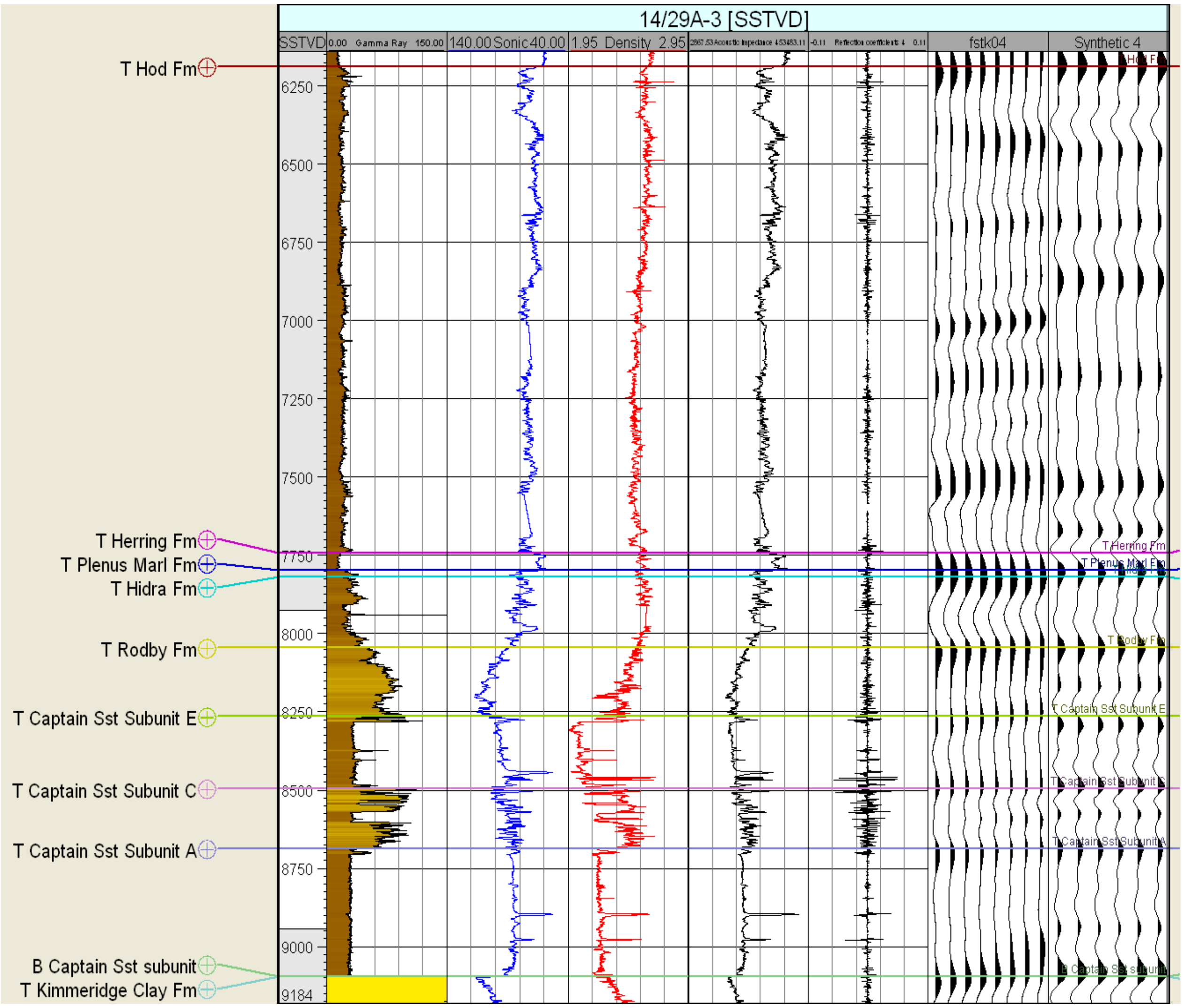

Figure 5-1: Seismic-to-well tie through reservoir section (14/29a-3), depths in ft [1ft = 0.3048m].

There is no Captain sandstone present in well 14/29a-2, and tying to the Top Rødby there is a clear soft kick correlation with the Base Cretaceous, as there is in all the Goldeneye wells (Figure 5-2).

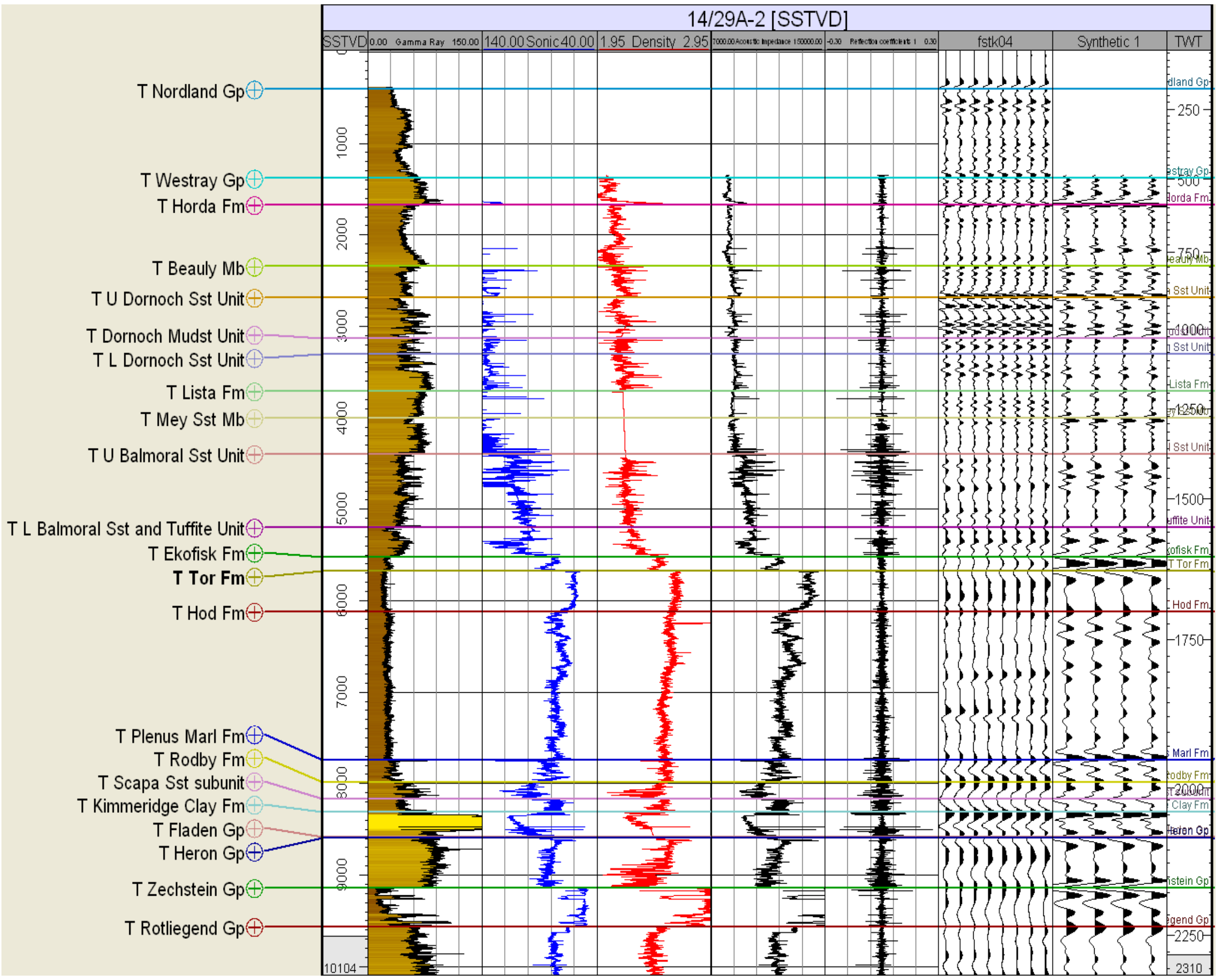

Figure 5-2: Seismic-to-well tie for well 14/29a-2

6. Horizon Interpretation

A detailed seismic interpretation was carried using reflectivity, semblance and Elastic Acoustic Impedance (AI) volumes to provide input horizons to the Goldeneye Field Static Model and to the Overburden Static Model, and to the Aquifer Static Model.

In total twenty horizons from the seabed down to the Top Zechstein were interpreted across the 3D PreSDM seismic cube (see Table 6-1 and Figure 6-1). The shallower more continuous events were easily autotracked, whilst the deeper events were picked on a seed grid and then autotracked where possible.

Table 6-1: Interpreted seismic horizons

Horizon	Display Response	Pick Quality
Top Nordland Gp	Red Trough	Good
Top Lark Fm	Red Trough	Fair - Good
Top Horda Fm	Black Peak	Very Good
Top Beauly Fm	Red Trough	Fair – Good
Top Coals	Black Peak	Good
Top Dornoch Mudst	Red Trough	Good
Top L Balmoral Sst	Red Trough	Poor – Fair
Top Chalk Gp	Red Trough	Good
Top Tor Fm	Red Trough	Fair – Good
Top Hod Fm	Black Peak	Fair – Good
Top Plenus Marl	Black Peak	Good
Top Rodby Fm	Black Peak	Fair
Top Captain Reservoir	± Zero Crossing	Poor – Fair
Top Captain C Unit	Black Peak	Poor
Top Captain A Unit	Black Peak	Poor
Base Captian Reservoir	Variable	Poor
Top Scapa Set	Red Trough	Poor – Fair
Base Cretaceous Unconformity	Black Peak	Fair – Good
Top Triassic Gp	Red Trough	Fair
Top Zechstein Gp	Red Trough	Poor - Fair

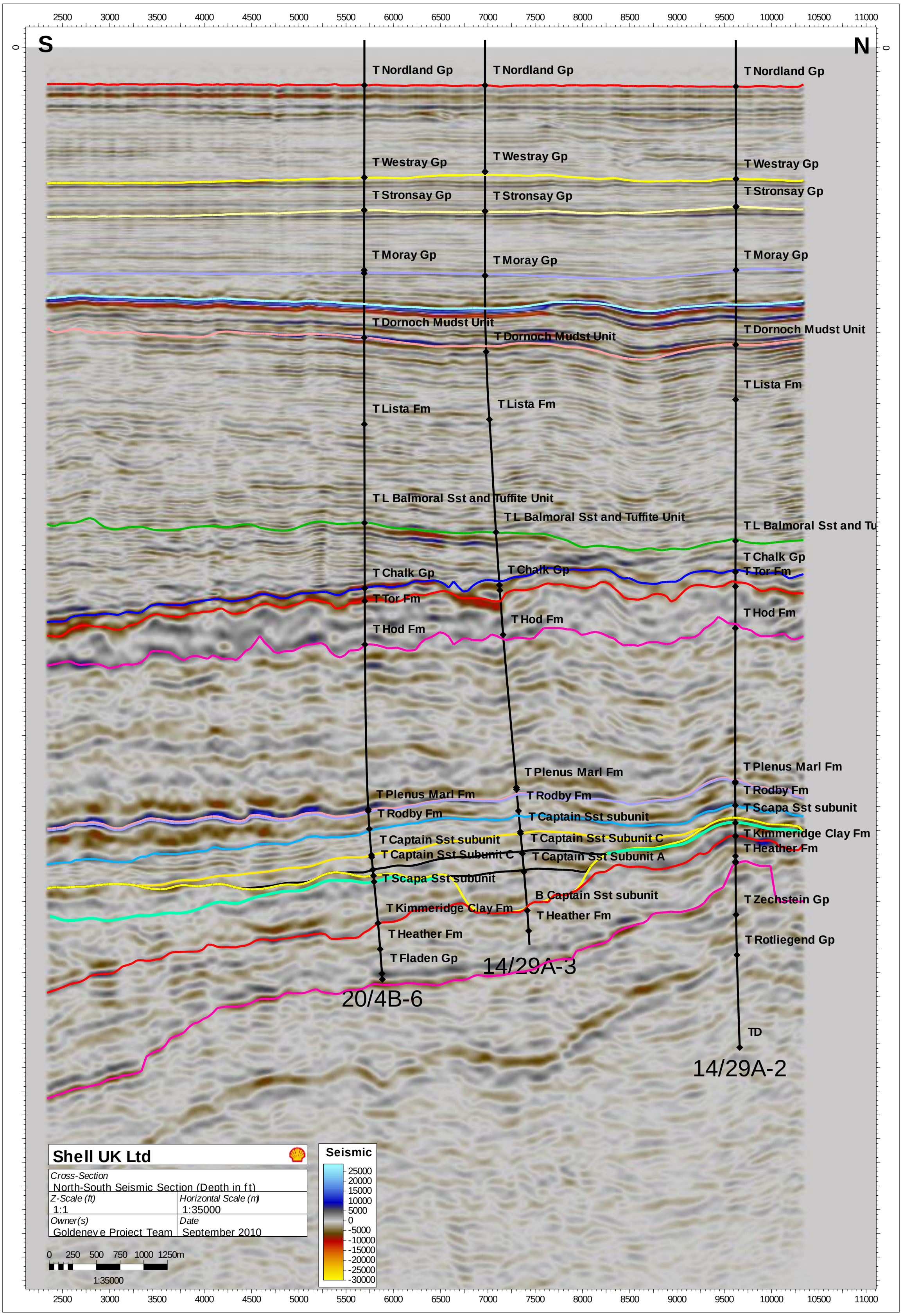

Figure 6-1: Seismic section (S-N) in depth through wells 20/4b-6 and 14/29a-2 showing interpreted horizons.

Note: Well 14/29a-3 has been projected onto the section.

6.1. Top Nordland Group

This is a good quality hard kick, marking the seabed. Water depths are fairly constant around 400 ft [122 m] deep.

6.2. Top Lark Formation (Top Westray Group)

The Lark pick is good quality across much of the AOI (Area of Interest).

6.3. Top Horda Formation (Top Stronsay Group)

The Top Horda Formation is marked by a strong amplitude reflection that can be very easily autotracked across the survey. It marks a sharp downhole decrease in GR from the glauconite-rich shales of the Lark Formation.

6.4. Top Beauly Member (Top Moray Group/Dornoch Formation)

The top Beauly reflector is a weak negative preceding the underlying high amplitude coals. The horizon consists of a varying overburden of Early Eocene fan deposits, which wedge generally eastward. A "Supra-Beauly wedge" of anomalously high (7400 ft/s [2255 m/s]), constant velocity sediment was identified between the 14/28b-2 and 14/29a-3 wells (Figure 8-1) which is an important layer in the depth conversion. The Beauly Formation comprises a complex association of sands, silts, mudstones and lignites and represents fresh to brackish water sedimentation in a paralic, coastal plain environment.

6.5. Top Coals

The top of this lignitic coal package is marked by very bright high amplitude reflectors. The coaly beds show lateral variability in thickness (decreasing from east to west). The maximum thickness of the coal interval above the field is approximately 200 m [660 ft] thick. The paleo-shoreline is very clearly observed in semblance time slices and shows the shoreline regressing/retreating westwards, marked by the outlets of subaerial channels and estuaries (see Figure 6-2). These paleo-shorelines create sharp north-south lineaments over the Goldeneye Field that cause significant seismic artefacts in underlying layers (Figure 9-5).

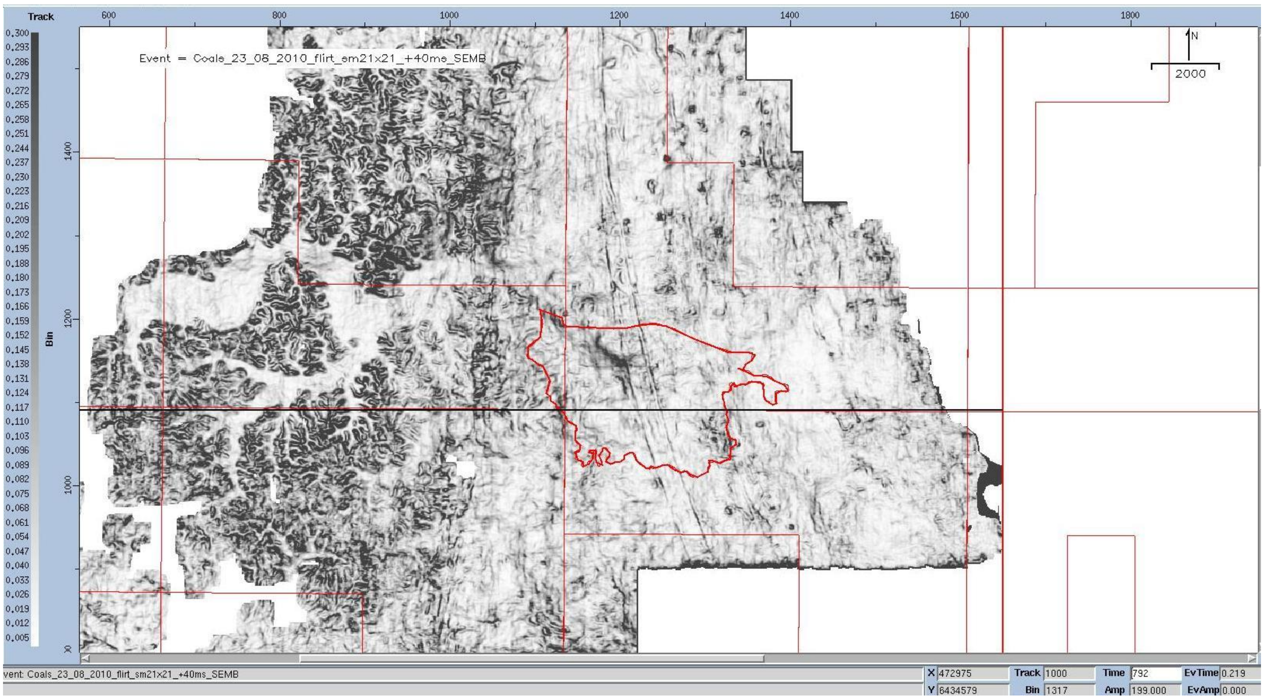

Figure 6-2: Paleo-shoreline and drainage network as observed in the semblance map (from the Greater Ettrick 3D survey) through the Eocene coals. Semblance extracted from interpreted coal event at approximately 760-975 m TVDSS.

Note: Field outline (OWC at 2619 m) is superimposed on this image.

6.6. Top Dornoch Mudstone Unit

The internal subdivisions of the Dornoch Formation exhibits variable log signatures and a discontinuous seismic response. As a result, in the Goldeneye area the Top Dornoch Mudstone unit is approximately equal to the base of a lignitic coal package which is seismically interpretable. This is a good quality negative trough below the bright amplitude coal packages. This coaly package generates considerable multiples and causes a lack of contrast (acoustic transparency) in the thick sequence of Montrose Group shales and sands (Lista Formation) below.

6.7. Top Lower Balmoral Sandstone and Tuffite Unit

This horizon in the lower part of the Mey Sandstone Member exhibits lateral variation due to on-lapping horizons of differing lithology. Further calibration of this horizon for the eastern half of the survey area is required from wells and seismic data to the east from well 20/5b-3. It is a difficult event to consistently track across the survey area.

6.8. Top Chalk Group/Top Ekofisk Formation

The horizon is lithologically quite variable due to erosion cutting down through the upper, and slower velocity, stratigraphic units. The Ekofisk thins to the south west, and merges into the Top Tor seismic loop. The top of the Chalk is an important velocity boundary that marks the top of deeper high velocity units (relative to the overlying Tertiary section).

6.9. Top Tor Formation

This is a dominant negative reflector that is relatively straight forward to map. Mapping difficulties are only encountered where the Ekofisk is thin or strongly eroded. It has an extremely high relative velocity, circa 16,000 ft/s log velocity.

6.10. Top Hod Formation

Top Hod is mapped as a positive reflector due to a reduction in velocity from the Tor. The pick is a low frequency positive event that suffers from doublet interference, resulting in a disturbed autotracked horizon. The interval velocity in this unit is nearly a constant 14,000 ft/s.

6.11. Top Plenus Marl Formation

The Plenus Marl is an excellent positive reflector and is regionally identifiable. It is a dominant acoustic impedance contrast which provides a reliable marker to align synthetic with the seismic when doing seismic to well ties.

6.12. Top Rødby/Base Hidra Formation

The Top Rødby horizon is recognised regionally in the Outer Moray Firth area and is a low-frequency positive event. The long wavelet period of this event, up to 30 ms, causes timing problems with the horizon interpretation when autotracking, producing a noisy surface. This medium to high confidence seismic pick appears one cycle beneath the Plenus Marl horizon and has a good seismic-to-well tie. The horizon assists in constraining the Top Captain interpretation as there is at least one black loop present between the Top Rødby and Top Captain reservoir at all well control points within the field.

6.13. Top Captain Sandstone (Subunit E, Top Reservoir)

The turbiditic Captain Sandstone reservoir exhibits a variable seismic character over the Goldeneye Field and its interpretation is hindered by the lack of P-wave impedance contrast with the overlying Rødby shales. Seismic-to-well ties demonstrate that the Top Captain seismic reflector changes polarity from a plus/minus zero crossing to a positive black loop and to a negative red loop in different parts of the survey. In order to reduce uncertainty of exactly where this reflector changes character, the Top Captain seismic pick has been consistently interpreted as a plus/minus zero crossing in this study. Any resulting seismic-to-well mis-tie will at most be one quarter of a cycle loop out. The detectable and resolvable limits of the seismic data at reservoir level are about 9 m and 23 m respectively. In the time-depth conversion all horizons have been tied back to true well depths by means of residual error correction surfaces. The Elastic AI volume did not assist in the definition of top reservoir, although it did give guidance to the form and geometry of reflector packages.

Figure 6-3 shows the inconsistent top reservoir reflector in wells 20/4b-6 and 14/29a-3. Given the lack of reflector continuity, a modelling approach to the interpretation was also necessary to decide where to cut across reflectors in order to tie the wells. This was achieved using the AI, offset and semblance volumes. This has resulted in a combination approach that allows the interpretation to honour the seismic data in terms of reflection character where ever possible, and a modelling approach that allows a consistent horizon interpretation to the well data.

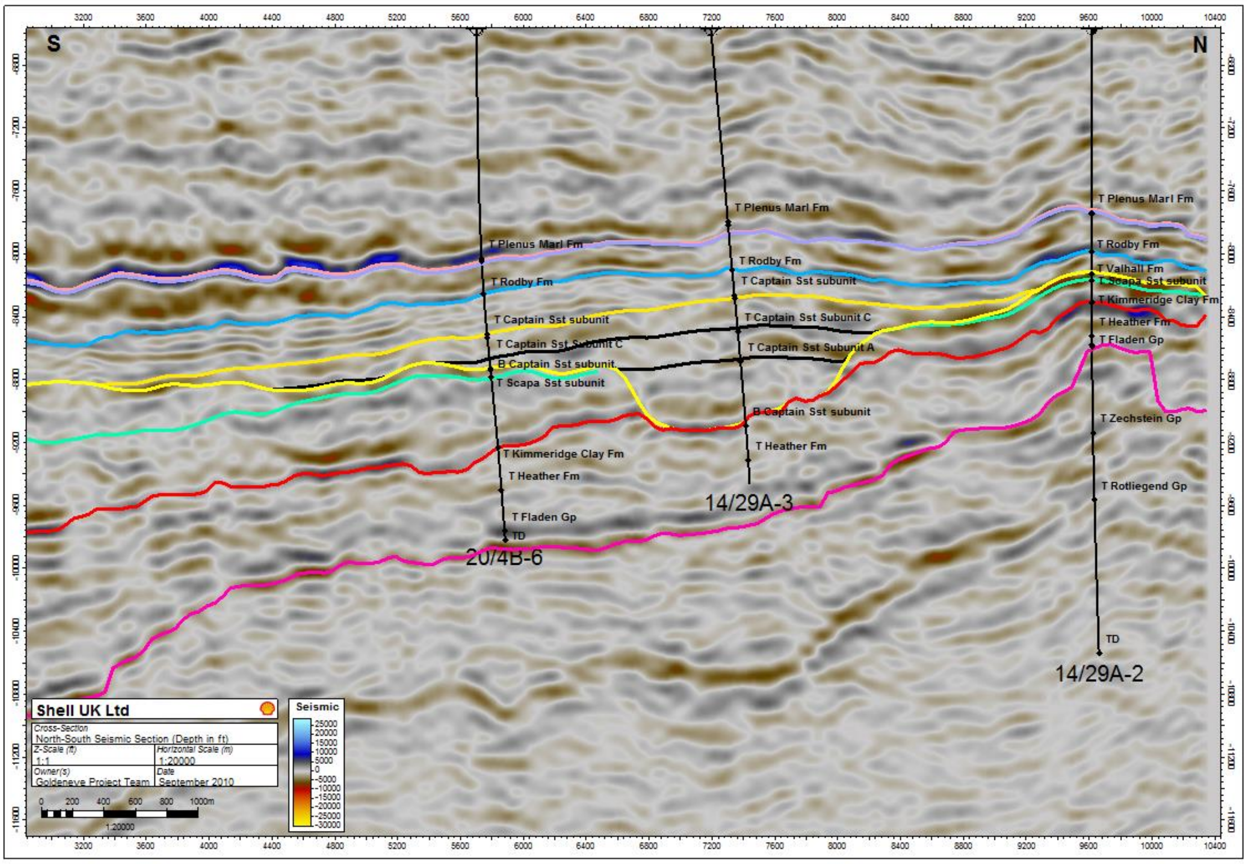

Figure 6-3: North-south seismic section in depth (ft) through wells 20/4b-6 and 14/29a-2.

Note: 14/29a-3 is projected onto cross section.

The Top Captain was interpreted in two phases. Initially a fine 4x4 seed grid was interpreted with infill of a finer grid where necessary to constrain the interpretation over the Goldeneye Field area and the 14/29a-4 Hoylake discovery well. This horizon was picked to determine the overall structure of top reservoir and was used as input to the Elastic AI inversion as part of the low frequency background model. The second stage of the interpretation made use of the AI volume (together with the reflectivity volume) to produce a high, mid and low case interpretation.

- **Top Captain Base Case:** This horizon is picked on a plus/minus zero crossing and represents the base case interpretation regarding the spatial extent (44 km^2) of the Top Captain reservoir. This case allows the Top Captain to drape over the northern bounding fault to a maximum of approximately 100 m north of the fault. This drape is consistent with the depositional model as it is interpreted that the mini-basin and northern bounding fault were present prior to the Captain Fairway deposition with the fault marking the northern edge of the channel. The horizon pinches out to the south, but extends to the west and east of the field (see Figure 6-4). This base case interpretation was used in the Goldeneye Full Field static reservoir modelling.
- **Top Captain High Case:** This high case represents the most optimistic interpretation. If there is the ability to take the pick higher in time in areas of poor seismic quality this horizon honours it yet remains consistent with the principle of a positive black loop always being present between the Base Hidra and Top Captain reservoir. It is also the most spatially extensive (46 km^2) of the three mapped cases and extends the top reservoir 200 m+ north of the bounding fault and further to the south than the base case.

- **Top Captain Low Case:** This horizon represents the most pessimistic interpretation. In order to capture uncertainty regarding reflector character this has been picked on the negative red loop immediately beneath the mid and high case plus/minus zero crossing, and covers the least area spatially (43 km^2). The horizon barely extends over the northern bounding fault and pinches less far to the south than the base case.

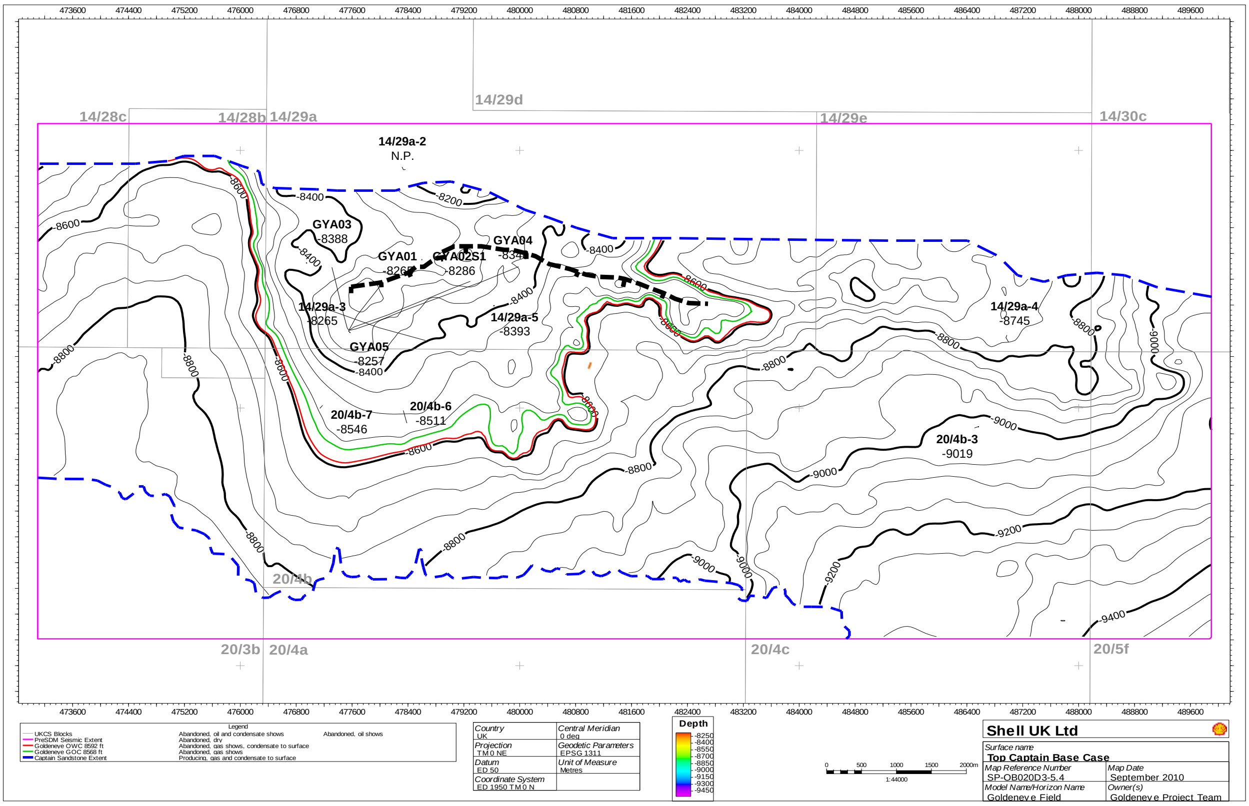

Figure 6-4: Top Captain Sandstone (base case) in depth.

Note: BCU (Base Cretaceous Unconformity) Northern Bounding Fault projected onto surface as dashed black line.

Both the seismic and semblance data were interpreted to include as many faults/baffles as possible (see Figure 7-1) for the Top Captain reservoir to provide flexibility for the 3D static modelling. This resulted in the mapping of numerous E-W faults at top reservoir that have almost no heave or throw. The data suggests the Captain Sandstone units have been subject to slumps and slides post deposition rather than excessive brittle fracture. Slump planes are suggested which appear to sole out on the Base Cretaceous Unconformity. These slump planes are shallow angle and poorly imaged on seismic, but suggest sand-on-sand juxtaposition and are therefore not considered as potential flow barriers.

6.14. Intra Captain Subunit C

This horizon is the top of the intra-reservoir shale unit that separates the D and A Unit sandstones in the Goldeneye Captain reservoir sequence. This important horizon marks the base of the high net-to-gross, high porosity D sand unit that contains the majority of the GIIP (Gas Initially In Place). All three mapped cases (high, mid, low case) have been consistently picked on a positive loop with extensive use of the Elastic Band Pass AI inversion volume that allows increased confidence in picking this intra-reservoir reflector. This horizon interpretation is well constrained between the four wells in the field (14/29a-3, 14/29a-5, 20/4b-6 and 20/4b-7). The Top C spatial extent and pinch-out uncertainty increases away from these wells so low, base and high case interpretations were generated. The differences between these mapped cases are primarily in a north-south direction over the survey area and they have similar extents to the east and west.

- Top C Unit Base Case: Unit C pinches out to the west, as it is absent in the 20/4b-3 well, and very thin in 14/29a-4. The base case has an approximate areal extent of 35 km^2.
- Top C Unit High Case: This case represents the high pick in TWT and therefore the most pessimistic in terms of the D unit thickness. Wherever ambiguity in the seismic pick allows this pick remains the shallowest in TWT. As a result the mapped horizon extends the furthest to the north of the northern boundary fault and the least to the south. The high case has an approximate areal extent of 31 km^2.
- Top C Unit Low Case: This is picked on the low case in TWT and therefore allows the greatest thickness in the D reservoir unit. Generally it does not extend north of the northern bounding fault but extends furthest south of all three cases. The low case has an approximate areal extent of 36 km^2.

The fault interpretation is consistent with the methodology described for mapping faults at top reservoir level. Significant effort was taken to capture any intra-reservoir faults that may have caused compartmentalisation within the Goldeneye Field.

6.15. Intra Captain Subunit A

This horizon marks the base of the intra-reservoir C Unit shales and the top of the basal A Unit sands. This horizon is consistently picked as a positive loop. The Captain A Unit sands are only present in wells 14/29a-3 and 14/29a-5 and mark the base of the reservoir sequence within the mini-basin in the centre of the field. These A Unit sands are highly erosive in nature but they are not interpreted to extend outside the area of the central mini-basin as, it is limited to the north, south and west by faults, and is interpreted to pinch-out onto the Base Cretaceous Unconformity high to the east, sub-cropping beneath C Unit shales or D Unit sands. The high and low case field interpretations are shown in Figure 6-5.

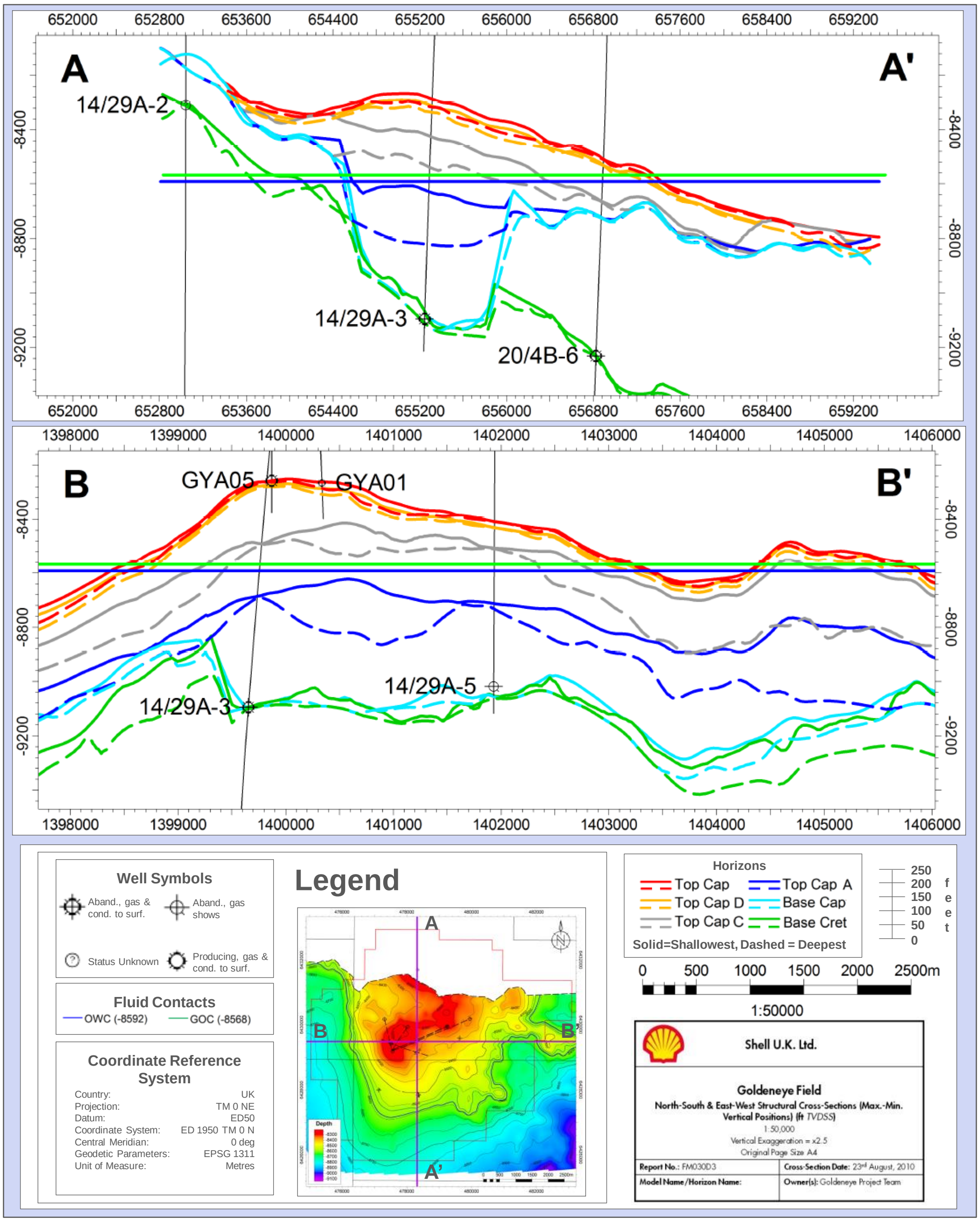

Figure 6-5: Cross sections though the Goldeneye Field showing high and low case interpretations. Well paths projected onto lines of section. Fluid contacts extended for clarity.

6.16. Base Captain Sandstone (Base Reservoir)

The Base Captain horizon, in combination with the Top Captain horizon, has a bearing on the position of the northern pinch-out of the Captain sands and the reservoir Gross Rock Volume (GRV) in the north of the field where the Base Captain is interpreted to rise above the hydrocarbon water contact. This horizon is the least well defined in this study. The base of the Captain varies in wells from Captain A unit sands in wells 14/29a-3 and 14/29a-5, to Captain C unit shales in wells 20/4b-6 and 20/4b-7, and Captain D sands in wells 14/29a-4 and 20/4b-3. There is no Captain reservoir in well 14/29a-2 and so the base reservoir interpretation is known to terminate south of this well. As a result, the seismic response of the Base Captain is variable across the survey. Resolution at base reservoir level is at best moderate. This has led to a combination of tracking a negative red loop where possible outside of the mini-basin, a positive black loop that corresponds to the Base Cretaceous Unconformity within the mini-basin, but modelling a base reservoir pick in the areas between the two where uncertainty exists away from well control and/or the horizon is interpreted to erode the underlying sediments. Regional interpretations show that the Captain Sands pinch-out south of the field and do not extend to wells further south in the 20/4c block.

6.17. Top Scapa Sandstone Subunit

The distribution of the Scapa Sandstone is an indication of the erosive nature of the overlying Captain Sandstone mass flow deposits. There is no Scapa present in wells 14/29a-3 and 14/29a-5. Both these wells have a complete Captain reservoir section. The Scapa Sandstone is also not present in wells 14/29a-4 and 20/4b-3. The Scapa has been mapped with a 3x3 seed grid in an attempt to constrain the Base Captain/base reservoir interpretation.

6.18. Base Cretaceous Unconformity (BCU)

The Base Cretaceous Unconformity was interpreted on a fine 2x2 seed grid with particular emphasis on structural style and correlated fault patterns. In addition to the reflectivity seismic data, a semblance volume, and both time-slices and sections through this volume were extensively used in producing a high confidence fault interpretation for this horizon. The horizon pick is a positive black peak, representing a reduction in impedance, marking the top of the Kimmeridge Clay Formation. This is generally a high confidence reflector, exhibiting a consistent and correlatable seismic response with generally clear offsets and changes in dip marking fault throws. The reflector is weak and poorly imaged in some parts of the field, probably due to erosion by the Captain Sands. There is also onlap onto the South Halibut Shelf and interference from other fringing sediments such as the Lower Cretaceous Scapa Sandstone.

6.19. Top Triassic (Top Heron Group)

The Top Triassic pick is a fair quality event that shows the dominant structural trends in the Goldeneye area.

6.20. Top Zechstein Group

The Top Zechstein was briefly mapped across the AOI. It is a poor quality negative trough.

7. Fault Interpretation

The Goldeneye faults were interpreted using the 2001 PreSDM reflectivity data together with a semblance volume. The Goldeneye Field fault interpretation was carried out in two iterations concurrent with the two-stage horizon interpretation approach, with emphasis on both the structural style of (a) the Base Cretaceous Unconformity horizon and (b) the intra-reservoir faults. Firstly close attention has been paid to the fault patterns at the Base Cretaceous Unconformity level which describe the basement of the Goldeneye accumulation and the overall field morphology. Secondly during the horizon interpretation that involved iteration with the Elastic AI impedance data, detailed fault mapping identified faults/baffles at the top, intra and base reservoir reflectors that might act as barriers or conduits to CO_2 flow during injection. This approach generated as many intra-reservoir faults as possible in order to enable sensitivity to fault density to be incorporated into the static/dynamic models of the Goldeneye Field. Fault throws and heaves were calculated, and fault polygons digitised to represent each correlated fault. These polygons have been QC'd (Quality Controlled) by overlaying them on amplitude maps extracted from the semblance data along each relevant horizon.

7.1. Top Rødby/Top Captain Faults

Fault interpretation was focused on the Top Rødby and Top Plenus Marl Formations. To assist in interpretation, a Root Mean Squared (RMS) amplitude of the semblance seismic volume was extracted around these two surfaces (-30 ms and +50 ms search window) and displayed as an attribute on the surfaces. The mapped faults are of limited vertical and lateral extent with small throws that do not offset the sealing Rødby shales, and run approximately E-W, matching the observed regional structural trends. The faults in the top seal are usually a bit steeper than in the Captain Sandstone. The faults are concentrated towards the east of the Goldeneye structure.

The greatest fault density within the Captain Sandstones is evident around well 14/29a-3 where fracture zones have been identified in core from the Captain Unit D reservoir interval (see Figure 7-1). By contrast, few fracture zones have been identified in core from well 14/29a-5 which is located in an area with fewer mapped faults. However, blocks of Kimmeridge Clay have been identified within the lower Captain (Unit A) reservoir interval in well 14/29a-5. These blocks are believed to have been sourced from the area to the north-east of the well beyond where the limit of the Captain sands is defined by a mapped fault. The mapped pattern does not reflect that faults were active throughout deposition of the post-Captain Unit A reservoir interval, i.e. Units C, D and E, but suggests a younger, post-Captain deposition phase of faulting (Tertiary).

7.2. Intra Reservoir Faulting

There is little evidence for intra-reservoir compartmentalisation given the seismic resolution. Any faults propagating up through the reservoir from deeper horizons appear to have little or no throw, therefore any juxtaposition in the upper unit will be sand-on-sand and are not expected to present any barriers to CO_2 flow.

7.3. Base Captain Faults

The Base Captain fault trends also parallel regional trends. The mapped faults are continuous but do not totally extend across the accumulation. The fault pattern suggests a strong pre- and/or syn-depositional fault influence on the lower Captain reservoir interval. The distribution of the lower (Captain Unit A) reservoir interval, which is present in wells 14/29a-3 and 14-29a-5 but absent in wells 20/4b-6 and 20/4b-7, appears to be related to the observed Base Captain faults. This lower Captain reservoir thickness is contained within an area outlined by the mapped faults. The boundaries to this area could represent either pre-existing (fault) scarps, suggesting a pre-depositional influence on the lower Captain reservoir interval, or faults, suggesting active fault movement during deposition of the lower Captain, or a combination of both processes.

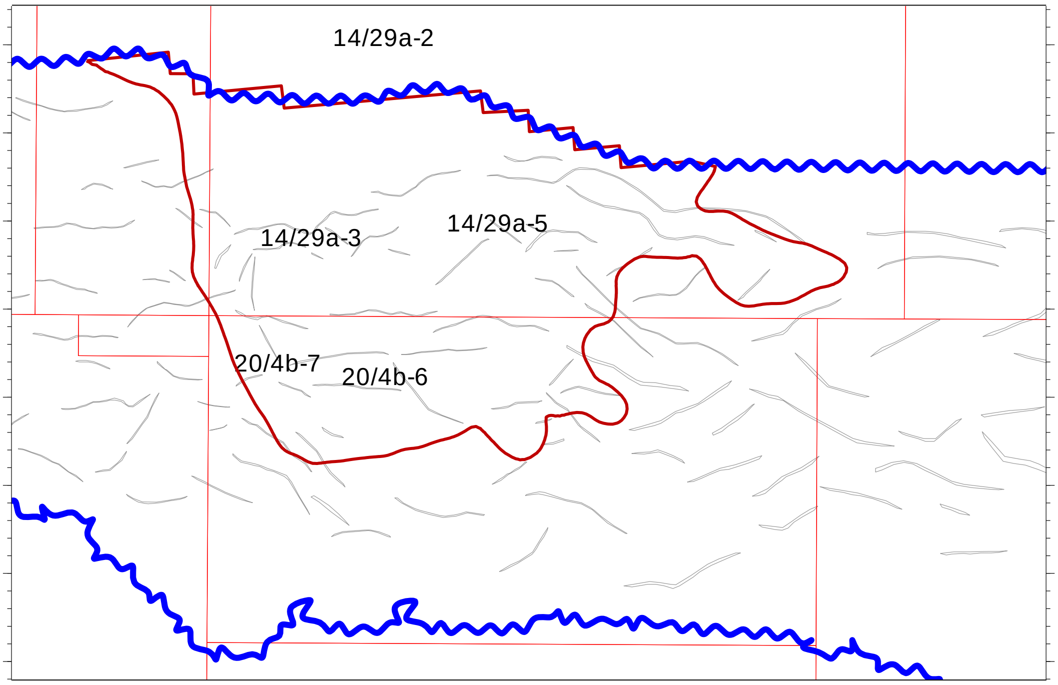

Figure 7-1: Top Captain fault polygons

7.4. Base Cretaceous Unconformity (BCU) Faults

The faults at this horizon are predominantly E-W, sub-parallel to the regional structural trend. They are apparent at BCU level but do not appear to offset the top reservoir yet influence the overall reservoir geometry. Figure 7-2 shows the BCU fault polygons in relation to the Goldeneye wells. There are three main fault zones that have the greatest impact on the Goldeneye Field which act to limit the distribution of the Basal A Unit Sands confirmed by the 14/29a-3 and 14/29a-5 wells and define the mini-basin.

To the north of the field, there is a zone of E-W southerly dipping faults that mark the northern limit of the thickest Captain sandstone accumulation. This northern bounding fault marks the transition from the thickest reservoir accumulation to the thin drape of sediments that extends to the north of the fault. At BCU level it has a maximum throw of approximately 120 m and generally increases in throw from west to east across the field. In the west of the field and north of the 14/29a-3 well, this fault tips out and another en-echelon fault takes up the throw. This second fault has a small SW-NE transfer or relay fault linking the two that makes the northern bounding fault a continuous feature in this area of the field. To the south of the field, there is a zone of northerly dipping E-W faults. There are a series of fault linkages and relay zones running to the east from the southern edge of this zone. At the western edge of the Goldeneye mini-basin, there is a terrace consisting of two N-S sub-parallel easterly dipping faults. The throws on these faults are approximately 20 m. This zone appears to act as a transfer zone at the western extent of both the northern and southern fault zones.

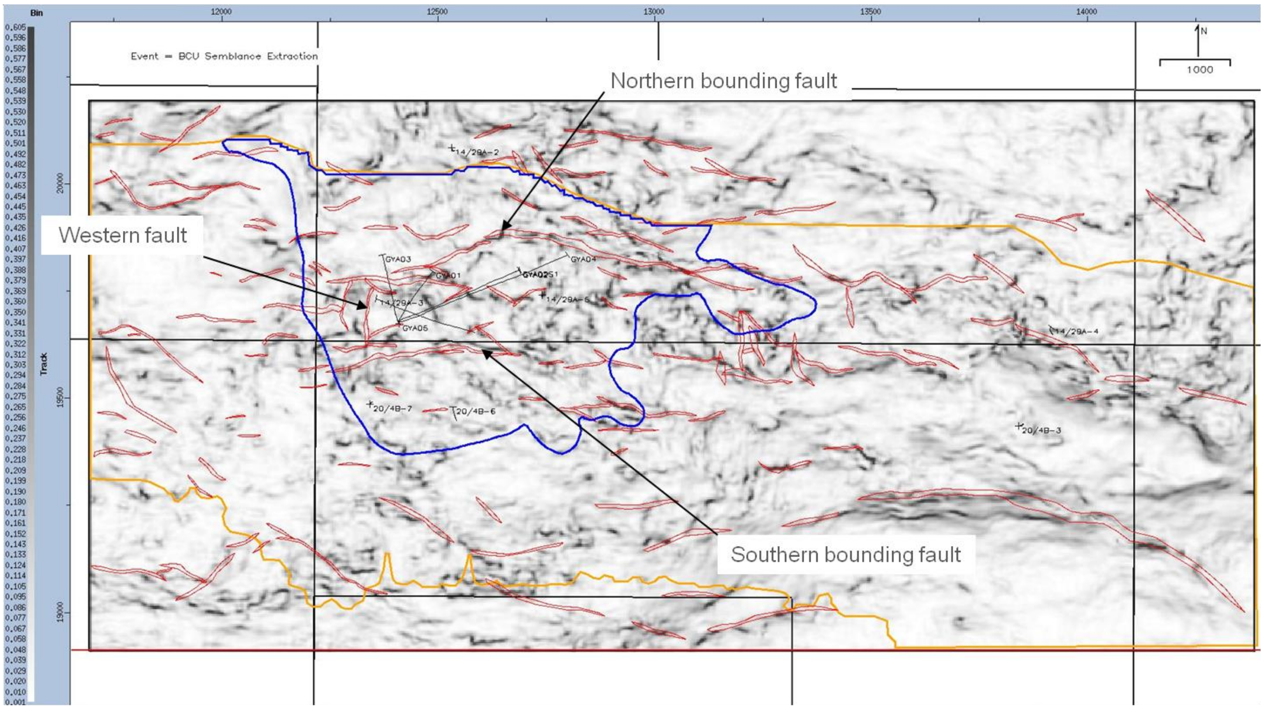

Figure 7-2: BCU fault polygons overlain on BCU semblance horizon

7.5. Overburden Faulting

Different fault types have developed at different stratigraphic levels and are clearly controlled by the mechanical characteristics of the different lithologies (see Figure 7-3). There are a series of faults that are well developed in the Chalk. These faults do not extend all the way to the seabed, and are in general decoupled from the reservoir section. All of the shallower faults appear to have developed after deposition of the Eocene coals. The orientation of these faults is NW-SE, with one exception of a fault that trends NE-SW. Based on observations of borehole breakouts, the present day stress field is NE-SW, suggesting that the latter fault might be related to relatively recent stress re-activation. All these faults are developed in the SE flank of the field.

Most of the faults developed in the reservoir section trend WNW-ESE to E-W. This suggests that the faults that offset the Chalk and Montrose Group sediments are most likely not related to the syn-rift to late rift faults observed in the reservoir section, and have developed in very different phases within the evolution of the region (late thermal subsidence phase).

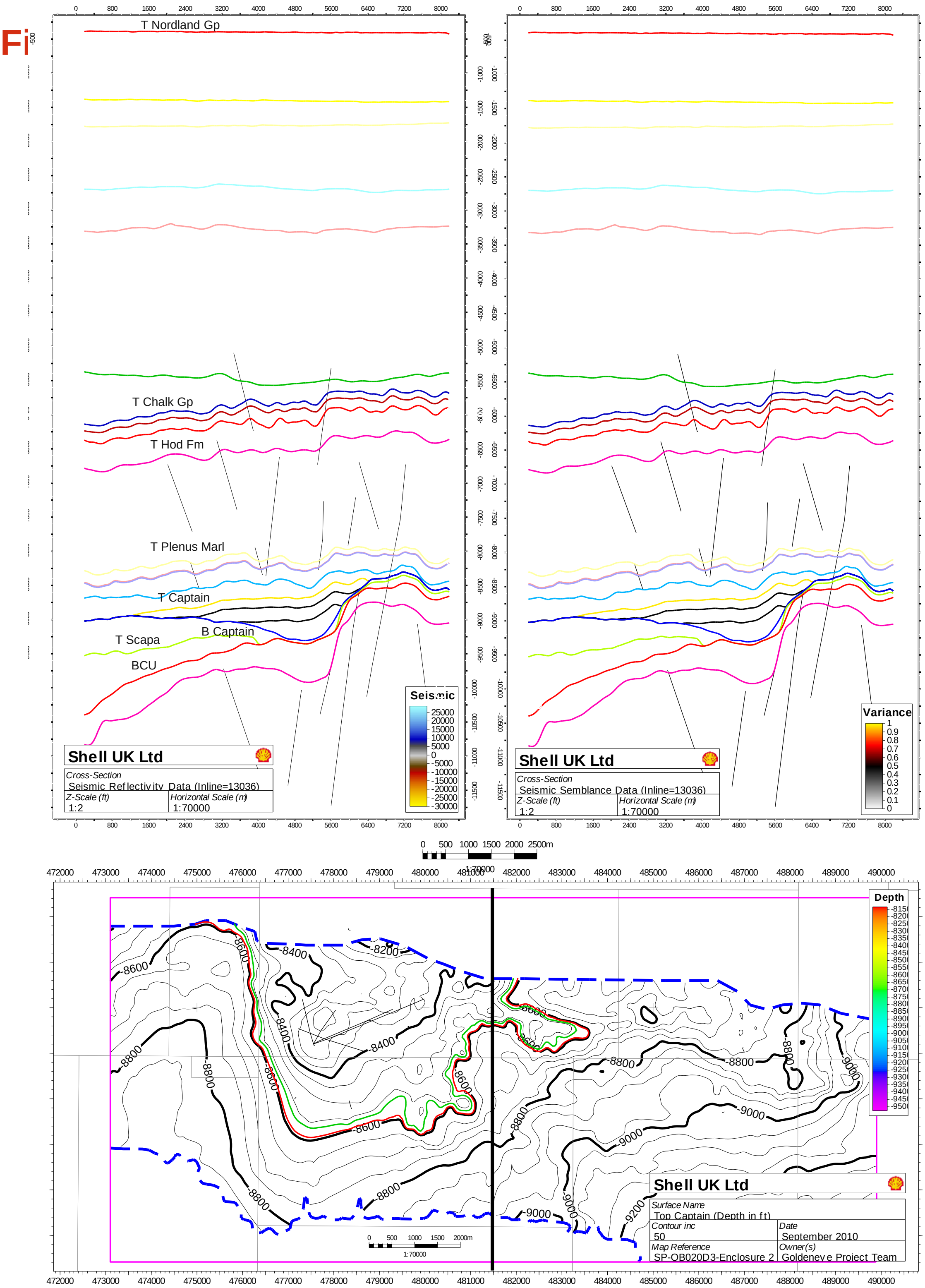

Figure 7-3: North-south TWT reflectivity seismic section, equivalent semblance section and Top Captain map for location.

Note: fault decoupling due to mechanical stratigraphy.

8. Depth Conversion

Depth conversion for the reservoir model was carried out using a 7-layer velocity model that honoured the Exploration and Appraisal wells and the subsequent Development wells. The method chosen was the result of progressive refinement as well data became available, as documented below.

Going into the Goldeneye development campaign, two different velocity models were carried for the field down to top Captain Sandstone; a 10-layer model using interval velocity vs. interval transit time regressions, and a model developed in the PreStack Depth Migration (PreSDM) of the seismic dataset. However, after examining the residuals from the newly drilled development wells, it was observed that the 10-layer model was on average closer to the top reservoir encountered by the wells than was the PreSDM model. It was decided to drop the PreSDM model and to proceed with the 10-layer model. The Development wells had also provided new information on the overburden layers above the Chalk and these were recorrelated: the 10-layer model was still superior to the PreSDM model but it was found that the top Captain depth was better matched if the velocity model was simplified to 7 layers by using a single surface to top Chalk interval. This is a consequence of limited to no logging suites being run above top Chalk in most wells rendering picks in shallower layers more uncertain.

The interpreted seismic time horizons were depth converted using the 7-layer depth conversion (Table 8-1). The shallowest layer (Mean Sea Level-Top Chalk) uses a constant velocity (linear depth/time relationship). Other intervals are calculated from well-based interval velocity vs. interval transit time regressions. A "Supra-Beauly wedge" of anomalously high constant velocity sediment (7400 ft/s [2256 m/s], derived from exploration well 14/28b-2 7.5 km west of the field) was inserted above the Top Beauly Member between the 14/28b-2 and 14/29a-3 wells (Figure 8-1, Figure 8-2), in order to capture the complex overburden velocity effects, and to achieve closure of the Goldeneye structure to the west. A further local adjustment was made within the Top Rødby-Top Captain layer in the area around well GYA03, to take account of a velocity anomaly (pull-up) observed in the seismic at this well location.

Below the top Captain additional layers were required to depth convert the base Captain, Base Cretaceous Unconformity (BCU) and horizons in the Jurassic. As the top Captain is not present over the entire survey area, to achieve a depth conversion to the regionally recognised Base Cretaceous Unconformity a regression was developed from Top Rødby to the BCU. The Captain Sandstone itself and intervals below the BCU were given (different) constant velocities on the basis of the logged time and depth data (Table 8-1)

Table 8-1: Velocities used for depth conversion (depth in feet).

Interval	Depth/TWT Regression	Interval Velocity/Interval TWT Regression
Surface-Top Chalk	Z = 4.2387*TWT - 1369	-
Supra Beauly Wedge	Constant velocity 7400 ft/s added to Top Chalk depth surface	-
Top Chalk Top Tor	-	V = 247.954*Chalk-Tor isochron + 17,863
Top Tor-Top Hod	-	V = 131.08*Tor-Hod isochron + 23,819
Top Hod-Top Plenus	-	V = 6.8924*Hod-Plenus isochron + 15,332
Top Plenus-Top Rødby	-	V = 277.9*Plenus-Rødby isochron + 23,534
Top Rødby-Top Captain	-	V = 93.879*Rødby-Captain isochron + 14,212
Captain Reservoir	Constant velocity 11000 ft/s	
Top Rødby-BCU		V = 2.801*Rødby-BCU isochron + 11,024
BCU and below	Constant velocity 10,500 ft/s	

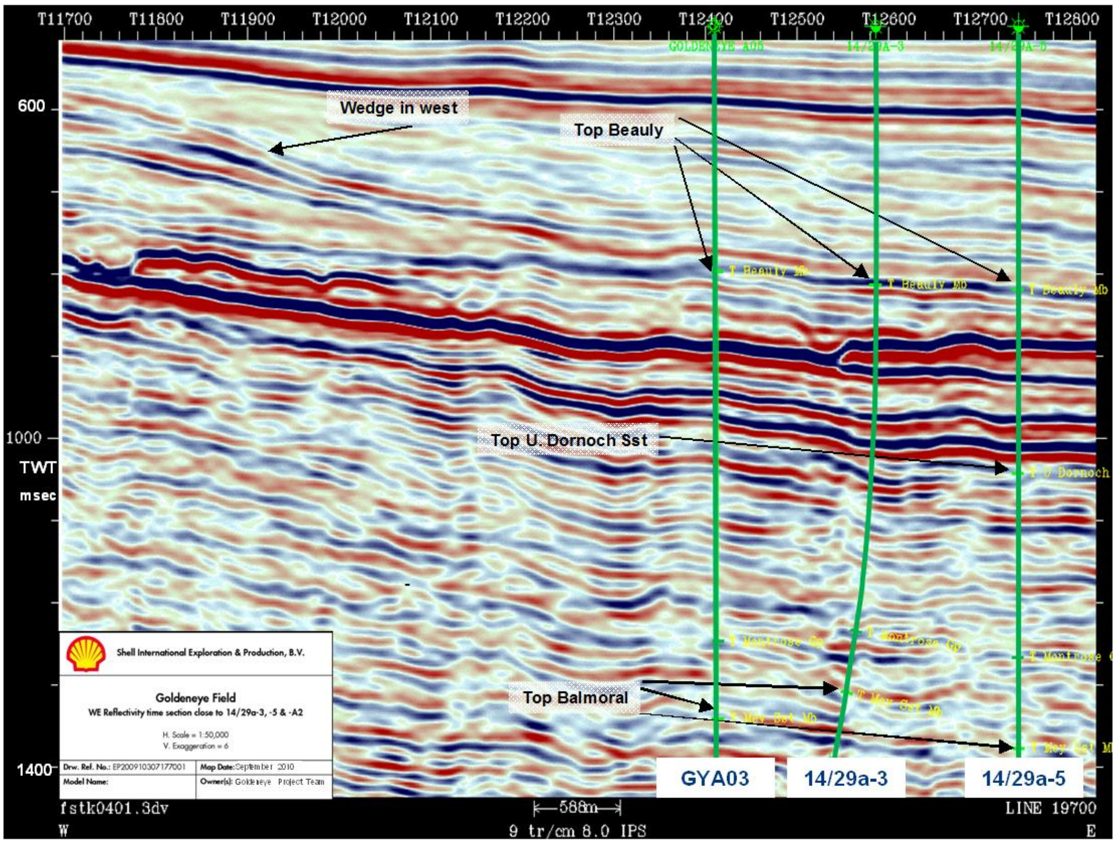

Figure 8-1: Supra-Beauly wedge in section.

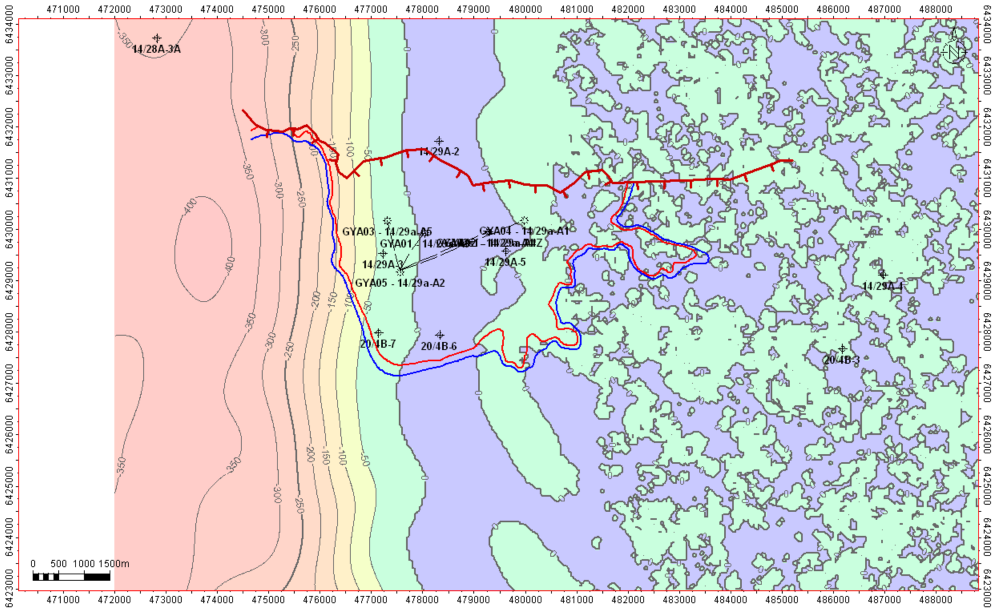

Figure 8-2: Map view of Supra-Beauly wedge: isochore thicknesses (ft).

After depth conversion, the residuals that remained at the well locations (Table 8-2) were gridded using Convergent Gridding without any influence limits and then added to the top structure map, tying the surface explicitly to its observation point in each well.

Table 8-2: 7-Layer Depth Conversion residuals (ft)

Depth Conversion Residuals								
Isochore Residuals (ft)							**Total Residual**	
Top Chalk	Top Tor	Top Hod	Top Plenus	Base Hidra	Top Capt	Well	Top Capt	RMS
-12	2	-7	51	-1	-13	14/29A-2	20	400
14	-7	10	20	2	8	14/29A-3	48	2304
-14	-27	31	-3	27	-5	14/29A-4	10	100
41	-11	-21	-22	-13	16	14/29A-5	-10	100
5	27	-10	-31	-40	24	20/4B-3	-24	576
-9	-10	11	-68	44	-9	20/4B-6	-41	1681
-39	51	-35	-36	-3	2	20/4B-7	-61	3721
-8	8	-12	-3	8	-6	GYA01	-14	196
-31	-10	74	30	3	-5	GYA02	62	3844
-33	24	-4	-9	-54	17	GYA03	-58	3364
50	-11	-20	-19	-17	0	GYA04	-17	289
37	-36	-18	90	-11	3	GYA05	65	4225
							Average	42
							Std Dev	43.4

The methodology is considered fit for CCS planning and subsequent activities.

9. Overburden Features

A number of features in the overburden cause imprints on underlying layers that need to be understood to allow accurate horizon and fault interpretation. They are addressed in the following sub-sections.

9.1. Seafloor pockmarks

The Top Nordland (seafloor) reflector reveals a number of circular features known as pockmarks, up to several hundred metres wide, several metres deep (Figure 9-1). These are a common occurrence in the North Sea and are thought to result from the periodic expulsion of gas that has become trapped in sediments immediately below the seabed. This gas is thought to derive from a regional, low concentration blanket which exists at slightly deeper levels below seabed and is ultimately of thermogenic and or biogenic origin. The pockmarks do not further impinge on seismic imaging or interpretation of deeper levels.

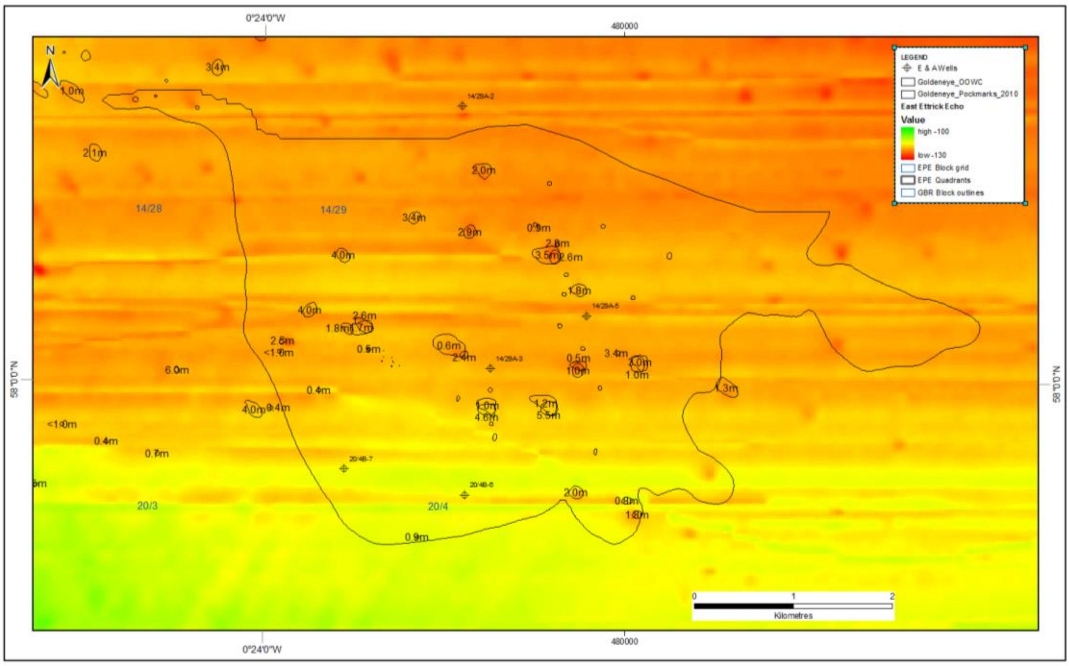

Figure 9-1: Pockmarks interpreted from site survey data compared to indications of seabed depressions from interpretation of 2002 PreSDM seismic survey.

9.2. Subglacial channels

A 240 m deep 2 km wide subglacial channel runs NW-SE across the north-eastern part of the Goldeneye Field area (Figure 9-2), cutting through the Nordland Group almost as deep as Top Lark. The channel is of Pleistocene age and has a complex fill which has contributed to imaging artefacts below the channel area, both imprints and lensing effects.

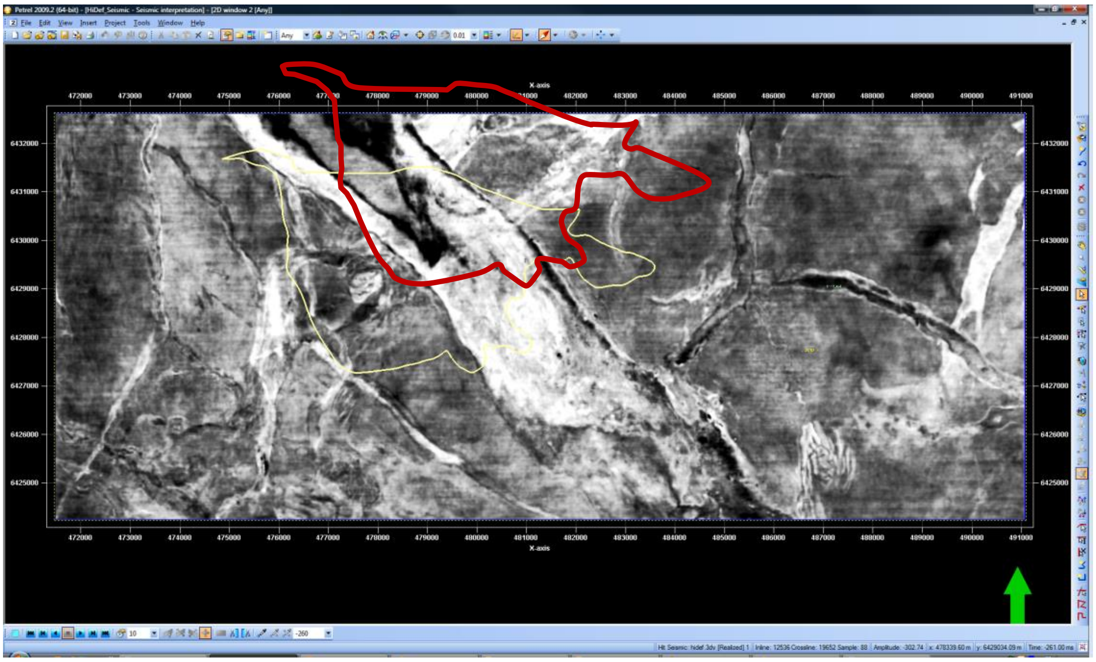

Figure 9-2: Subglacial channel (Field outline in red).

The channel imprint effect can be seen at Top Horda where changes in horizon dip still occur (Figure 9-3). This occurs to a greater or lesser extent on both HiDef and PreSDM throughout the Tertiary and below.

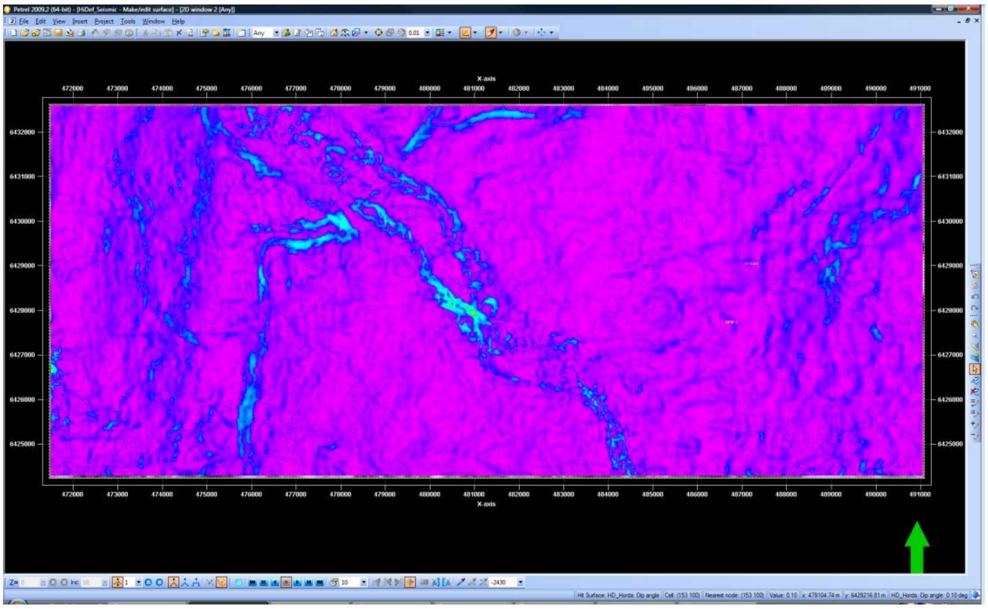

Figure 9-3: Imprint of Pleistocene channel on Top Horda dip map

Lensing effects are considered in Section 9.5.

9.3. Palaeo-seafloor piercements

In the Eocene at the level of the Beauly Formation the 2010 HiDef processing has revealed a number of high-impedance cones on top of one or more forced folds (Figure 9-4). These do not extend upwards beyond the Eocene. Analogous features can be seen on shallow seismic from other areas and they are interpreted as palaeo-seafloor piercements where gas was vented through ductile sediments causing forced folds. A rapid westwards build-out of sediment took place across the area in the Eocene and is the most likely cause of gas build up and escape at the time.

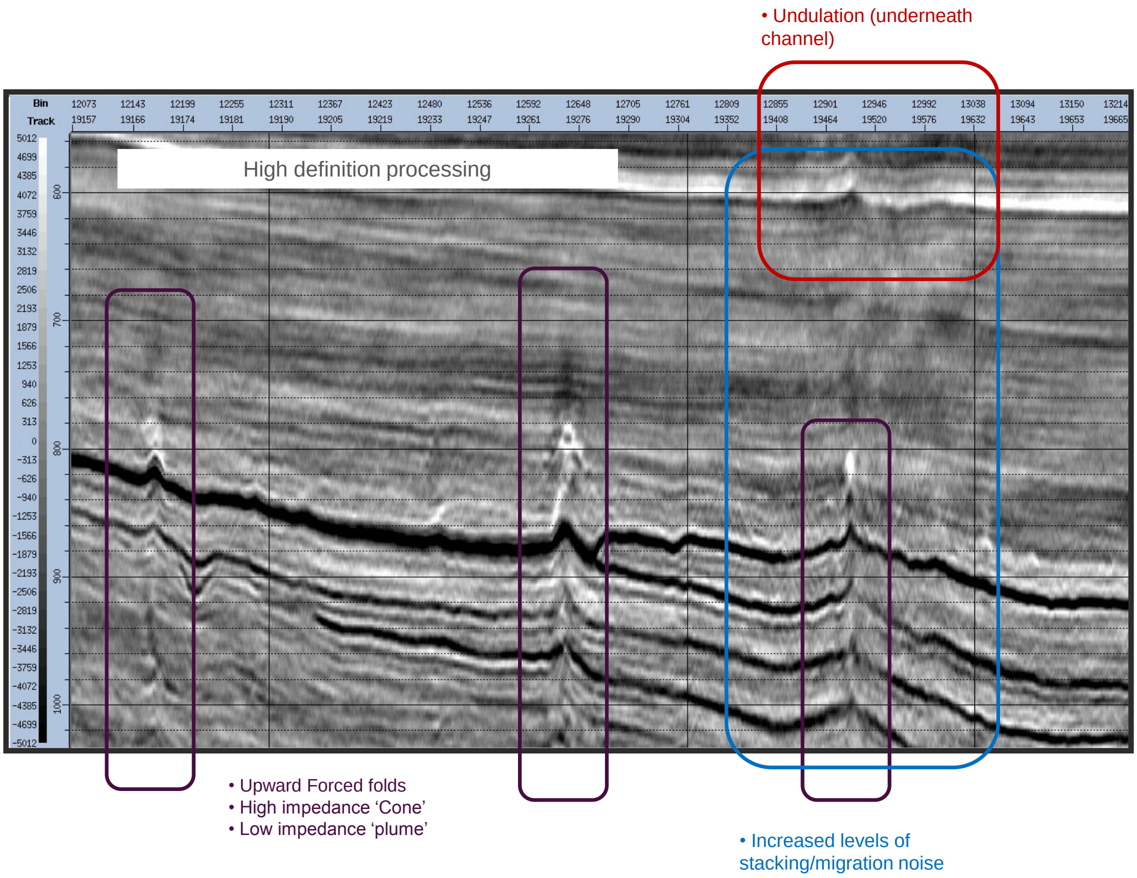

Figure 9-4: HiDef seismic at Beauly level through palaeo-pockmarks (purple boxes).

Note: The area in the blue box shows the combined effect of Pleistocene channel edge noise and a palaeo-seafloor piercement. Note also the undulations at Horda level.

9.4. Eocene Coals and Palaeo-shoreline

The coals are marked by very bright high-amplitude reflectors and are illustrated in Figure 3-3 and Figure 6-2. The coals die out eastwards at linear palaeo-shorelines and create artefacts in the underlying layers (Figure 9-5). These are addressed in the processing & seismic interpretation sections of this report.

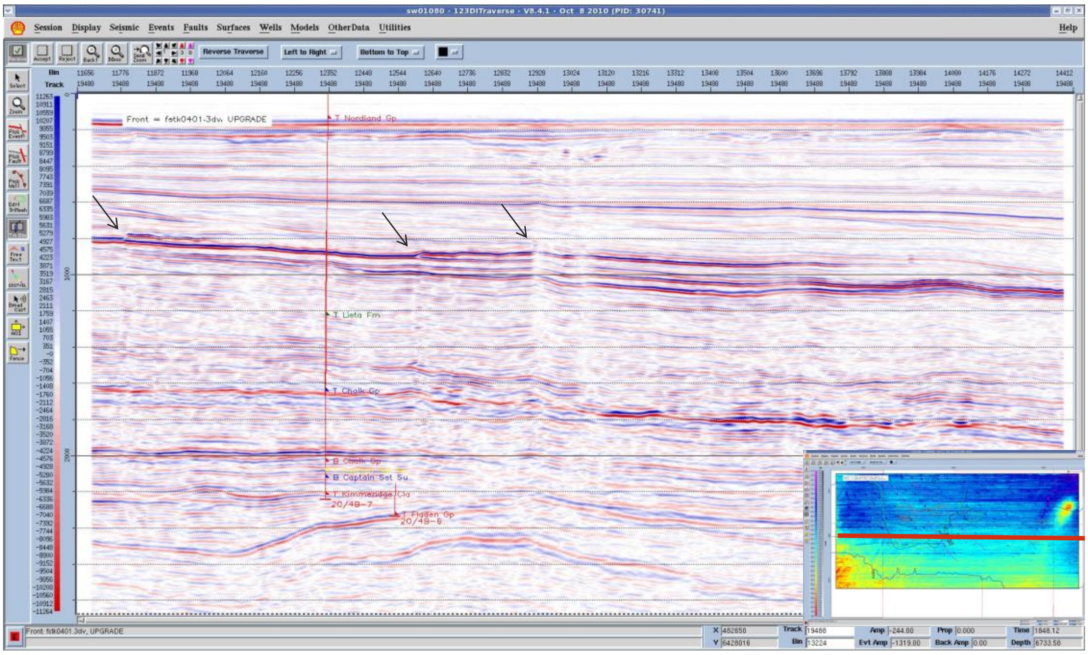

Figure 9-5: Edge of coal layers create vertical seismic disturbance directly below.

Note: Strong amplitude dimming is evident where a coal edge is also aligned beneath a buried glacial channel.

9.5. Lensing effects

In preparation for the Goldeneye CCS project the data acquired and processed in 2001 was scanned for possible conduits from reservoir to surface. A single feature was identified but as the 2001 data quality was limited it was unclear if this feature was an artefact of seismic acquisition/processing or an image of a fluid escape feature. The feature is picked out by a seismic dim zone flanked by a bright zone and was identified near the SE margin of the reservoir. It extends vertically through most of the overburden and underlies the Pleistocene channel.

The seismic data was reprocessed using Shell's proprietary HiDef technique which improved the imaging of the shallow subsurface. On the HiDef data, it could be demonstrated that seismic events were broken or continuous across the feature depending on offset, whereas with a genuine escape pipe the image should be independent of offset (Figure 9-6). The imaging is consistent with a seismic disturbed zone caused by curvature of a refracting surface at or just below the Pleistocene channel base and is clearly not a physical escape structure.

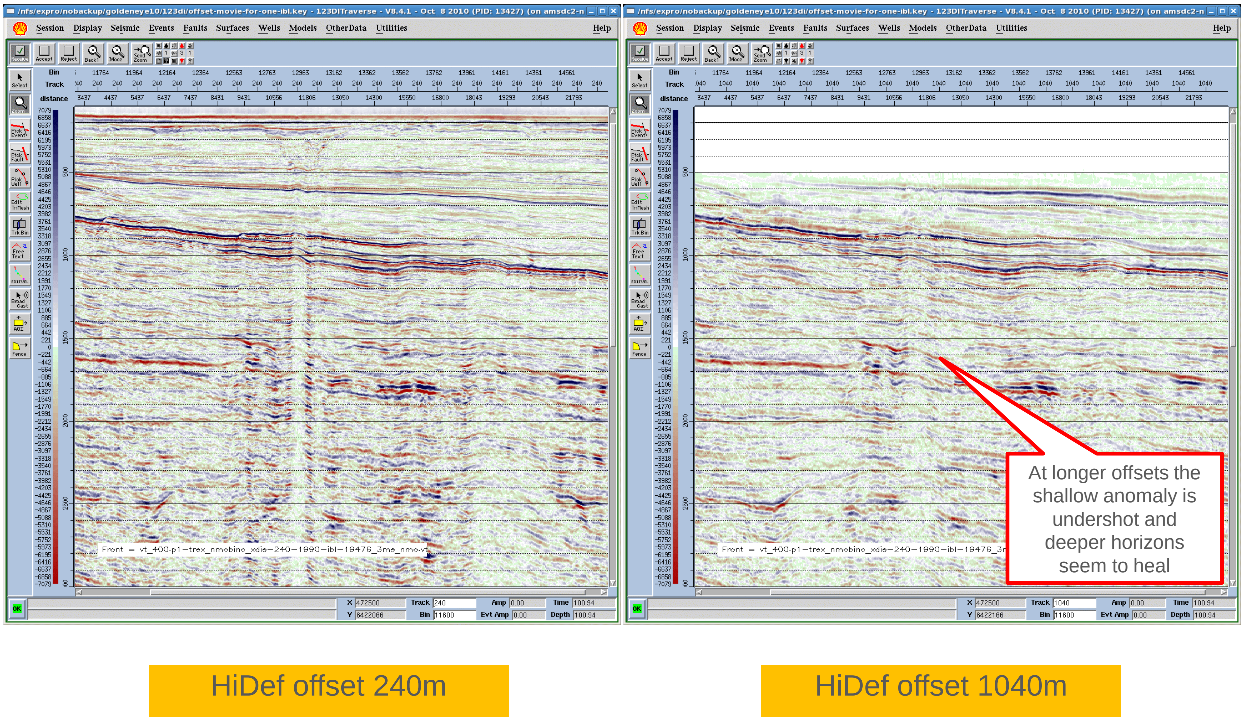

Figure 9-6: Focusing anomaly on HiDef survey

Similar features are well known from other areas of the North Sea and are in the published literature [4] (Figure 9-7).

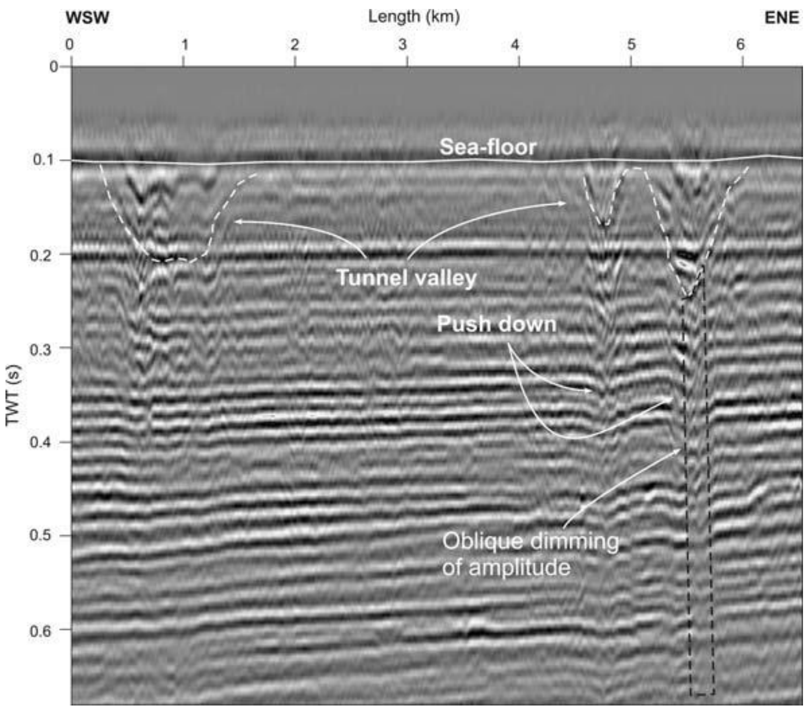

Figure 9-7: Vertical seismic artefacts below tunnel valleys, Danish North Sea

10. Regional Aquifer Seismic Interpretation

The mapping of the Lower Cretaceous Captain Sandstone Fairway over part of the Halibut Trough was carried out across four different seismic projects. The regional seed grid density varied between 250 m to 800 m, depending on the seismic project and the mapping complexity, with an average of some 350 m (see Figure 10-1). In addition to the Top and Base Captain reservoir, the envelope of the Cromer Knoll Formation (Lower Cretaceous) section was also defined by mapping the Base Hidra/Top Rødby and Base Cretaceous Unconformity (BCU) seismic markers. Seismic interpretation of the reflectivity data was carried out on the zero-phased data sets displayed with normal polarity (i.e. an acoustic impedance increase results in a hard kick shown as a red loop and negative number on tape). The seismic character of the mapped horizons is summarised below:

- Base Hidra/Top Rødby: Medium frequent soft (black) loop, low to high amplitude.
- Top Captain Formation: Weak hard (red) loop, frequently discontinuous.
- Base Captain Formation: Weak to medium hard (red) loop, frequently discontinuous.
- Base Aptian Shale: Medium frequent, medium to high amplitude soft (black) loop.
- BCU: Medium soft (black) loop, showing good continuity.

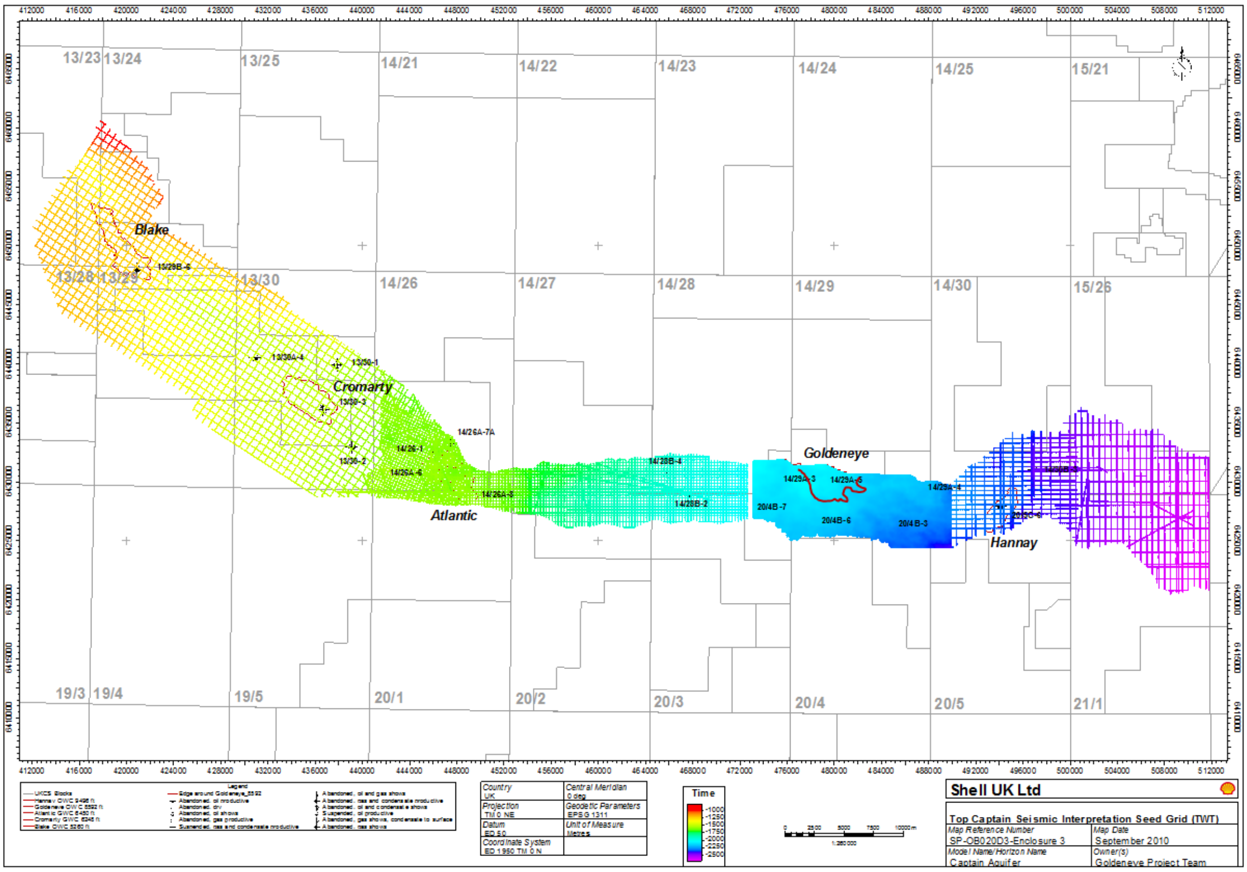

Figure 10-1: Top Captain TWT seismic interpretation seed grid.

After calibration with all the available well penetrations in the Captain Sandstone Fairway over the area of interest, the Top and Base Captain events were tentatively mapped to delineate the reservoir fairway. As mention before, the Captain Sandstone cannot unambiguously be mapped along the fairway due to its weak expression on the seismic data as a result of the poor impedance contrast at top reservoir between the Captain Sandstones and the overlying Rødby shales. As a result, mapping of coeval shales using some of the basinal wells was carried out to constrain the position and extent of the Captain Sandstone Fairway. This was done by mapping the basinal (i.e. shaley) equivalent to the Top Captain reservoir and the Base Aptian shale marker which slightly predates the deposition of the Captain Sandstone reservoirs and is often eroded in the area of sand deposition. The individual seismic interpretations were joined together in the static model with some minor editing where two different survey interpretations overlapped.

Whilst the position of the northward pinchout of the Captain reservoir could be recognised with some confidence, the delineation of the southward shale-out/pinchout appears less reliable, especially in Blocks 13/29 and 20/3b. Within the mapped area, there is no clear evidence observed for large scale faulting (clearly offset reflections) along the Captain Fairway, except in a few areas. There is significant faulting in Blocks 21/1 and 21/2 towards the Glenn Ridge which is interpreted as the easternmost extent of the Captain Fairway (see Figure 10-2). There is also substantial thinning of the Captain interval observed over the Grampian Arch (Blocks 14/26a and 14/27b) to the east of the Atlantic field. It is not clear whether the faulting around the Grampian Arch disconnects the Captain Fairway at this location.

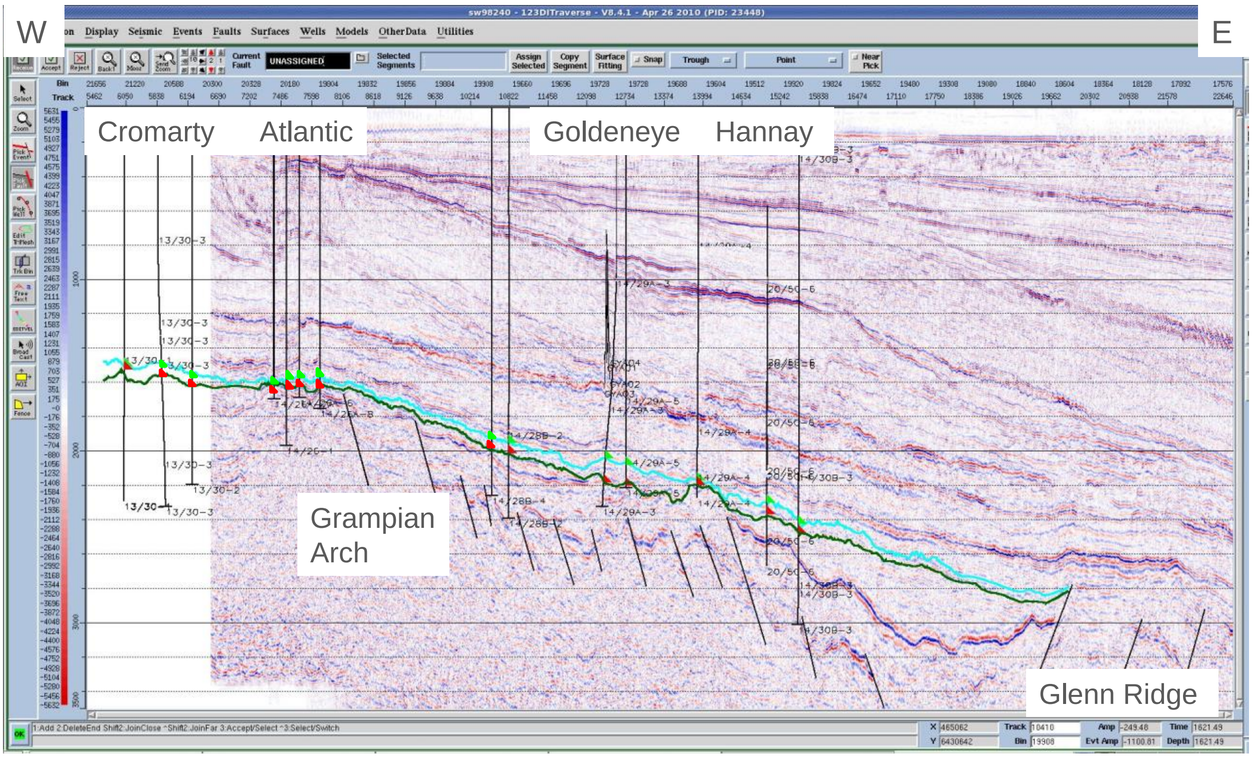

Figure 10-2: Regional west-east seismic section in TWT from the Cromarty Field to the Hannay Field with the Top Captain interpretation (light blue) and the Base Captain interpretation (green).

The Captain Sandstone turbidites were deposited in a deep marine environment, settling around the intra-basinal highs. Two contrasting depositional models exist for the Captain Sandstones along the Halibut Trough. The principle depositional model envisages axial flow of turbidite sands along the Captain Fairway from west to east. The collapse of the southern flank of the Halibut shelf led to the development of a west-east lineament parallel to the southern margins of the Halibut Horst (Jeremiah

2000). Sands accumulated up on the East Orkney High could then flow along the southern flanks of the Halibut Horst into the Cromarty Sub-basin and into the Renee Sub-basin. The alternative model is of sand-prone turbidite fan systems feeding directly off the Halibut Horst from the north. However, it is likely that a combination of both deposition models were active rather than one system or the other. Around the Blake Field, the axial system probably predominates whilst around the Goldeneye Field, and the eastern parts of the fairway, input from northerly sourced sediments are more prominent [5].

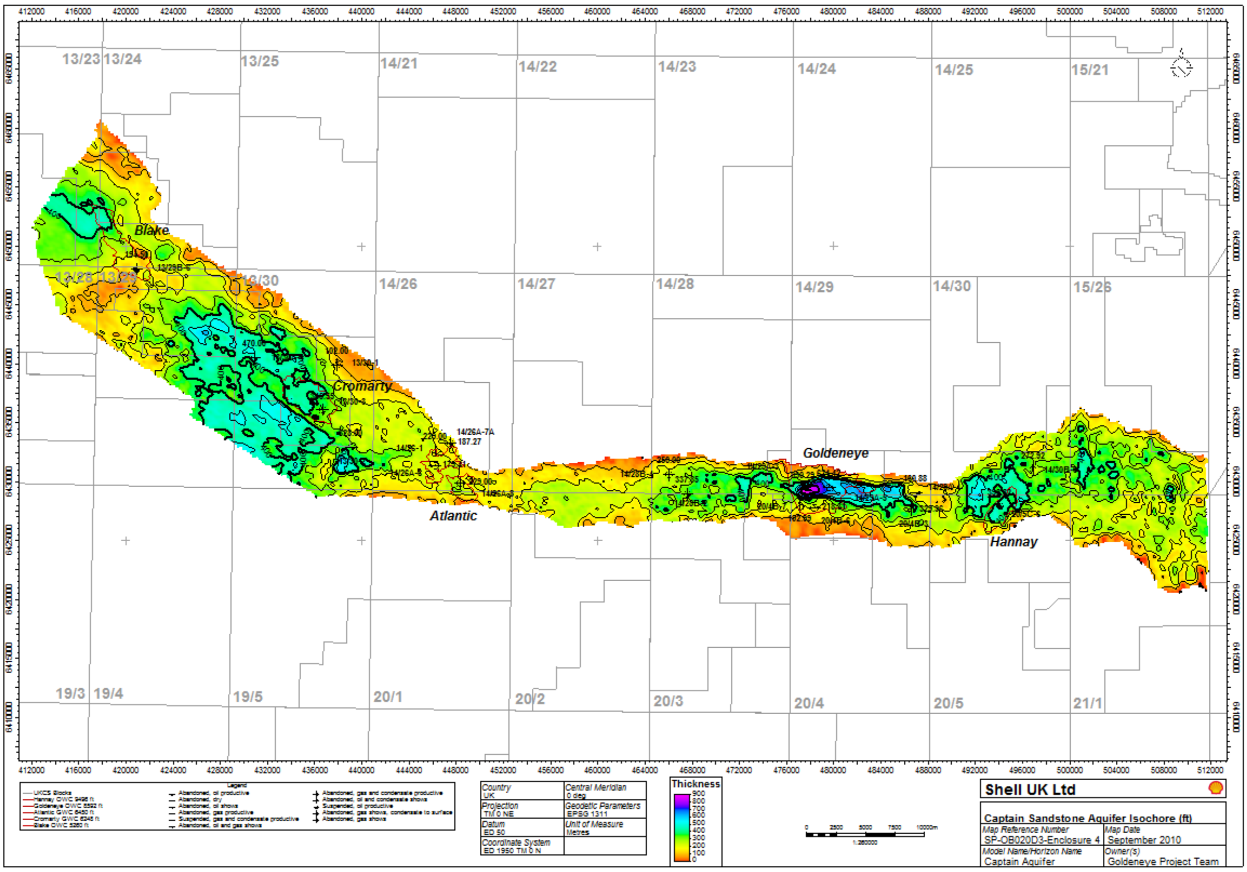

Figure 10-3: Captain Sandstone aquifer model, isochore (ft).

The existing basin topography controlled the sand distribution of the Captain Fairway. The isochore map (Figure 10-3) shows that the thickest deposition of Captain Sandstones occurs in the Goldeneye Field (250 m thick in well 13/29a-3). Typically however, the Captain Fairway is 60-120 m thick. There is a noticeable thinning over the Grampian Arch (a long-lived low relief feature in Blocks 14/26a and 14/27b), to the east of the Atlantic Field. This is the most likely major structural break point preventing communication from the Blake Field through to the Hannay Field. The nature of this disconnect point is perceived to be mainly sedimentological through thinning and resultant N/G deterioration. Dynamic pressure data from the fields however, indicates that some communication could be taking place. The eastern extent of the Captain Fairway is interpreted to be at the Glenn Ridge (Blocks 21/2 and 21/3) where significant faulting appears to offset the Captain Sandstones. Pressure data seems to also support this disconnection here. The western extent of the Captain Fairway is probably limited by the Captain Ridge, a major east-west Mesozoic tilted fault block that forms a west-plunging extension of the Halibut Horst [6] to the northwest of the Blake Field, disconnecting the Captain Field.

11. Regional Aquifer Depth Conversion

Depth conversion in the Halibut Trough is generally complex due to the variable Tertiary lithology and the rugosity of the Top Chalk surface (which marks an important velocity break). Many of the fields along the Captain Fairway have required localised edits to the velocity field in order to achieve closure on the western flanks, counter to the regional dip from west to east. With a significantly expanded wellstock and variable geology the field-specific 7-layer depth conversion used for Goldeneye itself was not applicable across the entire Captain Fairway and an alternative approach was needed.

Regional Top and Base Captain TWT seed grids were appended from several seismic workstation projects, and depth converted in order to construct a simple static model. Three different depth conversion techniques were attempted, and the residual mis-ties were examined:

- VoK technique.
- Average Pseudo-velocity from surface to Top Captain.
- Two layer model Surface-Top Chalk Vav=6,913 ft/s [2,107 m/s] then Top Chalk-Top Captain Vav=13,257 ft/s.

The two layer model (Surface-Top Chalk Vav=6913 ft/s then Top Chalk-Top Captain Vav=13,257 ft/s) actually produced the lowest RMS residuals, but the resulting Top Captain depth map suffered from strong imprinting of the erosive features evident in the Top Chalk depth map (see Figure 11-1).

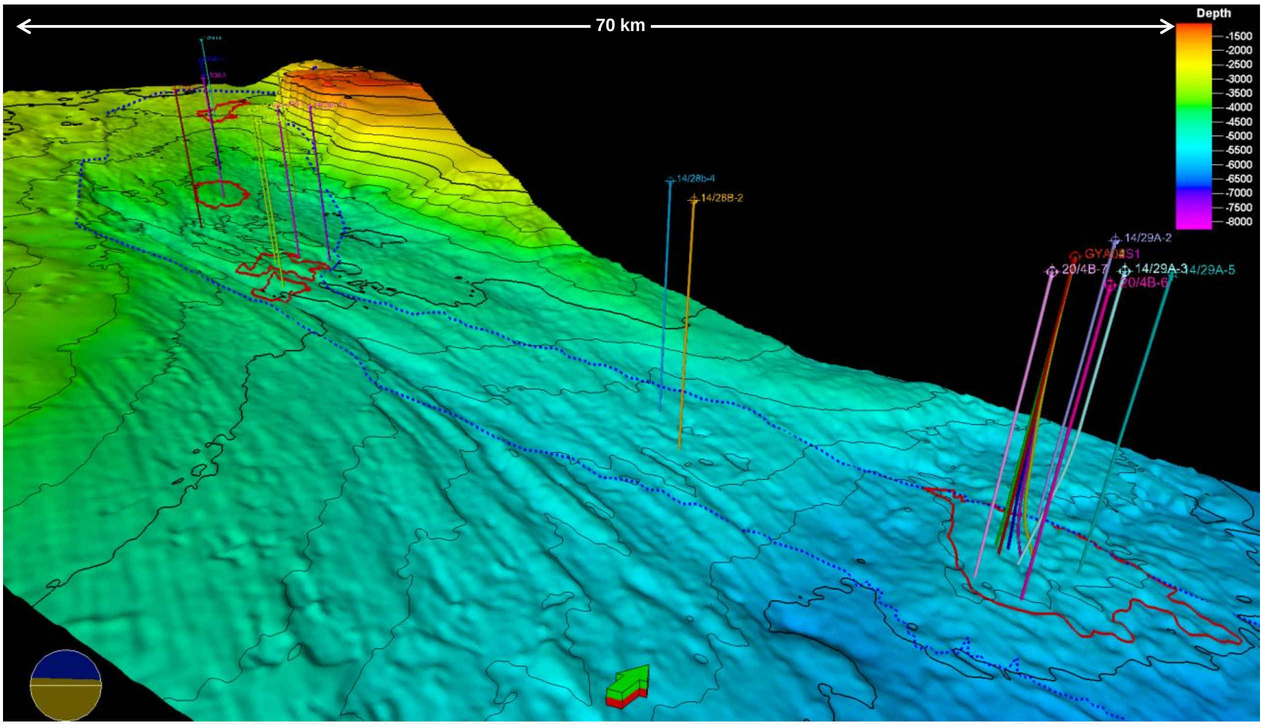

Figure 11-1: Regional Top Chalk depth surface. (Vertical exaggeration x 5).

Note: *Field outlines (red) and Captain Aquifer outline (dark blue) have been superimposed onto this surface. The structural high is the southern flank of the Halibut Horst.*

The regional aquifer 3D static reservoir model is designed to complement the detailed 3D Full Field Static Model (FFSM) and the overburden 3D static model which are being constructed in parallel. The FFSM is designed to model detailed geological features in the Goldeneye Field, and allow dynamic simulation to predict fluid interactions and movements during the injection and post injection periods. The intention is to transfer the results of the detailed dynamic simulation to the other, less detailed models as required, so for example denser formation brine with CO_2 moving by gravity 'out' of the FFSM is modelled regionally in the aquifer model. This means that the three subsurface models must share sufficient common features (such as field volume, reservoir fairway dimensions, etc.) for this to be consistent.

As a result, the Top and Base Captain TWT surfaces were depth converted using an average velocity map. The average pseudo-velocity (from surface to Top Captain) at each well was extracted and the resulting velocity data points were gridded to create an average velocity map across the Halibut Trough AOI (Figure 11-2). This simplified approach was considered fit for purpose as a regional depth conversion.

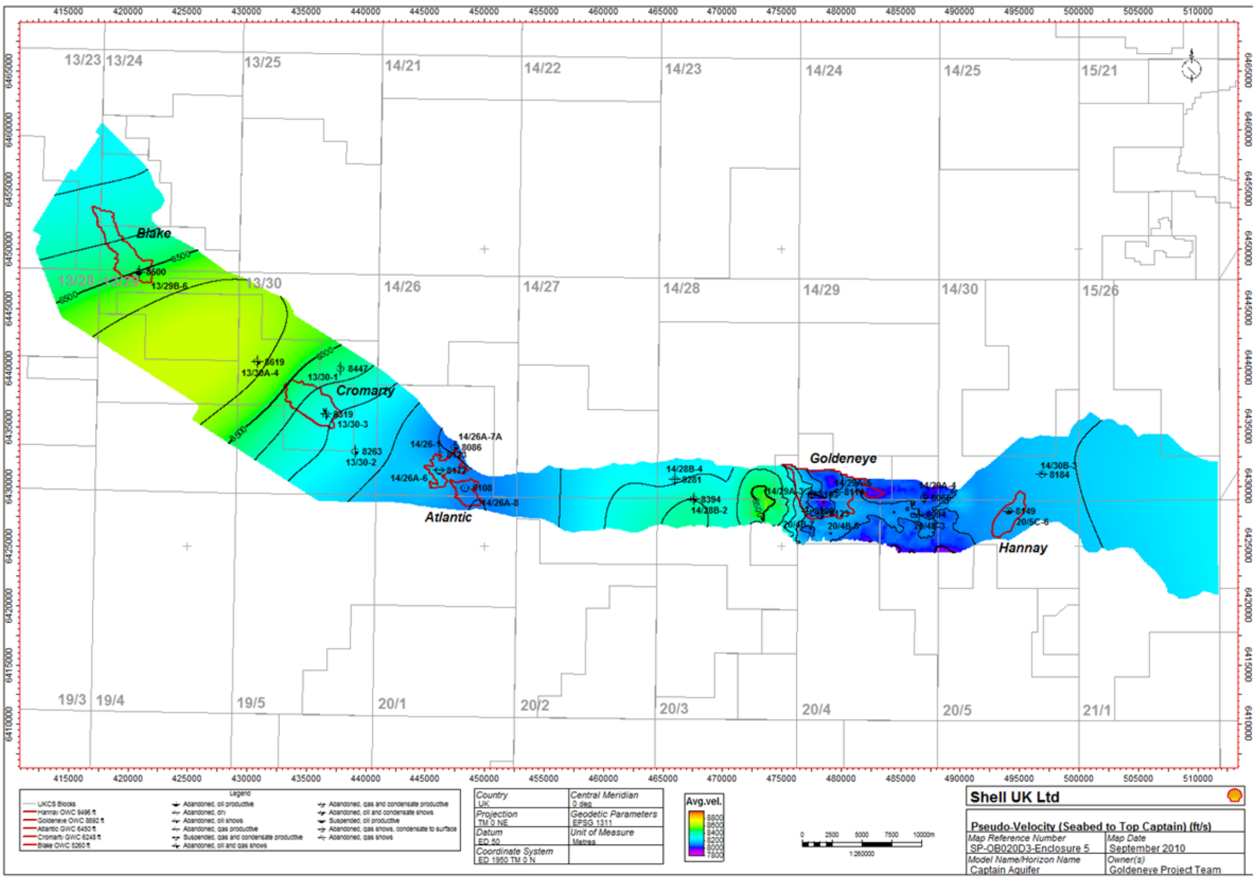

Figure 11-2: Average velocity map (seabed to Top Captain).

Using the regional depth conversion resulted in a slightly altered Top and Base Captain surface over the Goldeneye Field. However, in order for the detailed FFSM to be merged into the regional aquifer model at a future date in the dynamic domain, the exact same structural envelope of the Goldeneye Field was required in both models. As a result, the average velocity over the Goldeneye Field was back-calculated from the Full Field Static Model time and depth surfaces. This velocity grid was spliced into the regional average velocity grid (with smoothing at the interface) and used for depth conversion of the regional TWT seismic interpretations. The result is an identical structure (to the FFSM) over the Goldeneye Field, and an average velocity depth converted Top Captain elsewhere (Figure 11-3).

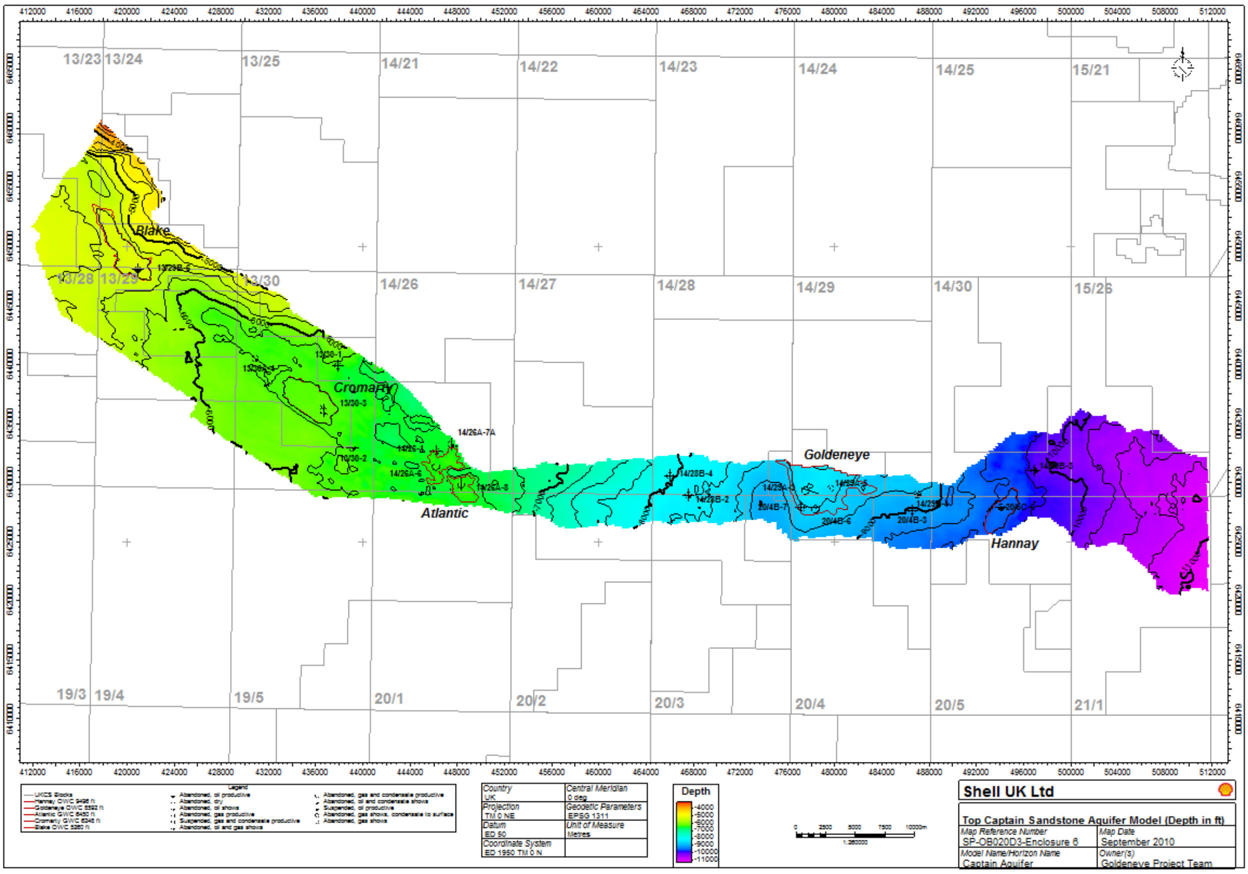

Figure 11-3: Regional Top Captain depth surface (ft).

12. Conclusions

The extensive seismic surveys over the Goldeneye field and the Captain Aquifer have been interpreted and depth converted and the resulting seismic horizons and faults have been used as input data to create three static model suites covering the Goldeneye Field itself, the overburden above the Goldeneye Field, and the regional aquifer of the Captain Sandstone. These suites are described in the document KKD 11.108 “Peterhead CCS Project Static Model Reports” and allow characterisation of the full Goldeneye Storage Complex: the Captain Reservoir; the seal, secondary storage and secondary seal intervals; and the associated aquifer system. These are required to assess the storage and containment capacity of the complex.

The seismic interpretations provide evidence that there are no features indicating leakage from the reservoir and no features that could be considered likely to impair the ability to store CO_2 in Goldeneye.

13. Glossary of Terms

Term	Definition
AGC	Automatic Gain Control
AI	Acoustic Impedance
AOI	Area of Interest
AVO	Amplitude versus Offset
BCU	Base Cretaceous Unconformity
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
E	East
E&A	Exploration and Appraisal
FFSM	Full Field Static Model
GIIP	Gas Initially In Place
GR	Gamma Ray (wireline log)
HiDef	High Definition
Hz	Hertz (SI measure of frequency)
ms	Millisecond
N	North
N/G	Net to Gross
NMO	Normal Moveout
OWC	Oil water contact
PosSTM	Post Stack Time Migration
PreSDM	Pre Stack Depth Migration
QC'd	Quality Controlled
RMO	Residual Move-out
RMS	Root Mean Square
S	South
SCAC	Surface-Consistent Amplitude Correction
SEGD	Standard format for seismic data
SOF	Structure-oriented Filtering
SRM	Static Reservoir Model
Std Dev	Standard Deviation
T	Time
TVDSS	True Vertical Depth Subsea
TWT	Two-Way Time
UKCS	United Kingdom Continental Shelf
W	West

Note: The polarity convention for the seismic data is that a hard kick increase in acoustic impedance is displayed as a negative number, shown as a red loop in all displays and figures in this report.

14. Glossary of Unit Conversions

Table 14-1: Unit Conversion Table

Function	Unit - Imperial to Metric conversion Factor
Length	1 Foot = 0.3048 metres

Table 14-2: Well name abbreviations

Full well name	Abbreviated well name
DTI 14/29a-A3	GYA01
DTI 14/29a-A4Z	GYA02S1
DTI 14/29a-A4	GYA02
DTI 14/29a-A5	GYA03
DTI 14/29a-A1	GYA04
DTI 14/29a-A2	GYA05

15. References

1. **Upper Jurassic. In The Millennium Atlas: petroleum geology of the central and northern North Sea. 2002.** *11: 157-189. Fraser, S.I., Robinson, A.M., Johnson, H.D., Underhill, J.R., Kadolsky, D.G.A, Connell, R., Johannessen, P. and Ravnas, R.*. The Geological Society of London, London.

2. **Timing, nature and sedimentary result of Jurassic tectonism in the Outer Moray Firth. In Tectonic Events Responsible for Britain's Oil and Gas Reserves.** *1990. **55**: 259–279. Boldy, S.A.R., & Brealey, S.*. Geological Society, London, Special Publications.

3. **Lower Cretaceous turbidites of the Moray Firth: sequence stratigraphical framework and reservoir distribution.** *2000. **6**: 309-328. Jeremiah, J.M.*. Petroleum Geoscience.

4. **Multistage erosion and infill of buried Pleistocene tunnel valleys and associated seismic velocity effects. In Glaciogenic Reservoirs and Hydrocarbon Systems.** *2012. **368**: 159-172. Kristensen & Huuse.* Geological Society, London, Special Publications.

5. **The Kopervik fairway, Moray Firth, UK.** *2000. **6**: 265-274. Law, A. et al.*. Petroleum Geoscience.

6. **Reservoir characterisation in the Captain Field: integration of horizontal and vertical well data.** *1999. : 1101-1113. Rose, P.T.S.*. Petroleum Geology of Northwest Europe: Proc. of the 5th Conference.