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1.0 Executive Summary

Storage in the Bunter Sandstone in the 4-way dip closure known as Bunter Closure 36 (UKCS block 44/26) in the Southern North Sea.

5 well development of Bunter Closure 36 from an unmanned platform supplied with CO_2 from Barmston via a 20" 160km pipeline.

Final investment decision in 2023 and first injection in 2027.

Capital investment of £254 million (PV10, 2015), equating to £0.9 for each tonne stored.

The store can contain the 280Mt from the assumed CO_2 supply profile of 7Mt/y for 40 years.

Storage capacity is strongly linked to injection rate.

This Energy Technologies Institute (ETI) Strategic UK CCS Storage Appraisal project has been commissioned on behalf of the Department of Energy and Climate Change. The project brings together existing storage appraisal initiatives, accelerates the development of strategically important storage capacity and leverages further investment in the building this capacity to meet UK needs.

The primary objective of the overall project is to down-select and materially progress the appraisal of five potential CO_2 storage sites on their path towards final investment decision (FID) readiness from an initial site inventory of over 500. The desired outcome is the delivery of a mature set of high quality CO_2 storage options for the developers of major power and industrial CCS project developers to access in the future. The work will add significantly to the de-risking of these stores and be transferable to storage developers to complete the more capital intensive parts of storage development.

Bunter Closure 36 was selected as one of five target storage sites as part of a portfolio selection process the Strategic UK CCS Storage Appraisal Project. The rationale behind the screening and selection is fully documented in the following reports:

- D04: Initial Screening & Down-Select (Pale Blue Dot Energy; Axis Well Technology, 2015)
- D05: Due Diligence and Portfolio Selection (Pale Blue Dot Energy; Axis Well Technology, 2015)

The Bunter Closure 36 site is one of many dome shaped/ elongate anticline structural closures within the Lower Triassic Bunter Sandstone Formation of the Bacton Group. It is located in the Silver Pit Basin, Blocks 44/26 and 44/27 of the UK sector of the Southern North Sea (SNS), approximately 150 Km off the Yorkshire coast, as illustrated in Figure 1-1. The site partially overlies the deeper Carboniferous Schooner Gas Field. The majority of these structures, including Closure 36, are brine-filled however there are some gas fields in the Bunter Sandstone, formed in areas where thinning of the underlying Zechstein salt allowed a short-lived hydrocarbon charge.

The primary storage unit is the Triassic Bunter Sandstone Formation, part of the Bacton Group. It is an extensive sandstone unit that stretches from Poland, Germany and Denmark in the East, to the UK sector of the Southern North Sea, outcropping UK onshore as the Sherwood Sandstone, and stretching to the East Irish Sea where it is known as the Ormskirk Sandstone.

The Bunter Sandstone was deposited in a fluvially dominated environment, mainly as sheet floods on a broad low relief alluvial plain in arid to semi-arid climate resulting in continuous but tortuous flow paths due to locally preserved channel abandonment, overbanks silts, and later digenetic cements acting as baffles. The formation rock quality is good with net to gross ratio over 0.8, average porosity of 22% and average permeability 200 mD (max 1970 mD). The depth to the crest of the structure is 1171m tvdss (3841 ft tvdss) and the Bunter Sandstone thickness at the site is approximately 215m.

Secure containment is provided by multiple seals. The primary seal is the Rot Halite Member which is typically continuous and 60m thick. The overlying Haisborough Group of laterally extensive mudstones is over 300m thick and provides the secondary seal for the Bunter Sandstone.

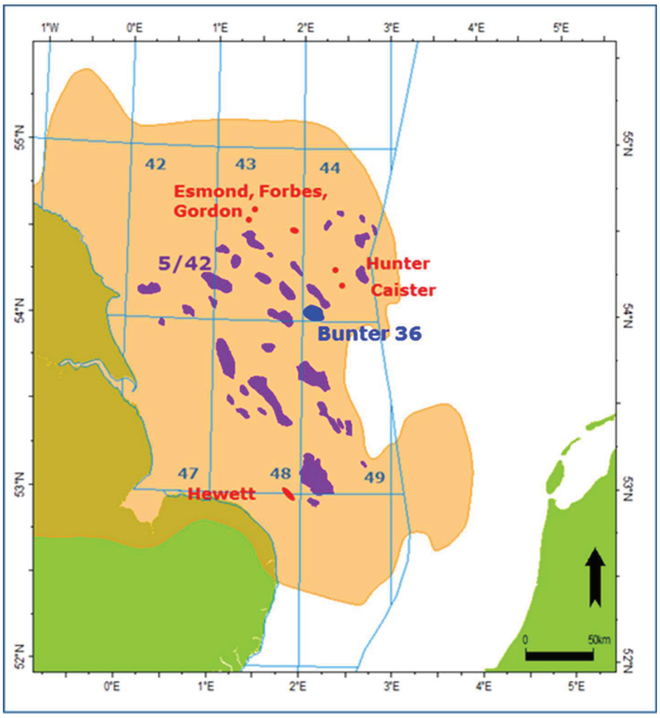


Figure 1-1 - Bunter Closure 36 Location Map

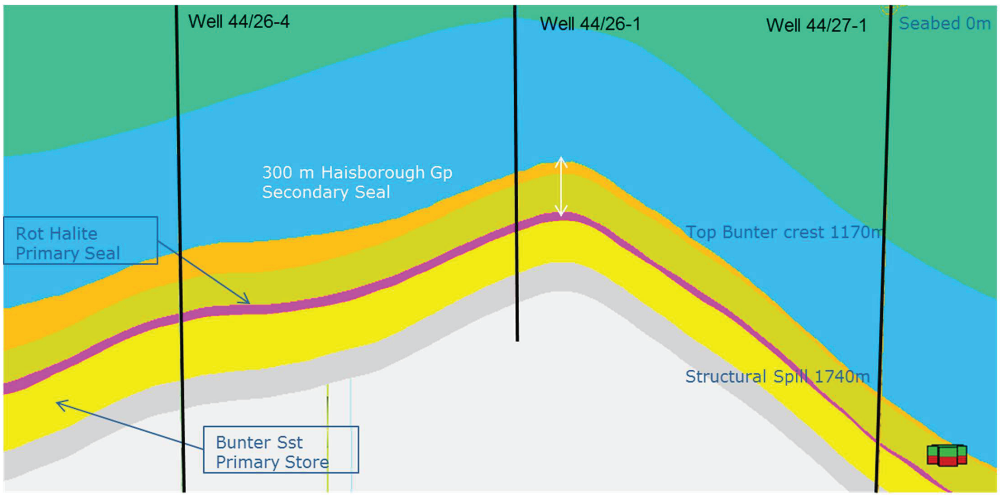


Figure 1-2 - Bunter Closure 36 Store and Seals

The basis for the development plan is an assumed supply of 7Mt/y of CO_2 from Barmston on the east coast of Yorkshire commencing in 2027. This would be representative of the CO_2 emissions from a 1200MW coal-fired power station. Typically power stations have an operational life of approximately 40 years and this has been adopted as the project life.

The Bunter Closure 36 development will consist of a new 160km 20" pipeline from Barmston to a newly installed multi-deck, minimal facilities platform on a 4-legged steel jacket in 75m of water. The infrastructure will have a design life of 40 years. The installation will be controlled from a shore base via dual redundant satellite links with system and operational procedures designed to minimise offshore visits. The installation will be capable of operating in unattended mode for up to 90 days with routine maintenance visits.

The well placement strategy is driven by geology, Bunter Closure 36 structural geometry, reservoir engineering considerations and the economics of development. To achieve the desired injection rate, 5 deviated injection wells will be located on the north west flank of the structure penetrating the full Upper Bunter sand sequence. The wells will be drilled using a jack-up rig positioned over the platform in a single drilling programme to Bunter Sandstone targets at approximately 1350m tvdss. Development well driling time will be around 77 days. No unusual drilling hazards are anticipated. Well life is assumed to be 20 years and consequently, provision has been made to replace all wells half-way through the development.

During the operational period 4 of the wells are expected to be injecting at any point in time with the 5th as backup in the event of an unforeseen well problem. In this manner, the facilities will maintain a robust injection capacity and inject 7Mt/y of CO_2 for the 40 year project life without breaching the safe operating envelope. Over the period a total of 280Mt CO_2 will have been stored and the structure could contain an additional 111Mt CO_2 at the same injection rate

The development schedule has 5 main phases of activity and is anticipated to require 7 years to complete, as illustrated in Figure 1-3. The schedule indicates that FEED, appraisal and contracting activities will commence 2-3 years prior to the final investment decision (FID) in 2022/23. The capital intensive activities of procurement and construction follow FID and take place over a 4-5 year period. First injection is forecast to be in mid-2027.

The development of the offshore transportation and injection infrastructure is estimated to require a capital investment of £254 million (in present value terms discounted at 10% to 2015), equating to £0.9/T. The life-cycle costs are estimated to be £347M (PV10), equating to a levelised cost of £15.9/T, as summarised in Table 1-1.

Whilst there is good seismic and reasonable well data coverage across the site, there are some key uncertainties and data gaps which will require careful and considered appraisal effort ahead of any development decision. Specifically this would include a new 3D seismic survey to eliminate the complexities associated with a merged 3D seismic data set. This will also provide a baseline survey from which quantitative 4D seismic monitoring of injected CO_2 can be performed. In addition, an appraisal well will be required to reduce uncertainty in reservoir quality distribution across the site and collect reservoir and caprock core and fluid samples to support detailed development planning. The well will be located to provide important information on the seismic velocity field above the target store to further improve the depth imaging of the top reservoir structure ahead of any development.

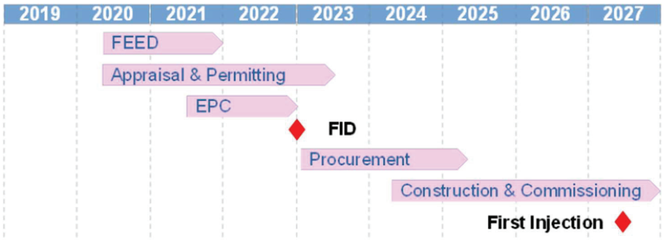


Figure 1-3 - Summary Development Schedule

£ million (PV10 in 2015)	Phase I	Phase II	Total
Transportation	117		117
Facilities	48		48
Wells	77	12	89
Opex	90		90
Decommissioning & MMV	3		3
Total	335	12	347

Table 1-1 Project Cost Estimate

A series of recommendations for further work are provided towards the end of this report. The principal ones being:

- Improve the characterisation of the regional and local aquifer by procuring and analysing pressure and production data from nearby fields and integrate this with a regional study of the evolution of the structure of the Bunter Sandstone reservoir and its formation fluid over time to fully understand the controls and timing of gas charge and local/regional reservoir quality development.
- Develop a detailed justification for the location of the appraisal well so that it can deliver maximum uncertainty reduction and value of information.
- Consider running the simulation model with finer vertical layering to eliminate any uncertainty associated with modelling technique on development well placement.
- Review in detail the options for cost and risk reduction across the development including potential synergies with other offshore operations and perhaps also designing the appraisal well such that it might be retained as a potential injector.

2.0 Objectives

The Strategic UK CCS Storage Appraisal Project has five objectives, as illustrated in Figure 2-1.

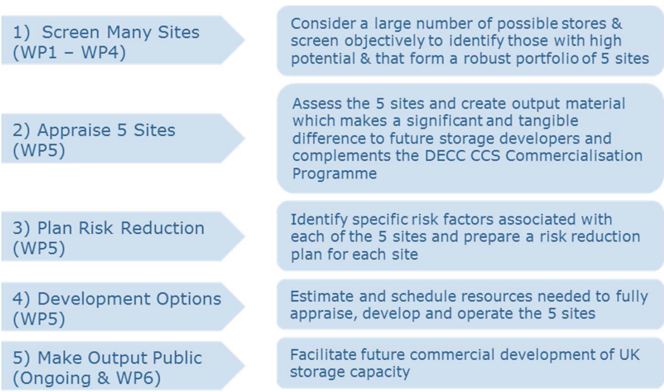


Figure 2-1 - The Five Project Objectives

Bunter Closure 36 is one of the five CO_2 storage targets evaluated as part of Work Pack 5 (WP5). The primary objective of this element of the project is to advance understanding of the nature, potential, costs and risks associated with developing the site, with the data currently available to the project and within normal budget and schedule constraints. The output fits within the broader purpose of the project to "facilitate the future commercial development of UK CO_2 storage capacity".

This report documents the current appraisal status of the site and recommends further appraisal and development options within the framework of a CO_2 storage development plan. An additional objective of this phase of the project is to provide a repository for the seismic and geological interpretations, subsurface and reservoir simulation models. These items have been supplied separately and are listed in Appendix 11.

WP5 has seven principal components:

1. Data collection & maintenance.
2. Seismic interpretation and structural modelling.
3. Containment.
4. Well design and modelling.
5. Site performance modelling.
6. Development planning.
7. Documentation and library.

These components and their contribution to the storage development plan are illustrated in Figure 2-2.

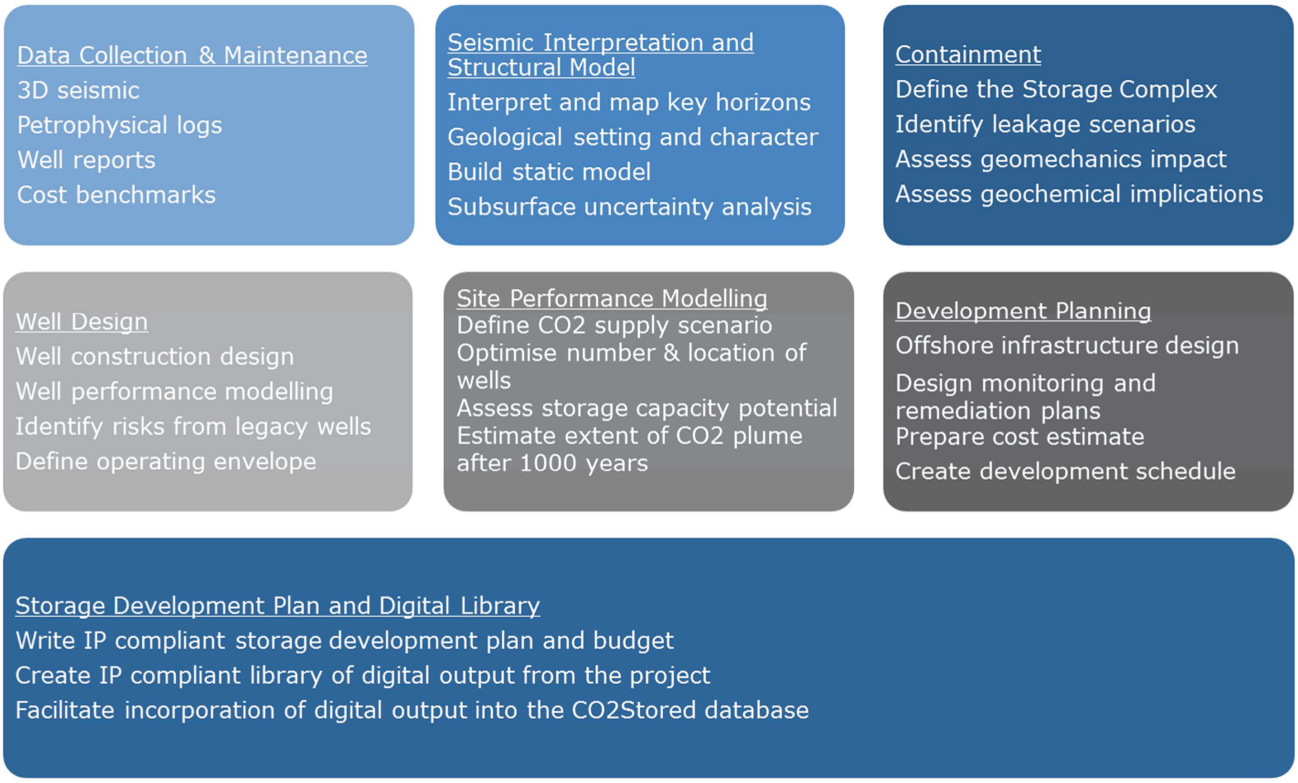


Figure 2-2 - Seven Components of Workpack 5

3.0 Site Characterisation

3.1 Geological Setting

Bunter Closure 36 was selected as part of a portfolio of five target storage sites in the Strategic UK CCS Storage Appraisal Project. The rationale and process behind the screening and selection is fully documented in the following reports:

- D04: Initial Screening & Down-Select (Pale Blue Dot Energy; Axis Well Technology, 2015)
- D05: Due Diligence and Portfolio Selection (Pale Blue Dot Energy; Axis Well Technology, 2015)

The Bunter Closure 36 site is one of many dome shaped / elongate anticline structural closures within the Lower Triassic Bunter Sandstone Formation of the Bacton Group in the Southern North Sea (SNS). It is located in the Silver Pit Basin in UKCS blocks 44/26 and 44/27, approximately 150 Km off the Yorkshire coast.

The primary storage unit is the Triassic Bunter Sandstone Formation which is part of the Bacton Group. It is an extensive sandstone unit that stretches from the Poland, Germany and Denmark in the East, to the UK sector of the Southern North Sea, outcropping onshore in England as the Sherwood Sandstone, and stretching to the East Irish Sea where it is known as the Ormskirk Sandstone.

Bunter Closure 36 is underlain by the deeper Carboniferous Schooner Gas Field. This was discovered in 1987 by 44/26-2 with first gas production in 1996. According to Wood Mackenzie analysis commissioned as part of this study, the Schooner field, currently operated by Faroes Petroleum, is due to cease commercial production in 2021.

The distribution of the Bunter Sandstone Formation in the UK sector of the SNS, and the location of other Bunter Sandstone Formation closures, is shown in Figure 3-1.

Within the UK CCS commercialisation effort over the past ten years, two other significant Bunter Sandstone storage sites have been evaluated to FEED level. The Hewett depleted gas field in the southern part of the gas basin was the subject of detailed investigations by Eon as part of the Kingsnorth CCS project in 2011. The results of this work are available in the UK Government web archive as knowledge transfer products. The proposed 5/42 “Endurance” site has also been studies to FEED level by National Grid Carbon. Whilst there is an expectation that the results of this project will be put into the public domain, at the time of this report, very little detailed information is available. This project has benefited however from guidance provided by experts from National Grid Carbon on several matters of key importance.

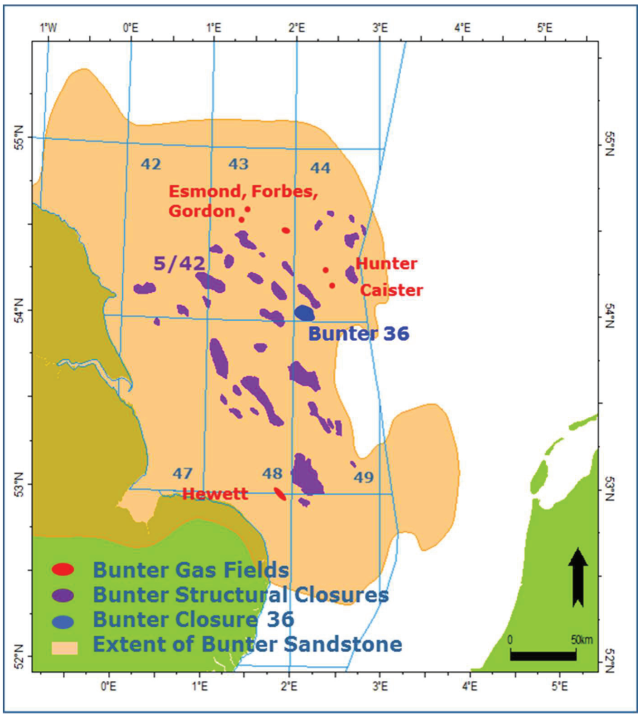


Figure 3-1 - Location Map

3.2 Site History and Database

3.2.1 History

Bunter Closure 36 is a dome shaped structural closure. The structure is the result of tectonic movement during the mid-Triassic which initiated halokinesis (salt movement) within the underlying Zechstein. This continued through into the Tertiary and formed the many dome and pillow structures observed today in the overlying Bunter Sandstone.

There are no seismically interpretable faults within the Bunter Sandstone over the site area, although a small number of faults are observed within other structures elsewhere in the Bunter Sandstone fairway.

Some fault offsets can be interpreted higher up the stratigraphy within the Chalk Group.

3.2.2 Hydrocarbon Exploration

Within the SNS the Bunter Sandstone is largely a saline aquifer, many of the Bunter dome structures have been drilled and shown to be water bearing. Migration from deeper Carboniferous source rocks is impeded by thick sequences of shale and evaporates within the underlying Permian

These structures do however form the reservoir for a small number of gas fields (including Esmond, Forbes, Gordon, Hunter to the North and Caister to the East) proving the integrity of the top seal. In these instances, salt withdrawal and thinning of the Zechstein have opened up migration pathways into the Triassic from deeper underlying Carboniferous source rocks. Bunter Closure 36 has been the target of exploration drilling in 44/26-1 and 44/26-3. These wells were located very close to the observed structural crest of the structure and contained no hydrocarbon shows in the Bunter Sandstone. Whilst the possibility of a very thin gas column updip of 44/26-1 cannot be discounted (since such thin columns are typical of the Bunter gas fields in the area), Bunter Closure 36 is considered most likely to be fully water bearing.

Seismic

There are many 2D and 3D seismic data sets available over and around the area of Bunter Closure 36 which have resulted from years of hydrocarbon exploration and development activity. The seismic data set used for the Bunter Closure 36 site interpretation was the PGS Southern North Sea MegaSurvey (PGS, 2015). These data were loaded to Schlumberger's proprietary PETREL software where the seismic interpretation was undertaken. Figure 3-2 shows the extent of seismic available together with the area of the fairway interpretation and site model. Interpreted surfaces were interpolated across areas not covered by the seismic data. There is complete seismic coverage over the area of the Bunter 36 site however the seismic volume is made up of several different volumes that have been merged post stack (Figure 3-3).

Seismic data SEGY summary is provided in Appendix 3.

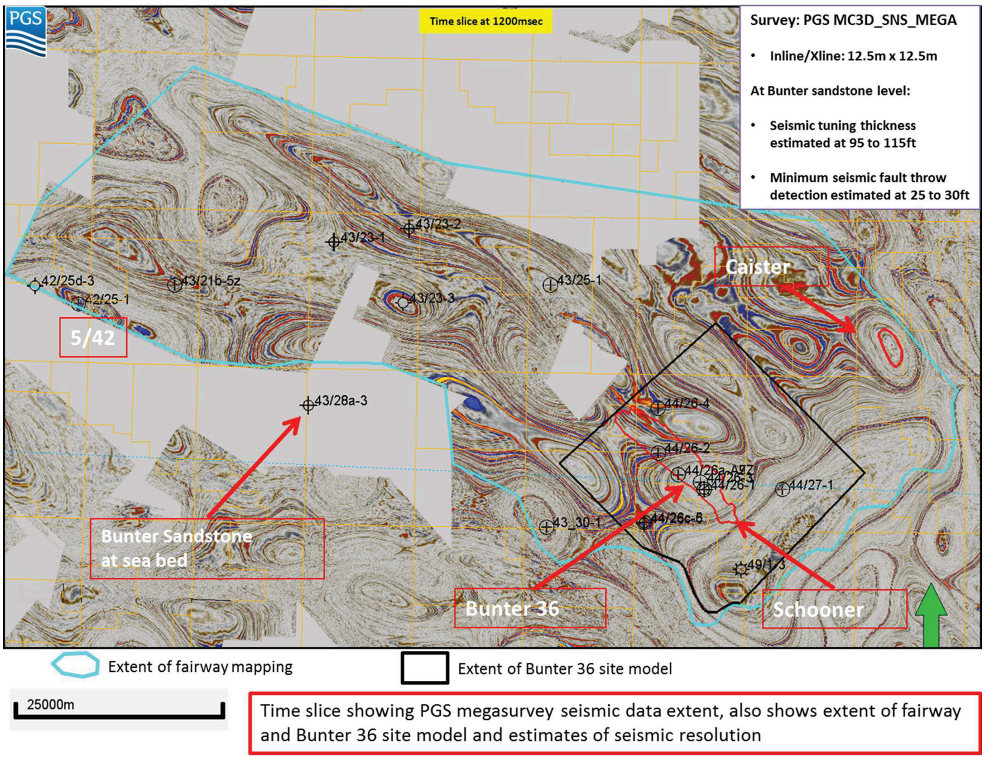


Figure 3-2 - Extent of Seismic Survey

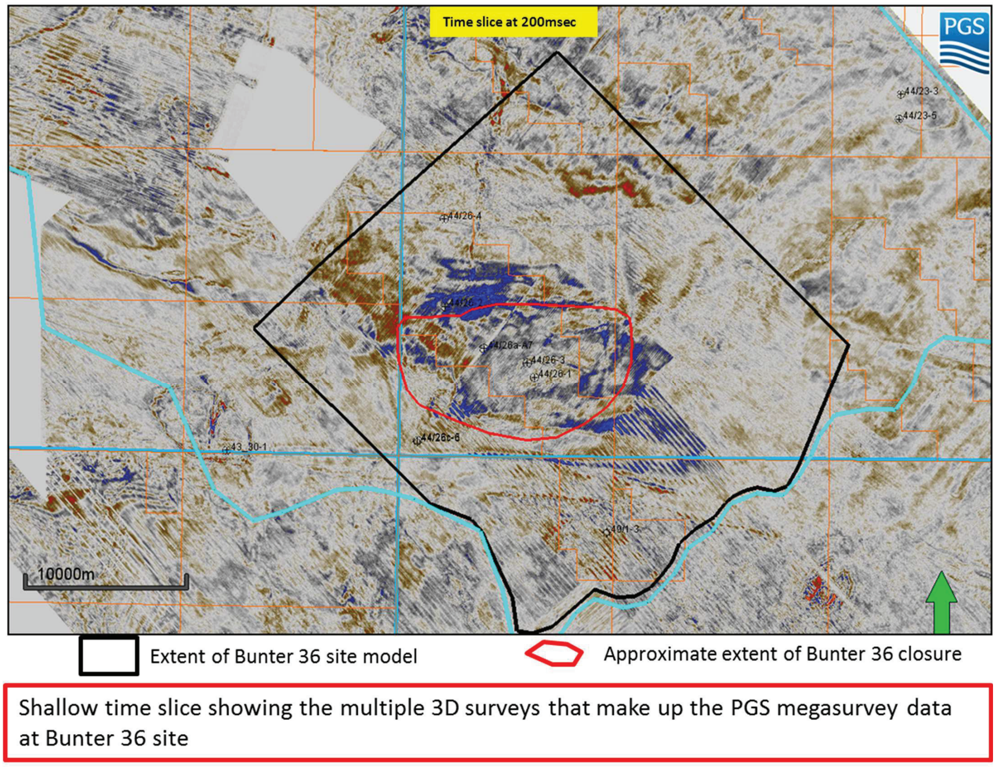


Figure 3-3 - Multiplicity of Sesimic Surveys in Data Set

3.2.3 Wells

All well log data was sourced from the publically available CDA database. These data are variable in range and quality, but generally included LIS or DLIS formatted tapes, field reports, end of well reports, composite logs and core reports. 28 wells were sampled from CDA and used for a range of activities from site to regional characterisation. These included wells from nearby Schooner and Caister gas fields as well as wells from the 5/42 structure. The most recent well drilled by National Grid, 42/25d-3 in 2013 was not available to the study - other than those aspects reported in (Furnival, et al., 2013).

A total of 15 wells across the interpreted fairway were screened for petrophysical evaluation, Table 3-1. From this inventory 11 wells were selected that have suitable data for quantitative reservoir quality analysis over the Bunter reservoir interval (4 of these are located within the Primary static model area). Of the 11 selected wells, only 4 have conventional core data (1 of these is located within the site model area). No SCAL data was identified from the available CDA database.

The quality of the wireline data is generally good. Where there was some uncertainty in log quality it was possible to reference back to the composite log or final well reports for guidance. Figure 3-4 shows the wells used for the seismic interpretation. 11 wells contain time depth information and 6 wells contained sonic logs. Within the defined storage complex, 8 wells were analysed, with only one of these having core information.

An inventory of well data accessed for the study is included in Appendix 3.

Well	Bunter	Within site storage complex?	Wireline	MWD	Core	Mud Type
42/25-1	✓	×	✓		✓	OBM
43/23-3	✓	×	✓			OBM
43/25-1	✓	×	✓			na
44/23-3	✓	×	✓		✓	na
44/23-5	✓	×	✓		✓	WBM
44/23a-A3	✓	✓	✓			Salt Sat WBM
44/26-1	✓	✓	✓		✓	Salt Sat WBM
44/26-2	✓	✓	✓			WBM
44/26-3	×	✓				
44/26-4	✓	×	✓			OBM
44/26a-A7	×	✓		✓		-
44/26a-A9Z	×	✓	✓	✓		-
44/26c-5	✓	✓	✓			OBM
44/26c-6	×	✓		✓		OBM
44/27-1	✓	✓	✓			OBM

Table 3-1 - 15 wells screened for petrophysical evaluation

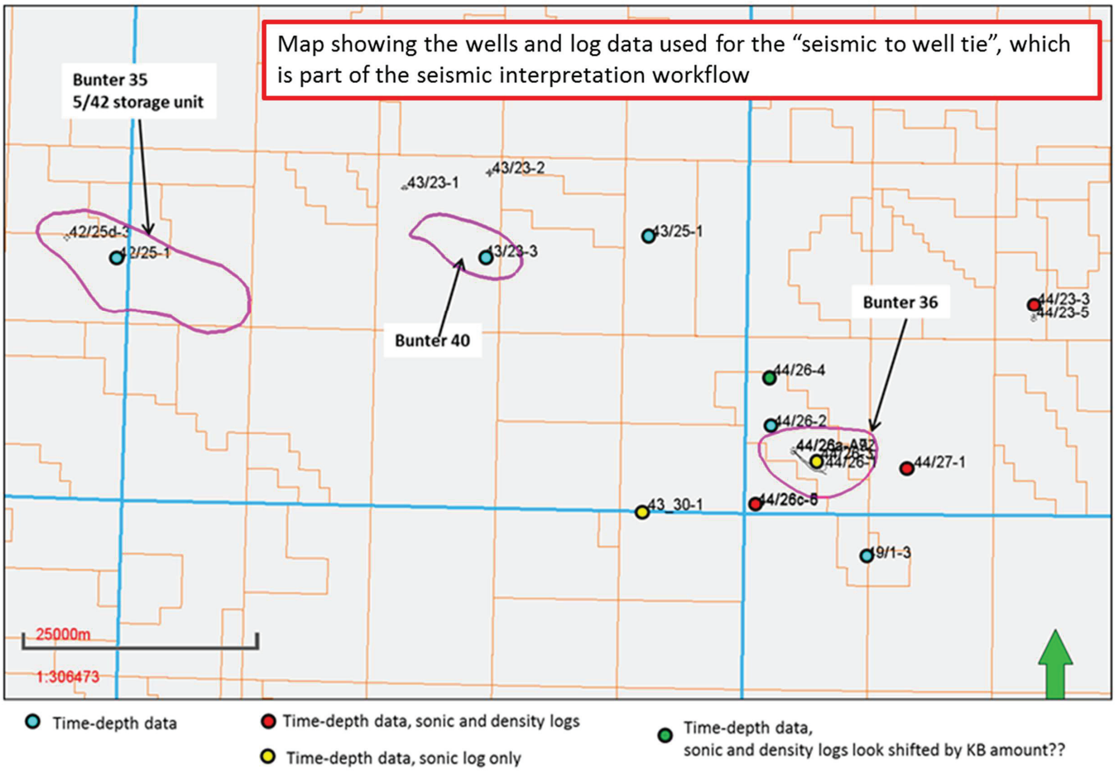


Figure 3-4 - Wells used in Seismic Interpretation

3.2.4 Other

Other information used in this characterisation of Bunter Closure 36 is broadly divided into three parts:

- Public domain information, such as Caister production records.
- Data available under license - this includes data from CO2Stored and also Wood Mackenzie estimates of cessation of economic production dates.
- Data available under non-disclosure agreements from petroleum operators which have been used for general guidance only consistent with the terms of the NDA.

3.3 Storage Stratigraphy

A stratigraphic column of the site area is shown in Figure 3-5.

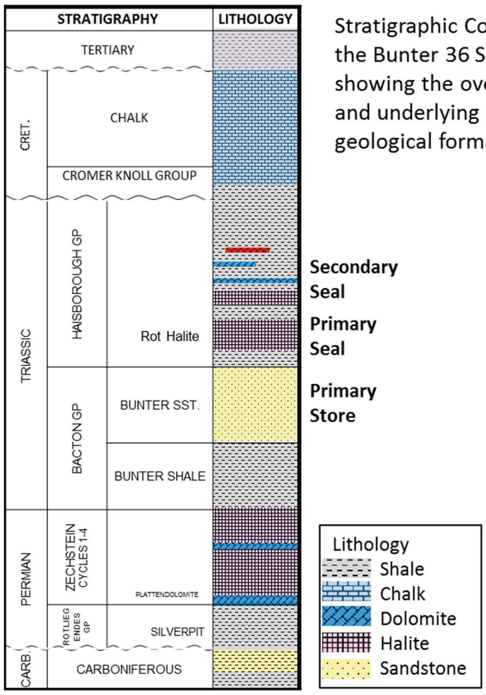


Figure 3-5 - Stratigraphic Column

Carboniferous

The deepest wells in the site area penetrate Carboniferous rocks of the underlying Schooner Field. The oldest formations observed in wells belong to the Namurian aged fluvio-deltaic Millstone Grit Group which is overlain by over 900 m (almost 300 ft) of the Westphalian coal measures succession (Moscariello, 2003).

Permian

The Lower Permian is represented by playa-lake sediments (interbedded shales and evaporates) of the Silverpit Formation, these are the lateral equivalent of the aeolian sands of the Leman Sandstone Formation deposited to the South. This is overlain by thick sequence of Upper Permian, Zechstein evaporites comprising thick halites, with anhydrites together with dolomite and limestone intervals. These were deposited in a large enclosed sea during the Late Permian.

Triassic

The continued contraction of the Zechstein Sea into the Early Triassic resulted in the SNS basin becoming the site of continental clastic sedimentation and the deposition of the Bacton Group. The Permian-Triassic boundary associated with a distinct lithology change where the Triassic Bunter Shale overlies the Permian Zechstein evaporites.

The thick mudstones of the Bunter Shale represent the maximum extent of an early Triassic playa lake. These were gradually replaced by deposition of the sands and silts of the Bunter Sandstone, prograding into the centre of the basin as a series of depositional pulses. The Bunter Sandstone thickness ranges from 0 – 350m (0 – 1150 ft) in the SNS, the Bunter Sandstone thickness at the site location is approximately 215 m (700 ft).

The overlying Haisborough Group forms a thick and laterally extensive sequence of multiple sealing formations for the Bunter Sandstone. It marks the re-establishment of restricted marine influences and is comprised of a thick sequence of mudstones, claystones and evaporates commonly more than 500m in thickness (Heinemann, Wilkinson, Pickup, Haszeldine, & Cutler, 2011), deposited as distal flood plain and shallow marine, alternating with coastal sabkha (Glennie, 1998).

Jurassic

Whilst present in the west of the basin, the Jurassic and top of the Triassic are eroded by the Base Cretaceous Unconformity (BCU) at Bunter Closure 36. Uplift to the east and north have essentially stripped any Jurassic and Late Triassic sediments that were deposited.

Cretaceous

A thin section of Cromer Knoll is overlain by approximately 800 m of the Chalk Group comprising limestones, chalks and marls.

Tertiary - Quaternary

The upper part of the stratigraphic sequence is over 400m of often unconsolidated clays and muds.

3.4 Seismic Characterisation

3.4.1 Database

The seismic data set used for the Bunter Closure 36 site interpretation was the PGS Southern North Sea MegaSurvey (PGS, 2015). These data were loaded to Schlumberger's proprietary PETREL software where the seismic interpretation was undertaken. Figure 3-2 shows the extent of seismic available together with the area of the fairway interpretation and site model. Interpreted surfaces were interpolated across areas not covered by the seismic data. There is complete seismic coverage over the area of the Bunter Closure 36 site however the seismic volume is made up of several different volumes that have been merged post stack (Figure 3-3).

Wavelet extraction confirms the seismic volume to be SEG reverse polarity (North Sea normal) with a trough (negative value) representing an increase in acoustic impedance and a peak (positive value) representing a decrease in acoustic impedance. It also shows the seismic volume is close to zero phase with a change in acoustic impedance being represented by either a peak or a trough.

To aid fault identification, semblance volumes were generated using the OpendTect open source software then exported and loaded into the Petrel project. A non-dip adapted semblance volume over the entire fairway and a dip adapted semblance volume limited to just the Bunter Closure 36 site area were generated (Figure 3-6).

Figure 3-4 shows the wells used for the seismic interpretation. 11 wells contain time depth information and 6 wells contained sonic logs.

3.4.2 Horizon Identification

The well data are in depth and the seismic volume in two-way time. The well data is used to identify the seismic events within the 3D volume. Using checkshots, recorded in the well, a time-depth relationship for the well is established. This time-depth relationship together with sonic and density logs are used to generate synthetic seismograms. The purpose of a synthetic seismogram is to forward model the seismic response of rock properties in the well bore with seismic data at the well location, convolving the reflection coefficient log with the seismic wavelet. This enables the interpreter to more accurately match the position of certain seismic reflectors with respect to the subsurface geology of an area.

Six synthetic well ties (43/23-3, 43/30-1, 44/23-3, 44/26-1, 44/26-4, and 44/27-1) were produced using available sonic and density logs in each well.

To generate the synthetic seismograms a theoretical Ricker wavelet was used with an appropriate frequency applied to each well (range 20-30Hz). 4 wells contained both sonic and density logs with an additional 2 wells containing only sonic logs. Missing density logs were generated using gardeners equation or by applying a constant density in the synthetic generation. An example synthetic for well 44/26-1 is shown in Figure 3-7. The synthetic seismogram and actual seismic display a good match. The identified horizons, their pick criteria and general pick quality are listed in Table 3-2 and illustrated on a seismic line in Figure 3-9.

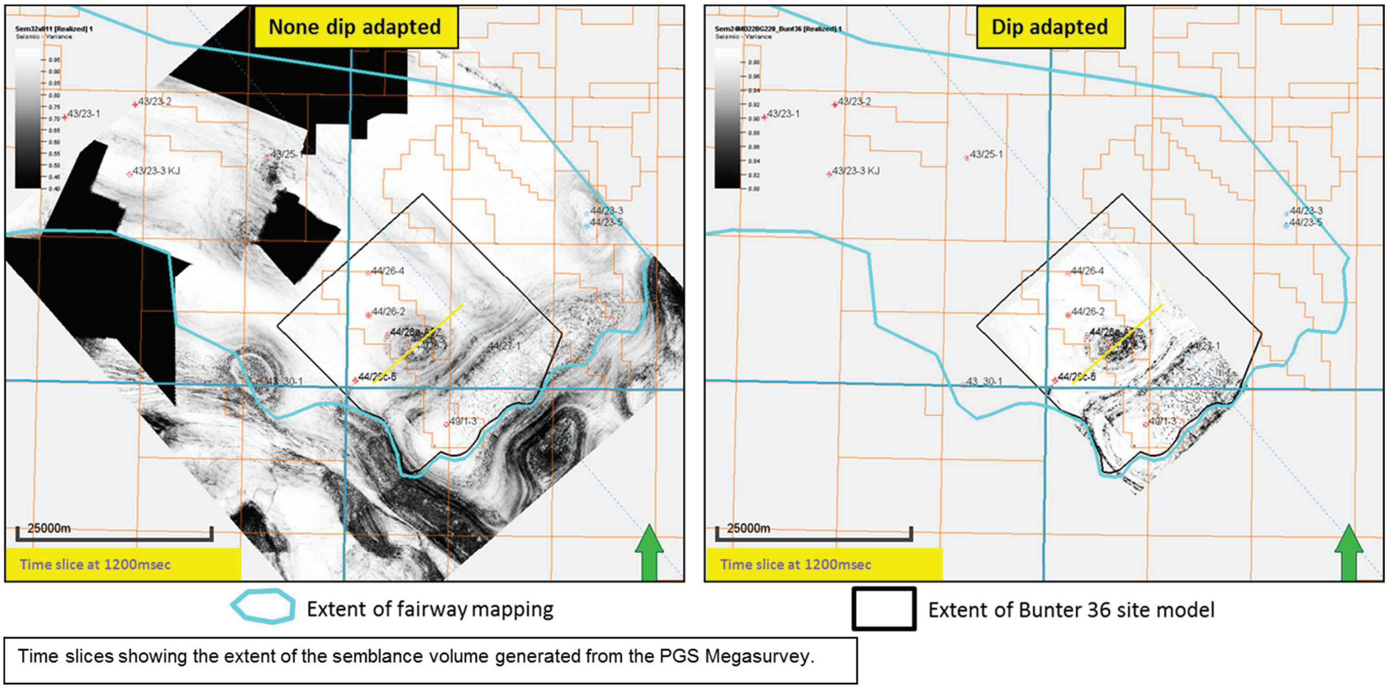


Figure 3-6 - Dip and Non-Dip Semblence Volumes

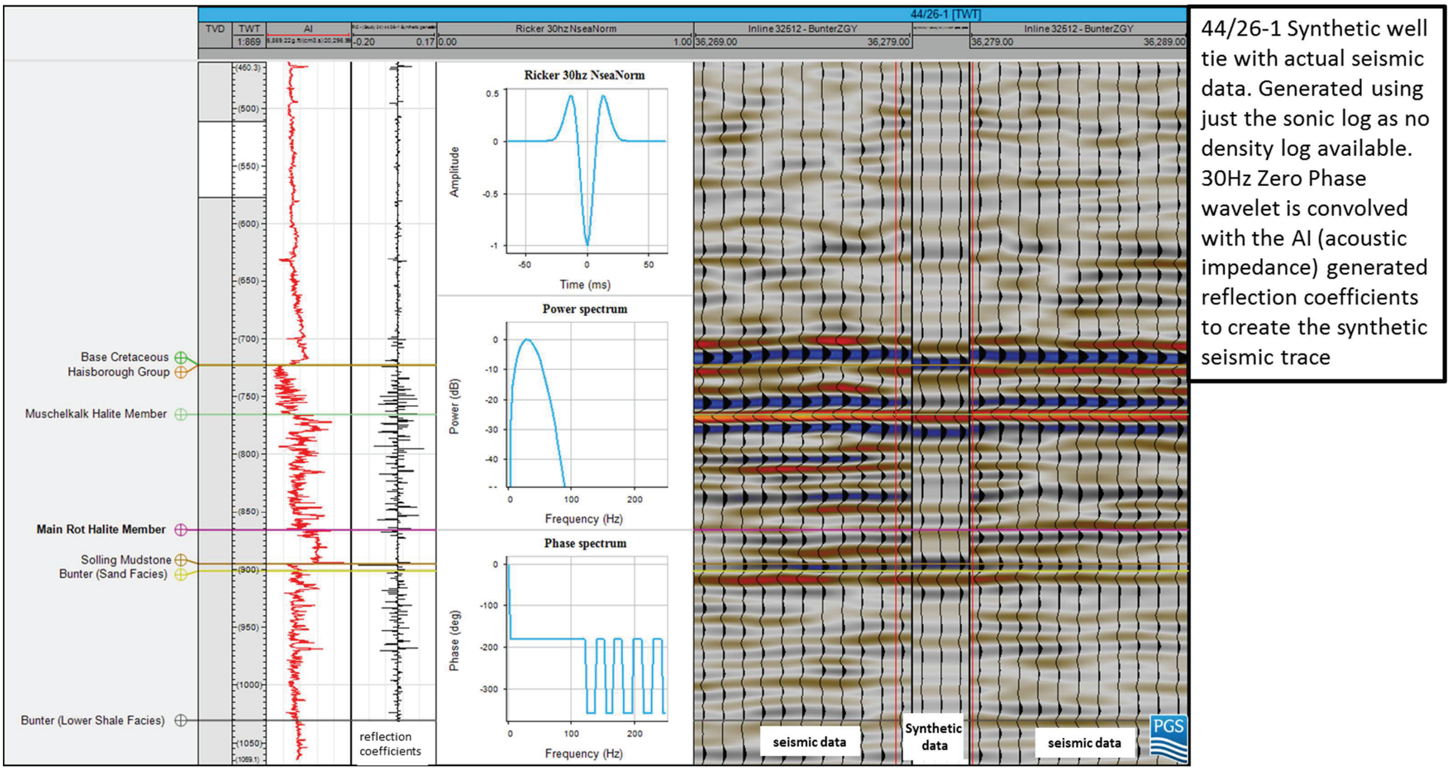
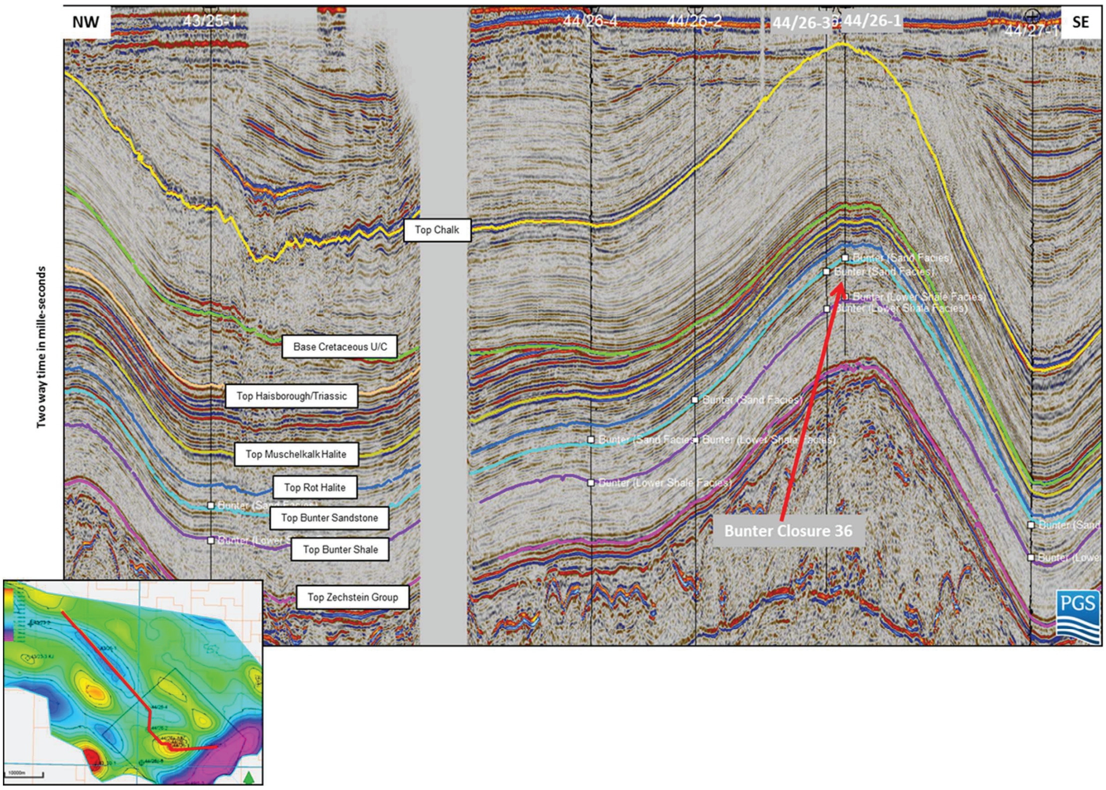


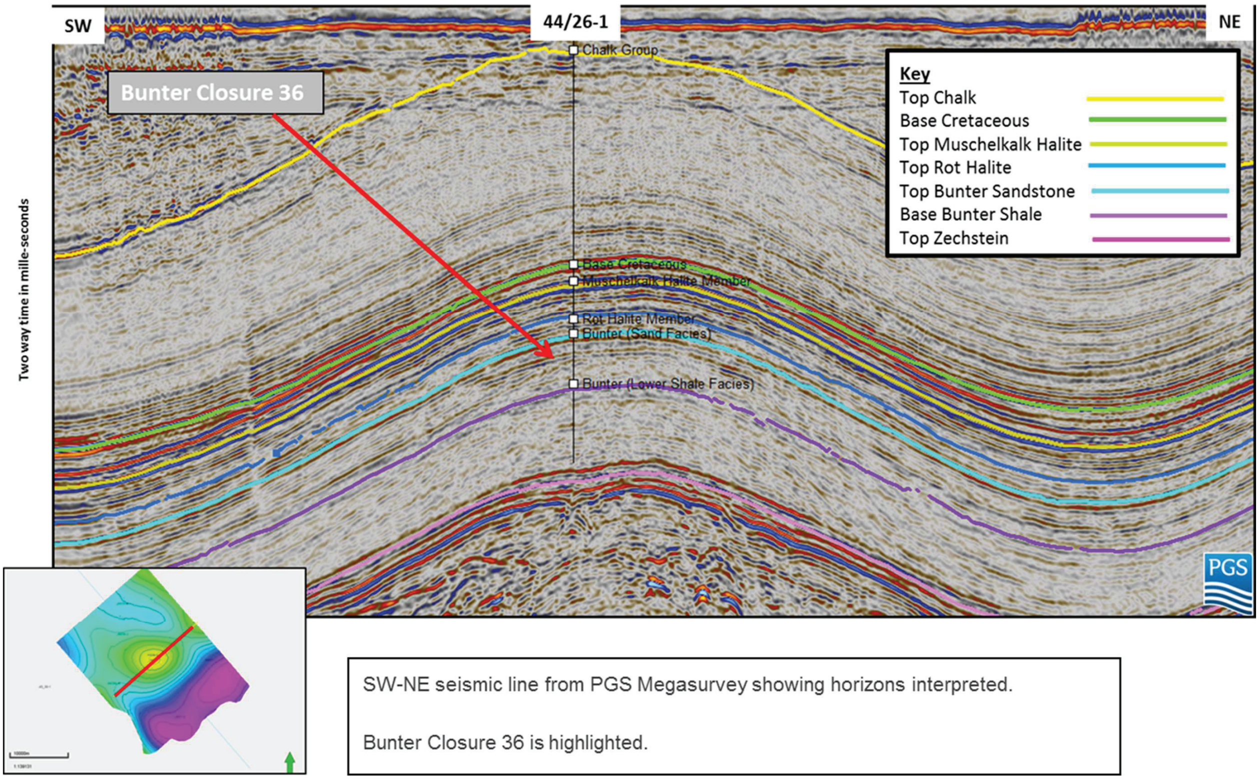
Figure 3-7 - 44/26-1 Synthetic Seismogram



NW-SE regional seismic line from PGS Megasurvey showing horizons interpreted.

Bunter Closure 36 is highlighted.

Figure 3-8 - NW-SE Regional Seismic Profile



SW-NE seismic line from PGS Megasurvey showing horizons interpreted.

Bunter Closure 36 is highlighted.

Figure 3-9 - SW-NE Regional Seismic Line

Horizon	Display Response	Pick Quality
Top Chalk	Trough	Very Good
Base Cretaceous Unconformity	Peak	Very Good
Top Triassic/Top Haisborough	Peak	Good
Top Muschelkalk Halite	Trough	Very Good
Top Rot Halite	Trough	Fair - Good
Top Bunter Sandstone	Peak	Fair - Good
Top Bunter Shale	Trough	Fair - Good
Top Zechstein	Peak	Good

Table 3-2 - Interpreted horizons

There were five wells (42/25-1, 43/25-1, 43/23-3, 44/26-2, and 49/1-3) that contained only checkshot data, allowing a well tie to be produced, but not a synthetic tie. Several wells required an additional time shift in order to tie the seismic.

3.4.3 Horizon Interpretation

A detailed seismic interpretation was carried using reflectivity and semblance volumes to provide input horizons to the Bunter Closure 36 Static Model, the Fairway Static Model and to the Overburden Static Model.

In total eight horizons from the seabed down to the Top Zechstein were interpreted across the 3D seismic data (see Table 3-2 and Figure 3-9). All events were picked on a seed grid and then autotracked.

The eight key seismic horizons were interpreted both over the Bunter Closure 36 site and the fairway (Figure 3-8 and Figure 3-9). The areas of missing seismic within the fairway have been interpolated using interpreted data around the edges to extrapolate over the regions of missing seismic. The autotracked horizons were gridded at 100x100m grid increment and the resultant time maps are shown in Figure 3-10 to Figure 3-16. The interpreted seismic horizons are described below;

Top Chalk – The Top Chalk reflector is a high-amplitude continuous trough, representing an increase in acoustic impedance at the top of the high velocity Chalk unit. In the far north west of the fairway, the Top Chalk outcrops at the seabed (Figure 3-10). The horizon was manually picked at a seed increment inline/crossline spacing of 256 enabling the event to be accurately autotracked with a high level of confidence.

Base Cretaceous Unconformity – This event is a prominent regional unconformity (Figure 3-9). The reflector is a high-amplitude peak representing a soft kick at the base of the high velocity Cretaceous interval. In the North West part of the fairway it is underlain by the Jurassic interval. To the South East the unconformity has eroded down into the upper part of the Triassic. The horizon was manually picked at a seed increment inline/crossline spacing of 256 enabling the event to be accurately autotracked with a high level of confidence (Figure 3-11).

Top Haisborough (Top Triassic) –Top Haisborough event is a peak of moderate amplitude at the base of the Jurassic interval. The event is restricted to the North West of the fairway due to truncation by the overlying Base Cretaceous unconformity in the south east. For depth conversion purposes the Top Triassic horizon has been merged at the point that it is truncated by the Base Cretaceous Unconformity to form one continuous surface. The horizon was manually picked at a seed increment inline/crossline spacing of 256 enabling the event to be accurately autotracked with a high level of confidence (Figure 3-12).

Top Muschelkalk Halite –The seismic response of the event is predominately a high amplitude trough, representing a hard kick at the top of the high velocity Muschelkalk Halite. In the North West region of the fairway, the seismic response weakens, and in places becomes a lower amplitude doublet. The horizon was manually picked at a seed increment inline/crossline spacing of 256 enabling the event to be accurately autotracked with a high level of confidence (Figure 3-13).

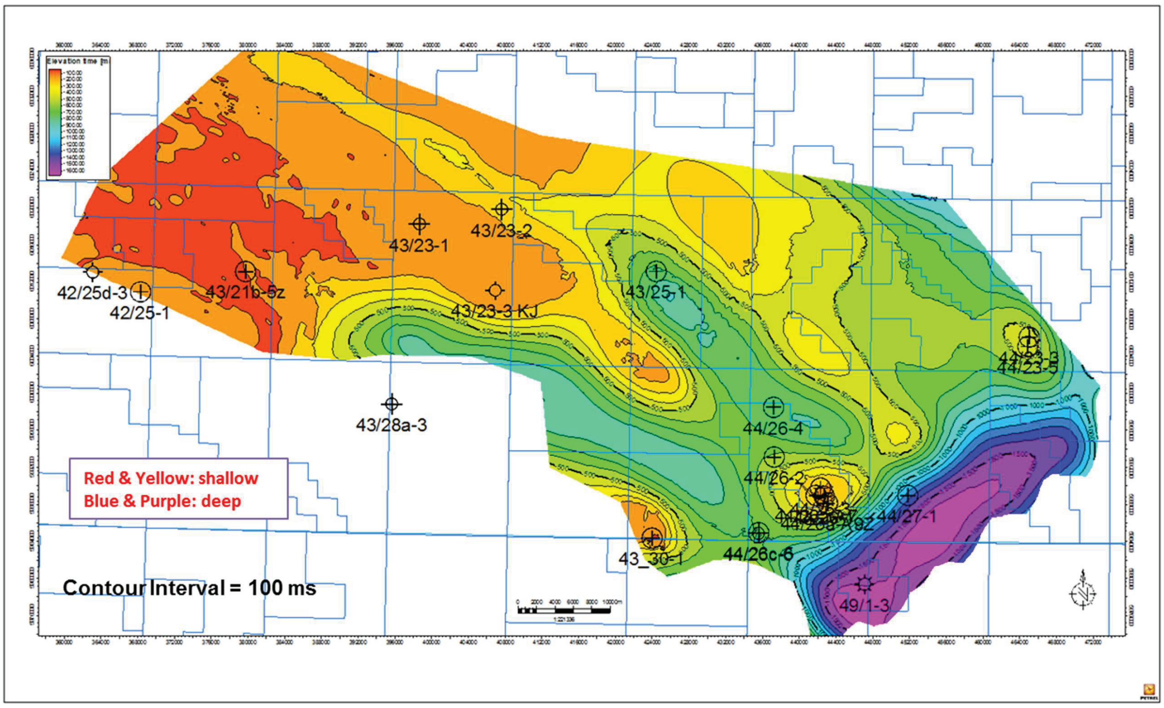
Top Rot Halite – The seismic response of the event is predominately a moderate amplitude trough, representing a hard kick at the top of the high velocity Rot Halite. The event significantly dims in amplitude in the North West part of the fairway. The horizon was manually picked at a seed increment inline/crossline spacing of 256 enabling the event to be accurately autotracked with a fair to good level of confidence (Figure 3-14).

Top Bunter Sandstone – Seismic-to-well ties demonstrate that the Top Bunter Sandstone seismic reflector changes polarity from a moderate-amplitude peak (soft kick) to the zero crossing below the peak depending upon the thickness of Solling Claystone below the Rot Halite. In order to reduce uncertainty of exactly where this reflector changes character, the Top Bunter Sandstone seismic pick has been consistently interpreted as a black peak in this study. Any resulting seismic-to-well miss-tie will at most be one quarter of a cycle loop out.

There appears to be a distinctive phase reversal visible on the seismic towards the North and North West of the fairway. However, no wells with sonic logs are available in this area to confirm this. This is discussed further in section 3.5. For consistency the Top Bunter Sandstone was picked on the peak over the whole fairway. Due to its low frequency and amplitude the event has been manually picked at a finer seed increment inline/crossline spacing of 128 than the overburden horizons, and auto tracked with a medium level of confidence (Figure 3-15). The autotracking around the 5/42 site was of low confidence due to the apparent phase reversal, and had to be manually picked and gridded in this area.

Top Bunter Shale – The Top Bunter Shale is picked on a moderate to low amplitude trough. The event is continuous across the fairway and varies laterally in amplitude. It is picked at the top of a “seismically” opaque package which defines the extent of Bunter shale deposition. Due to its low frequency and amplitude the event has been manually picked at a finer seed increment inline/crossline spacing of 128 than the overburden horizons, and autotracked with a medium level of confidence (Figure 3-16).

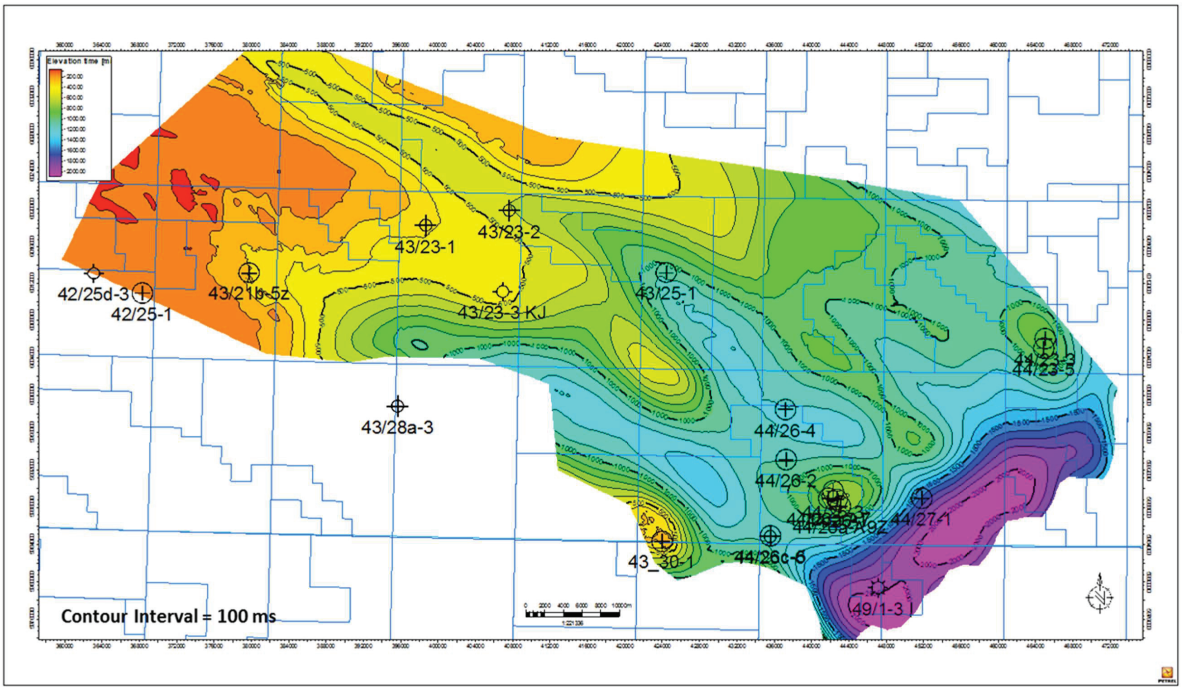
Top Zechstein – Seismic-to-well ties demonstrate that the high amplitude trough related to the increase in velocity at the base of the Bunter Shale unit is the Top Brockelschiefer. The Top Zechstein is the lower amplitude peak immediately beneath the Top Brockelschiefer. The Top Zechstein is recognised regionally across the area and maps out the top of a series of bright high amplitude package of reflectors representing an episode of extensive salt deposition. The horizon was manually picked at a seed increment of 256 and has been auto tracked. The long wavelet period of this event, up to 25ms, causes timing problems with the horizon interpretation when autotracking, producing a noisy surface in places. This event was interpreted for "completeness sake" and has not been used in any of the subsequent static modelling.



Top Chalk two-way time structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

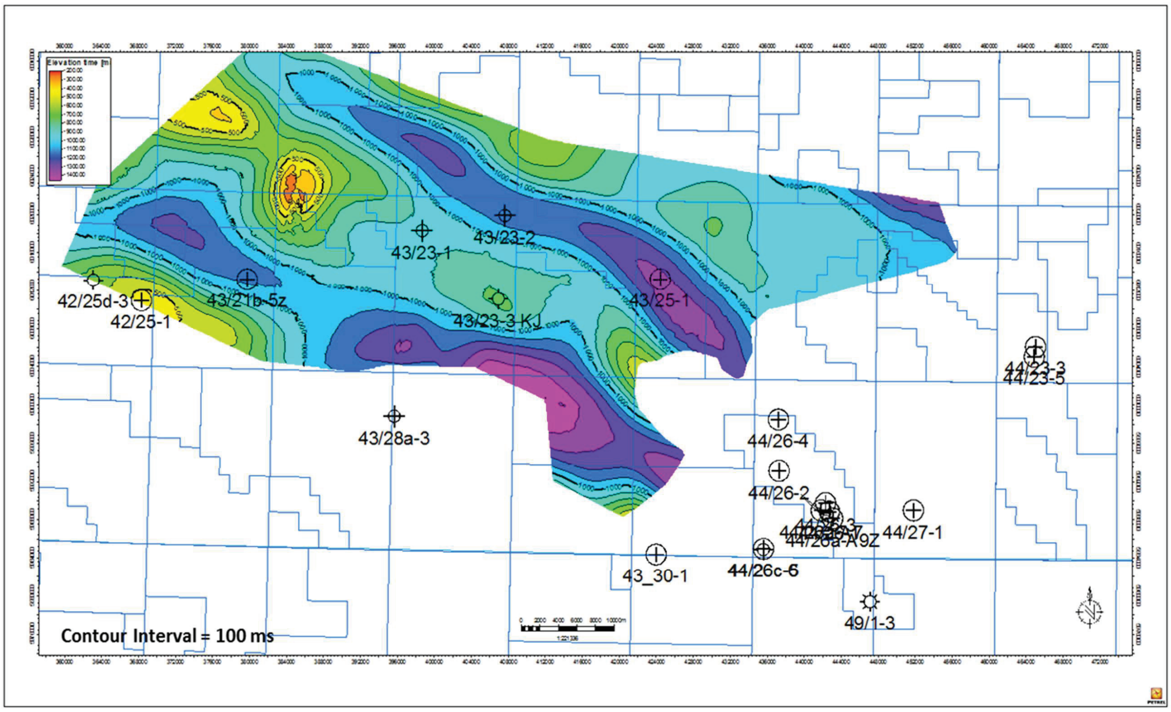
Figure 3-10 - Fairway and Closure 36, Top Chalk two-way time structure



Base Cretaceous Unconformity two-way time structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

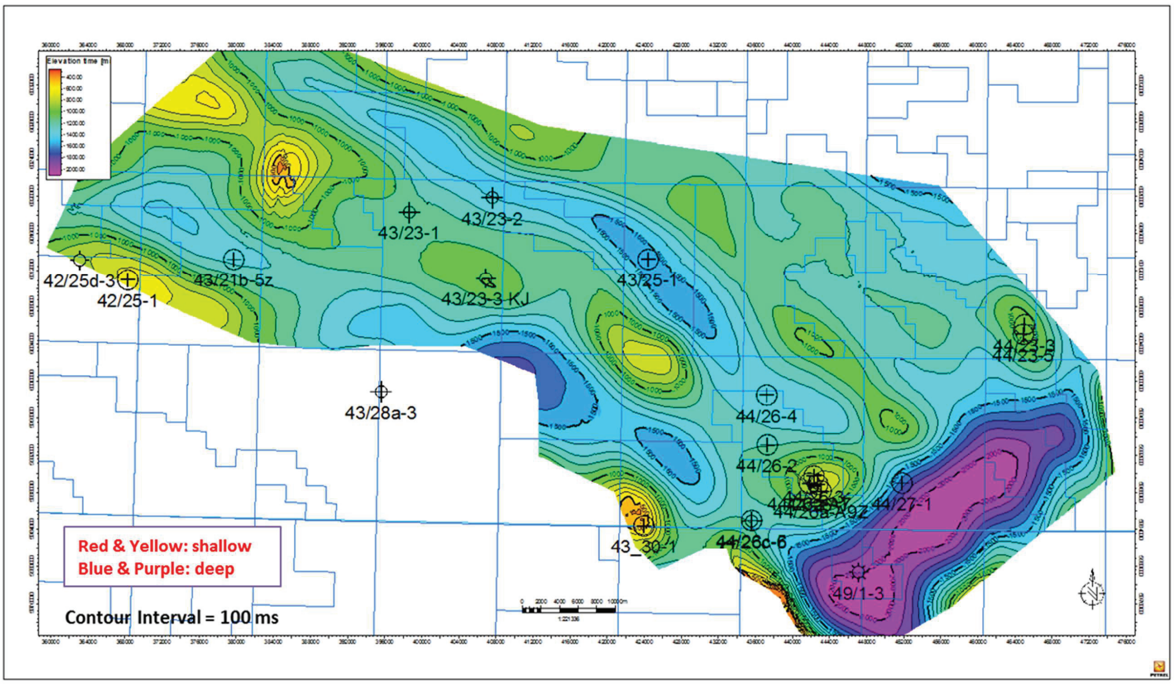
Figure 3-11 - Fairway and Closure 36, Base Cretaceous Unconformity two-way time structure



Top Triassic/Top Haisborough two-way time structure map over the Fairway and Closure 36.

The seismic event is only present in the North Western part of the fairway; it is eroded to the east by the Base Cretaceous Unconformity.

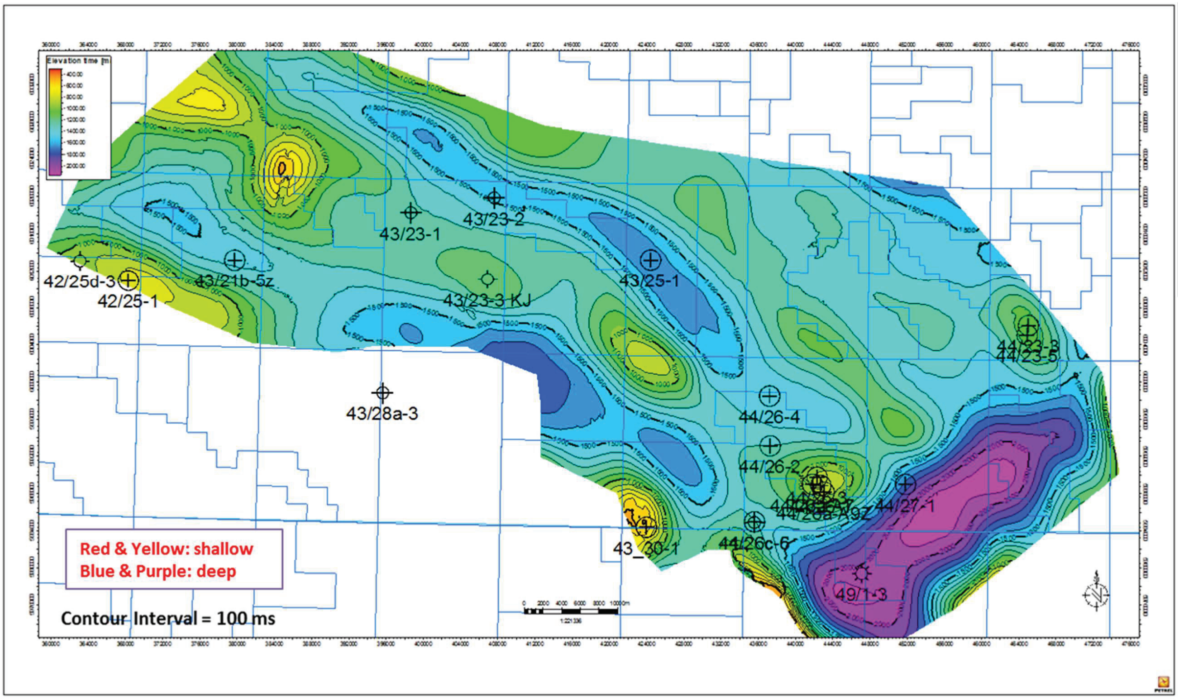
Figure 3-12 - Fairway and Closure 36, Top Triassic/Top Haisborough Unconformity two-way-time structure



Top Muschelkalk two-way time structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

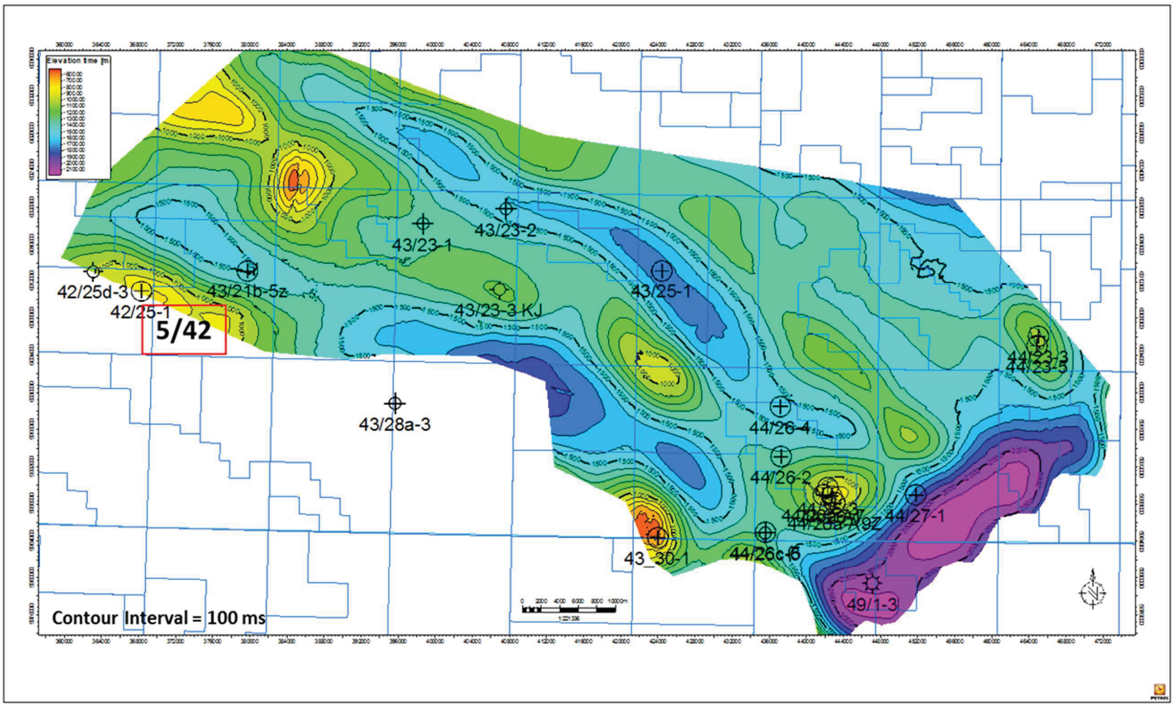
Figure 3-13 - Fairway and Closure 36, Top Muschelkalk two-way-time structure



Top Rot Halite two-way time structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

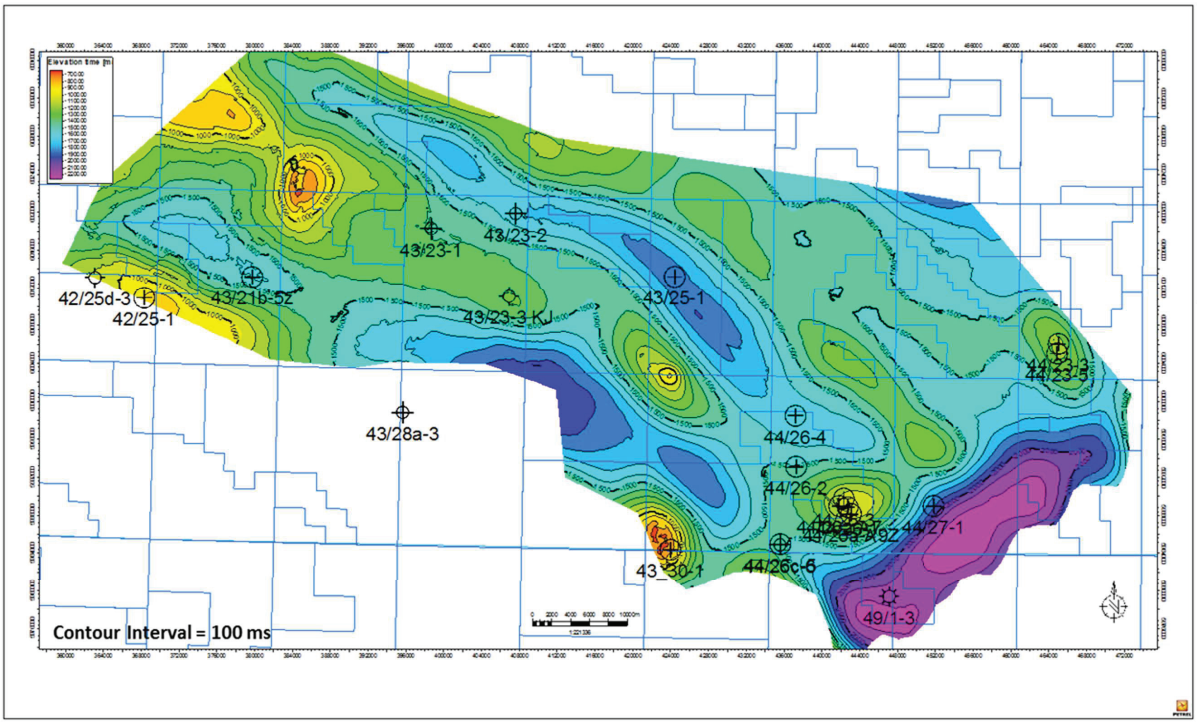
Figure 3-14 - Fairway and Closure 36, Top Rot Halite two-way-time structure



Top Bunter Sandstone two-way time structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

Figure 3-15 - Fairway and Closure 36, Top Bunter Sandstone two-way-time structure



Top Bunter Shale two-way time structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

Figure 3-16 - Fairway and Closure 36, Top Bunter Shale two-way-time structure

3.4.4 Faulting

The fairway area contains a number of 4-way dip closed structures (domes) formed by post deposition halokinesis in the underlying Zechstein Group Halite (Figure 3-17). These have been previously been identified and named (Energy Technologies Institue, 2011). In general the low relief anticlinal structures have little or no evidence of any significant faulting (i.e. greater than the thickness of the Rot Halite primary seal which is approximately 170ft thick). The only prominent faults identified in the Bunter fairway are in dome 41 were the Bunter Sandstone is juxtaposed against the Upper Triassic mudstones which constitutes the secondary seal (Figure 3-18).

Over Bunter Closure 36 minor faulting is clearly visible at Top Chalk. Figure 3-19 shows a semblance horizon slice at Top Chalk and Base Cretaceous. At Top Chalk the faults trend in a South West to North East orientation. Over the Bunter Closure 36 the interference between the Top Chalk event and the seabed multiple masks the imaging of the faults. The faults sole out within the chalk section as they are not visible at Base Cretaceous (Figure 3-19).

The semblance slice at top Bunter level (Figure 3-20) shows South West – North East trending features, particularly on the South Eastern flank of Bunter Closure 36 site that could be related to minor faulting. In seismic section these events appear extremely vertical and may potentially be artefacts formed as a result of imaging issues in the overburden (Figure 3-21). There is a prominent feature on the North Western flank of the Bunter Closure 36 structure which is not a fault lineament and is related to seismic noise due to a gap in 3D seismic coverage (Figure 3-20). Similarly there is a North West – South East trending feature on the South West flank of the Bunter Closure 36 site which has not been formed by a fault and marks the join of two merged 3D seismic volumes (Figure 3-20).

At Top Bunter Sandstone, the minimum fault offset that is considered to be detectable with the current seismic data is 10m, significantly less than the Rot halite seal. Elsewhere in the fairway, minor crestal faults have been detected in Gas bearing closures such as Hunter field, without any loss of containment and so even when such faults occur they are likely to be sealing in the overburden. Overall faulting is very limited in the over burden and reservoir levels both regionally and over the crest of the Bunter Closure 36 target dome, posing little risk to containment. Sub seismic faults (with <10m offset) may also contribute to some directional permeability anisotropy in the reservoir. Without any guidance on fault trends locally, this factor has not been accounted for at this time.

3.4.5 Depth Conversion

Thickness variations in the overburden Tertiary and Cretaceous units (Figure 3-22) indicate that a layer-cake depth conversion is the appropriate method to use. The overburden down to Top Bunter Sandstone has been divided into three layers; Tertiary, Cretaceous and Jurassic/Upper Triassic velocity units. Below Top Bunter Sandstone an additional layer was required to depth convert the Top Bunter Shale. Each interval was depth converted using oil industry standard depth conversion techniques and these are summarised in Figure 3-23. The depth conversion was undertaken in the PETREL software using the velocity modelling plug-in. Top Chalk, Base Cretaceous Unconformity, Top Muschelkalk, Top Bunter Sandstone and Top Bunter Shale were depth converted directly using the Petrel generated velocity model. Two additional surfaces (Top Rot Halite and Top Triassic) were depth converted using the Petrel calculator tool to create isochores and then added onto surfaces generated in the velocity model to generate the Top Triassic and Rot Halite depth surfaces.

The depth conversion method for each interval or surface is outlined below;

Mean Sea Level to Top Chalk Interval – The shallowest layer was generated using a V0+K function (constant K and a mapped V0 surface). The defined K value (0.72) was derived from a velocity log calculated from the sonic log in well 44/26-4 (Figure 3-24). The V0 surface was generated by gridding V0 values derived at the wells (Figure 3-25). The derived V0s ensure that the depth surface ties at the wells. A smoothed Top Chalk time surface was used in the velocity model to minimise residual effects of faulting in the Top Chalk being carried through to depth converted surfaces below. The resulting Top Chalk depth surface is shown in Figure 3-26.

Top Chalk to Base Cretaceous Unconformity Interval – The Top Chalk to Base Cretaceous Unconformity layer was also depth converted by applying a V0+K function using the same method as the Mean Sea Level-Top Chalk layer. A K value of 1.1 was derived from the 44/26-4 velocity log (Figure 3-24). The V0 map is shown in Figure 3-27 and the resulting Base Cretaceous unconformity depth surface is shown in Figure 3-28.

Base Cretaceous Unconformity to Bunter Sandstone Interval – The Base Cretaceous Unconformity to Bunter Sandstone depth layer was calculated by using an interval velocity map derived from a linear function (Zi=(4.278*Ti)+250.04)) calculated from back interpolated time values and depth values at each well. The interval velocity map (Figure 3-29) was inserted into the Petrel Velocity model described above. The Top Bunter Sandstone surface was depth converted directly using the Petrel Velocity model and the resulting depth surface is shown in Figure 3-30.

Base Cretaceous Unconformity to Top Triassic Interval – This interval is only present to the North West of Bunter Closure 36 site. The Base Cretaceous Unconformity to Top Triassic layer was depth converted using a linear function derived from back interpolated time values at the wells. The function (Zi=(-3.7501*Ti)+112.35) were Ti is the isochron of the Base Cretaceous to Top Triassic interval. The function generates an isochore (Zi) which is then added onto the Base Cretaceous Unconformity surface to derive the Top Triassic depth surface (Figure 3-31).

Top Muschelkalk Surface – Top Muschelkalk surface was depth converted directly using the Petrel Velocity model described above. The resulting Top Muschelkalk depth surface is shown in Figure 3-32.

Top Rot Halite Surface – The Top Rot Halite surface was depth converted using a constant velocity of 15000 feet per second which was multiplied to the Rot Halite to Top Bunter Sandstone isochron to generate an isochore. The isochore was subtracted from the Top Bunter Sandstone depth surface to generate a Top Rot Halite depth surface (Figure 3-33).

Top Bunter Sandstone to Top Bunter Shale Interval – The Bunter Sandstone reservoir depth interval was calculated using the same V0+k depth conversion method as the Mean Sea Level to Top Chalk and Top Chalk to Base Cretaceous Unconformity intervals. The defined K value (0.92) was derived from the 44/26-4 velocity log (Figure 3-24). The V0 map is shown in Figure 3-34 and the resulting Base Cretaceous unconformity depth surface is shown in Figure 3-28.

3.4.5.1 Depth Conversion Uncertainty

The structural spill point for Bunter Closure 36 at Top Bunter Sandstone moves from the North East corner in the time domain, to the South West corner in the depth domain when using the layer cake depth conversion outlined above (reference case) (Figure 3-36).

A limited depth conversion sensitivity study was undertaken to understand the impact of the depth conversion method on the Gross Rock Volume (GRV) of the Bunter Closure 36. Three additional depth conversion methods were applied and are detailed in Table 3-3:

Case	Number of layers	Method
1	1	MSL-Top Bunter Sandstone: average velocity map (well depths and seismic times)
2	1	MSL-Top Bunter Sandstone: linear time depth function (well depths and seismic times) with depth residual correction (global gridding or restricted to 2000m around each well)
3	3	MSL-Base Tertiary: average velocity map (well depths and seismic times) Base Tertiary-Base Cretaceous Unconformity: average velocity map (well depths and seismic times) Base Cretaceous Unconformity-Top Bunter Sandstone: average velocity map (well depths and seismic times)

Table 3-3 - Depth conversion sensitivity methods

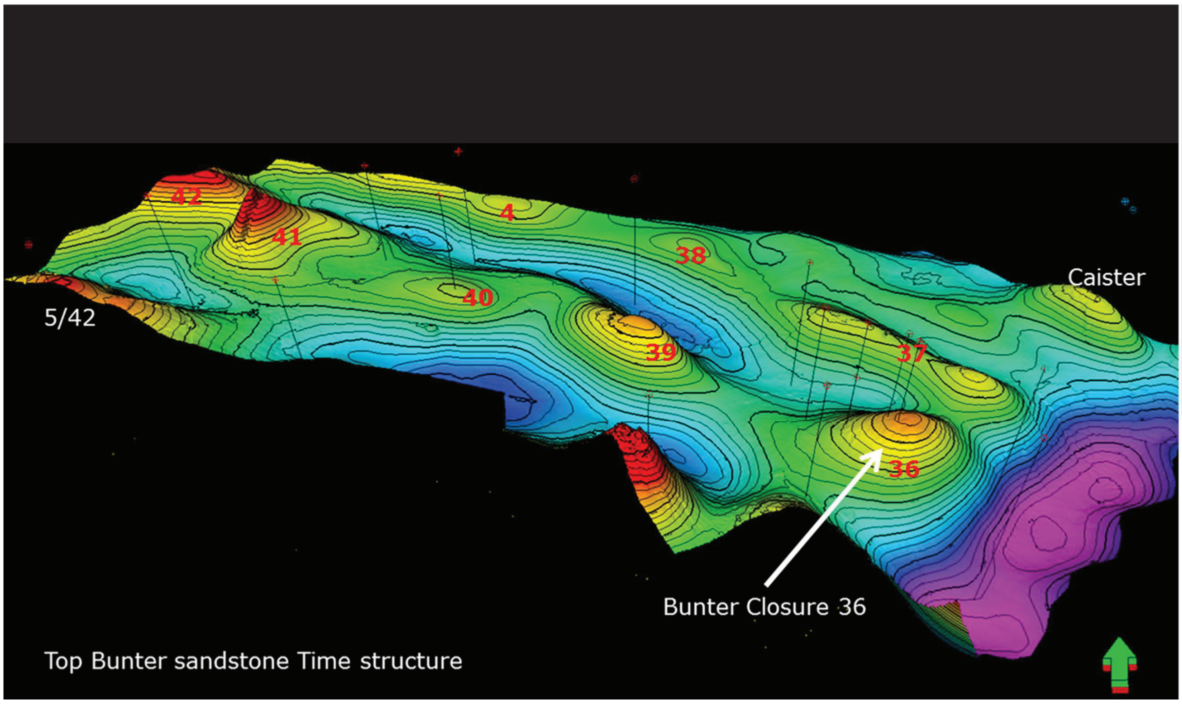
The resultant Top Bunter Sandstone depth surfaces are shown in Figure 3-37. The two single layer depth conversions result in a spill point in the North East of the Bunter 36 structure, similar to the time Top Bunter Sandstone time surface. The other layer cake method (Case 3) produces a similar result as the reference case depth conversion. The GRV was calculated for the structural spill point of each surface (varies in depth between each depth conversion case) using the same reference case Bunter Sandstone isochore. The results are shown in Table 3-4:

Depth conversion Case	Reference case	Case 1	Case 2 no well correction	Case 2 global well correction	Case 2 2000m well correction	Case 3 Layer cake
Bulk volume (*10^6 rm3)	13667	10191	12023	10433	11932	12954
% GRV of Reference Case	100	75	88	76	87	95

Table 3-4 - Bunter Closure 36 GRV comparisons

In the reference case depth conversion the Bunter Closure 36 the North East saddle is at approximately 6000ft tvdss (Figure 3-36). In the single layer depth conversion cases this is shallower at approximately 5660ft tvdss (Figure 3-37). The implications of this on the ability of Bunter Closure 36 to retain the planned volume of injected CO_2 are discussed in the section 3.7 Containment Characterisation.

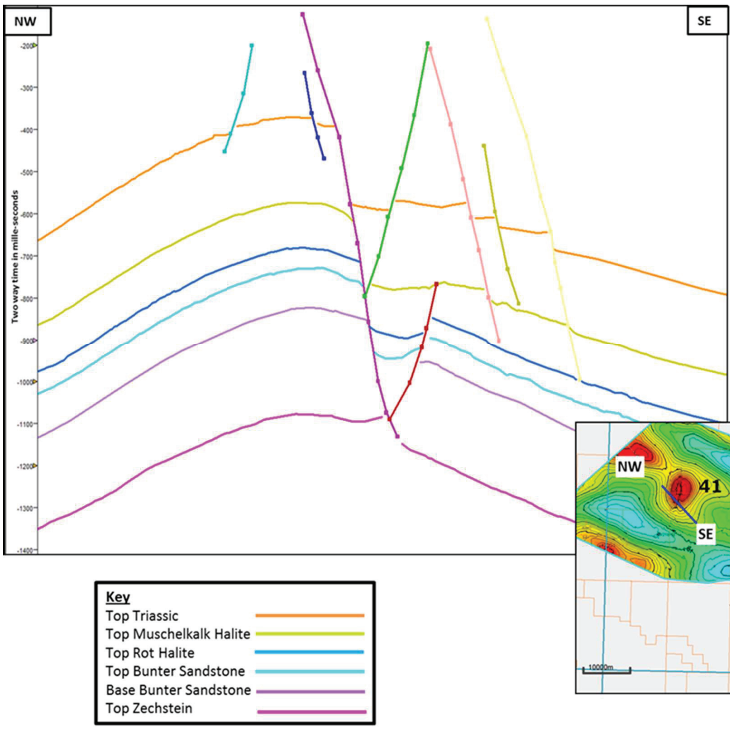
A layer cake depth conversion is considered to be technically more robust, as it takes into consideration velocity variations in the overburden Figure 3-22). Thickening in the slower Tertiary unit and thinning in the faster chalk unit to the west results in pull up in depth of the western flank, which is not taken into account when using a single one layer depth conversion.



3D view of Top Bunter Sandstone two-way time structure over the Fairway and Closure 36.

Shows 8 anticlines with the UKSAP numbers plus 5/42 and Caister.

Figure 3-17 - 3D view of Top Bunter Sandstone TWT interpretation Fairway



Cross section over Closure 41 some 50km NW of Bunter Closure 36. Here there is significant faulting across the crest of the structure and Bunter Sandstone is juxtaposed against the Upper part of the Haisborough Group potentially bypassing many of the higher quality sealing halite formations.

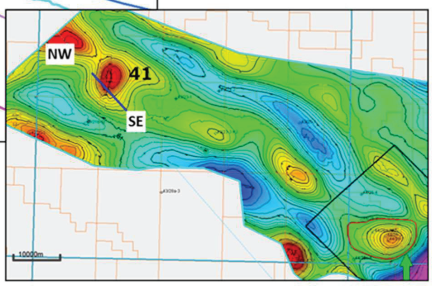
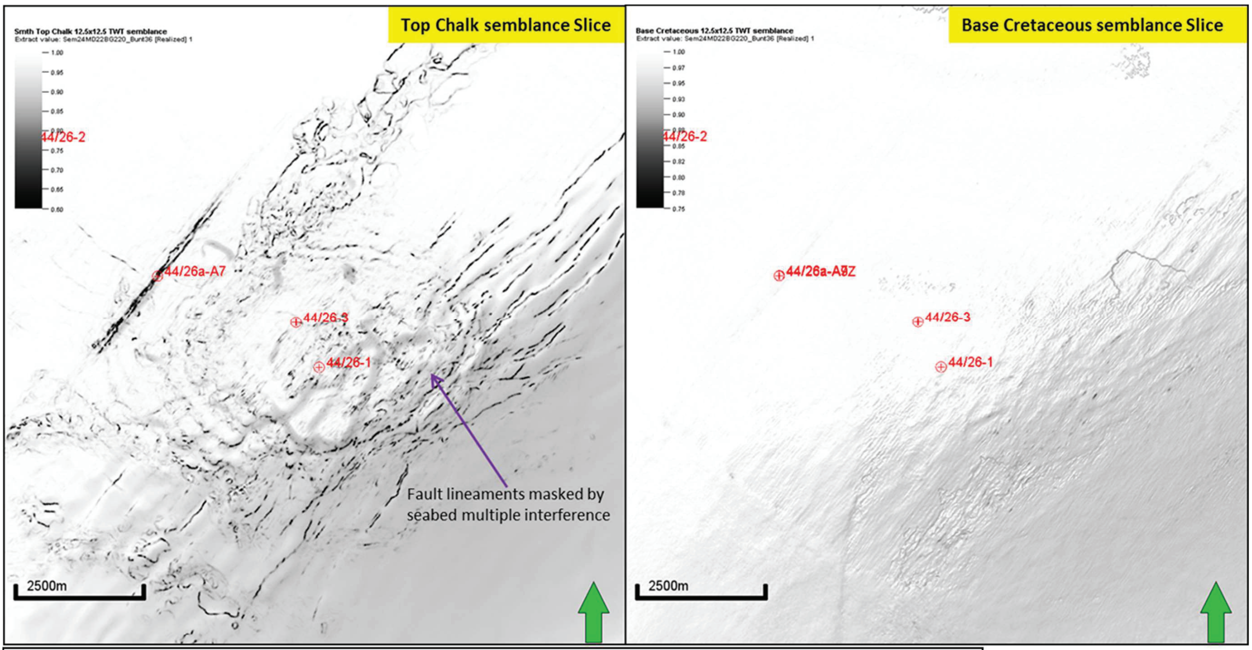


Figure 3-18 - Dome 41: significant faulting



Top Chalk and Base Cretaceous semblance slices.

The black lines show discontinuities i.e. faults

Numerous faults at Top Chalk which are partially masked by interference from the seabed multiple at Bunter 36.

These Chalk faults have died out by the Base Cretaceous

Figure 3-19 - Bunter Closure 36: chalk interval faulting

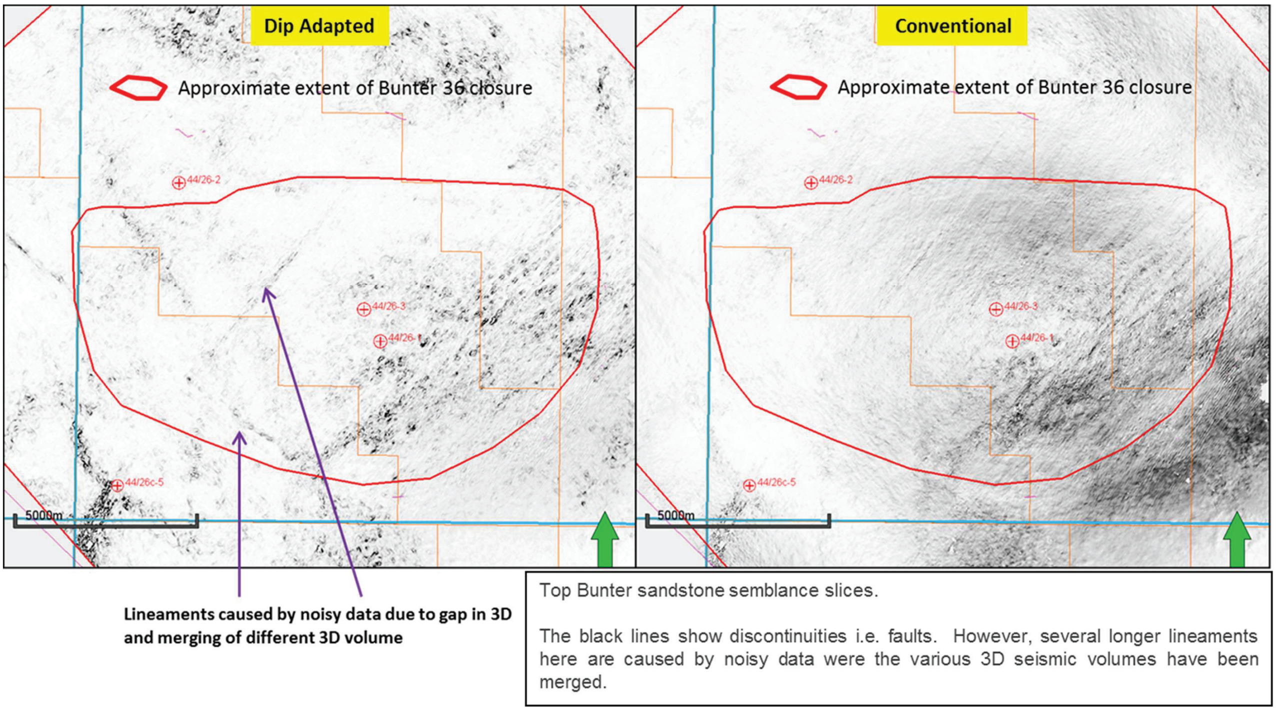
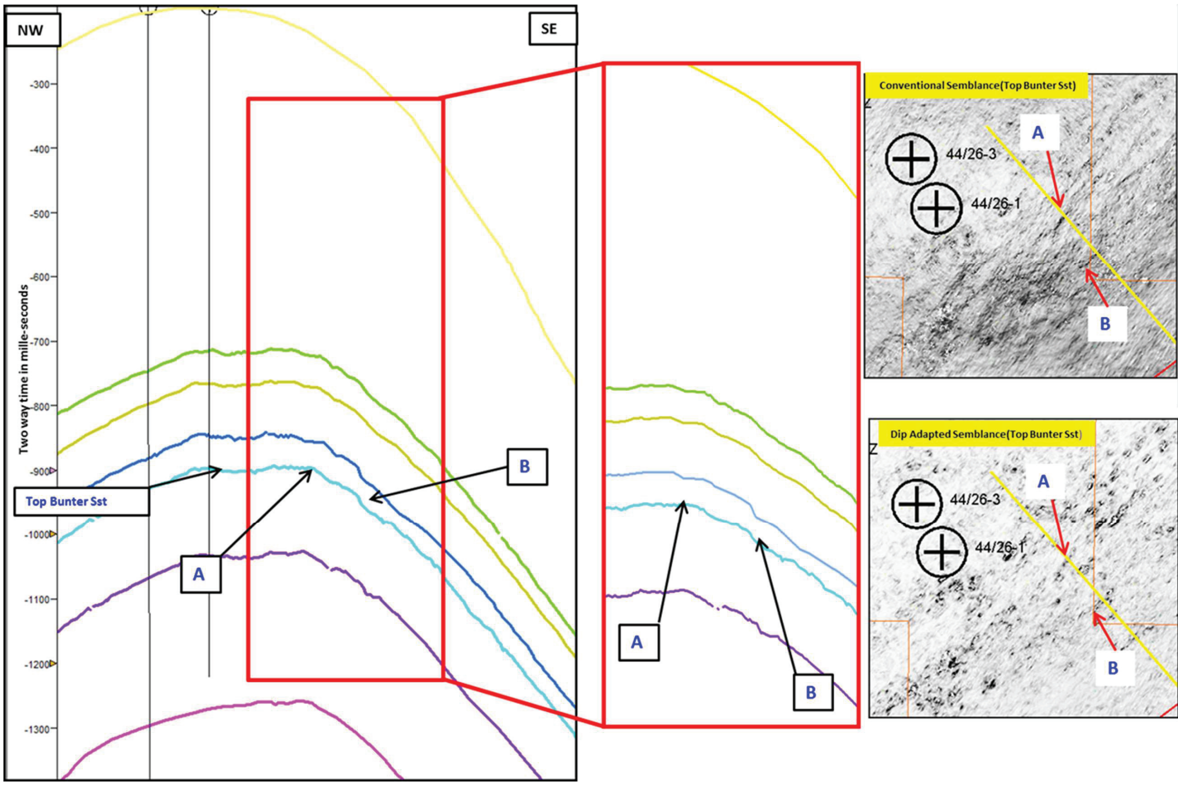
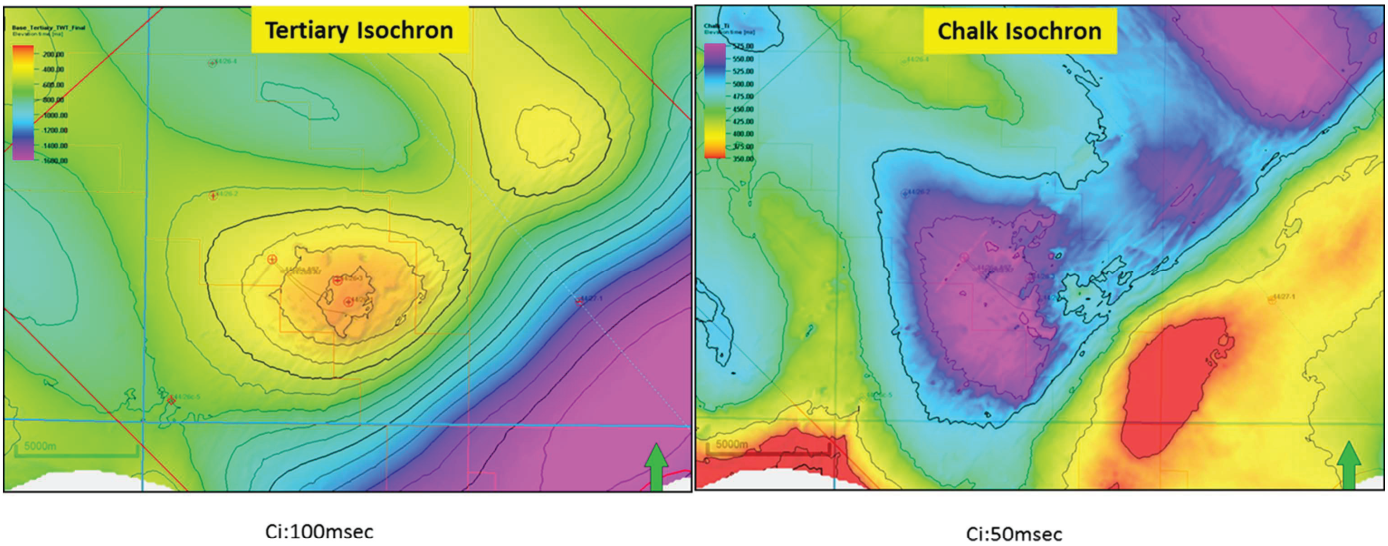


Figure 3-20 - Bunter Closure 36: Top Bunter Sandstone semblance time slice



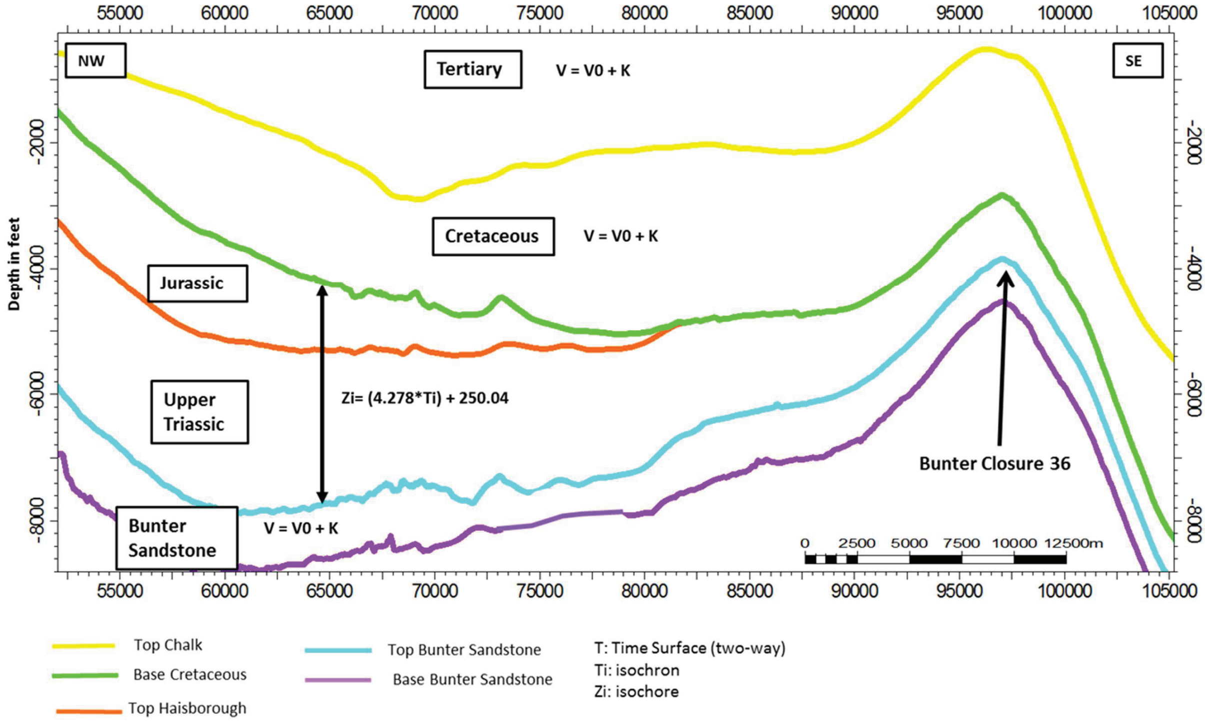
Cross section based on a seismic line. It illustrates possible very minor faulting over Bunter Closure 36. However, the inflections in the seismic events could be caused by noisy seismic data rather than by faulting.

Figure 3-21 - Potential faulting on south west flank of Bunter Closure 36 site



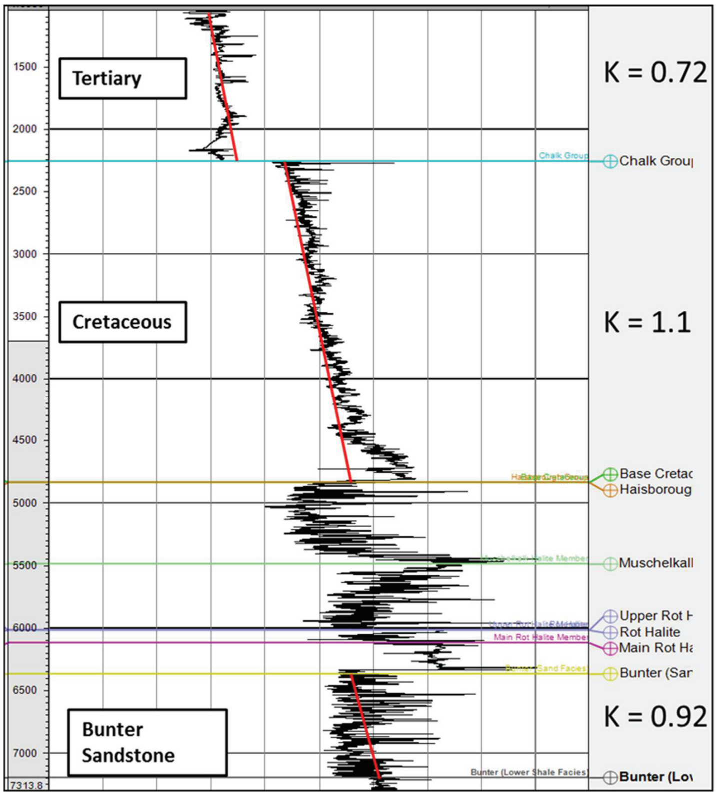
Time thickness maps showing thickness changes in the over burden above Bunter Closure 36. These two units have very different interval velocities and hence have a big impact on the depth conversion.

Figure 3-22 - Overburden velocity units thickness changes



Cross section based on a seismic line illustrating the depth conversion functions used for each velocity layer. Note the Jurassic interval is not present over Bunter Closure 36

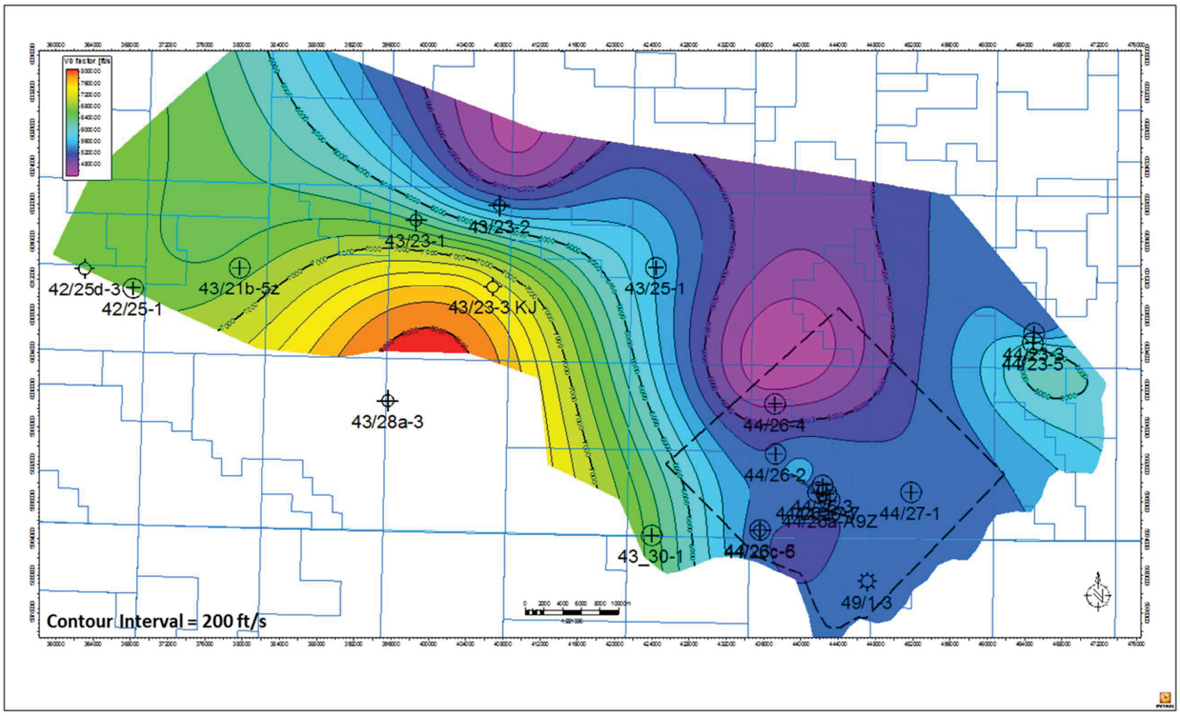
Figure 3-23 - Layer cake depth conversion summary



Well 44/26-4 Velocity log.

The K values (velocity gradient) used in the depth conversion are shown for the Tertiary, Cretaceous and Bunter Sandstone intervals.

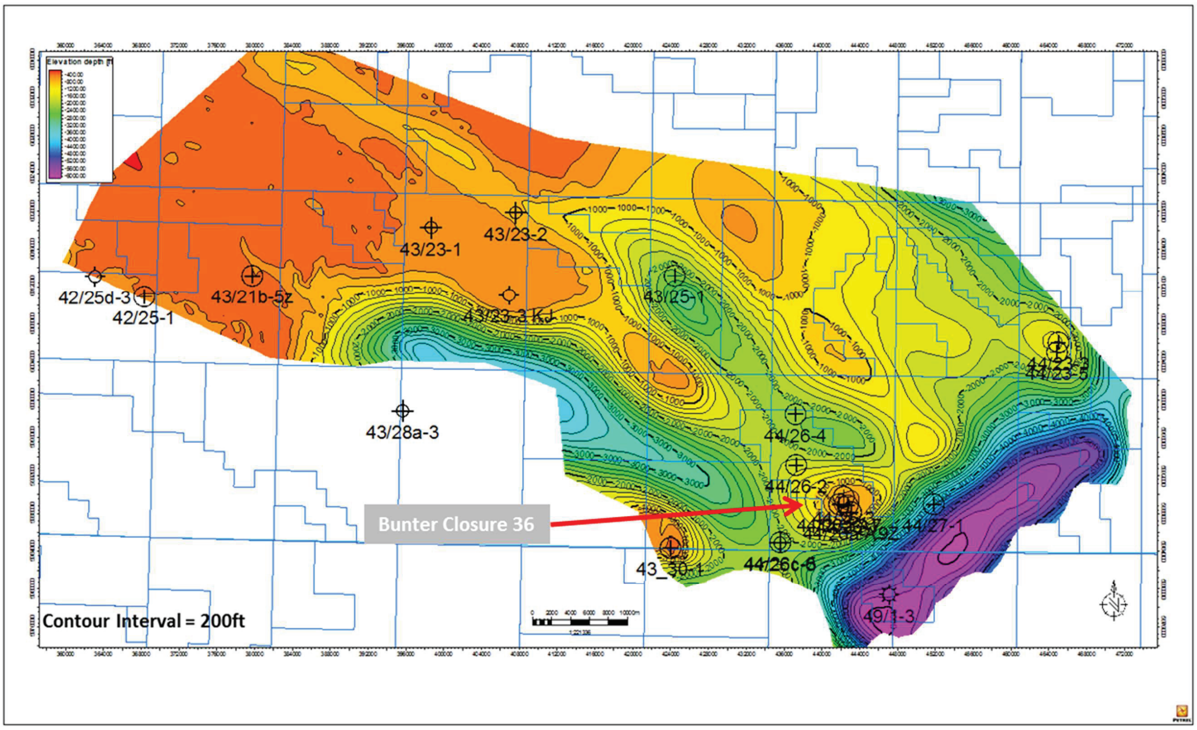
Figure 3-24 - K gradient calculations for well 44/26-4



Tertiary interval V0 map over the Fairway and Closure 36.

This is combine with a K value of 0.72 to depth convert this interval.

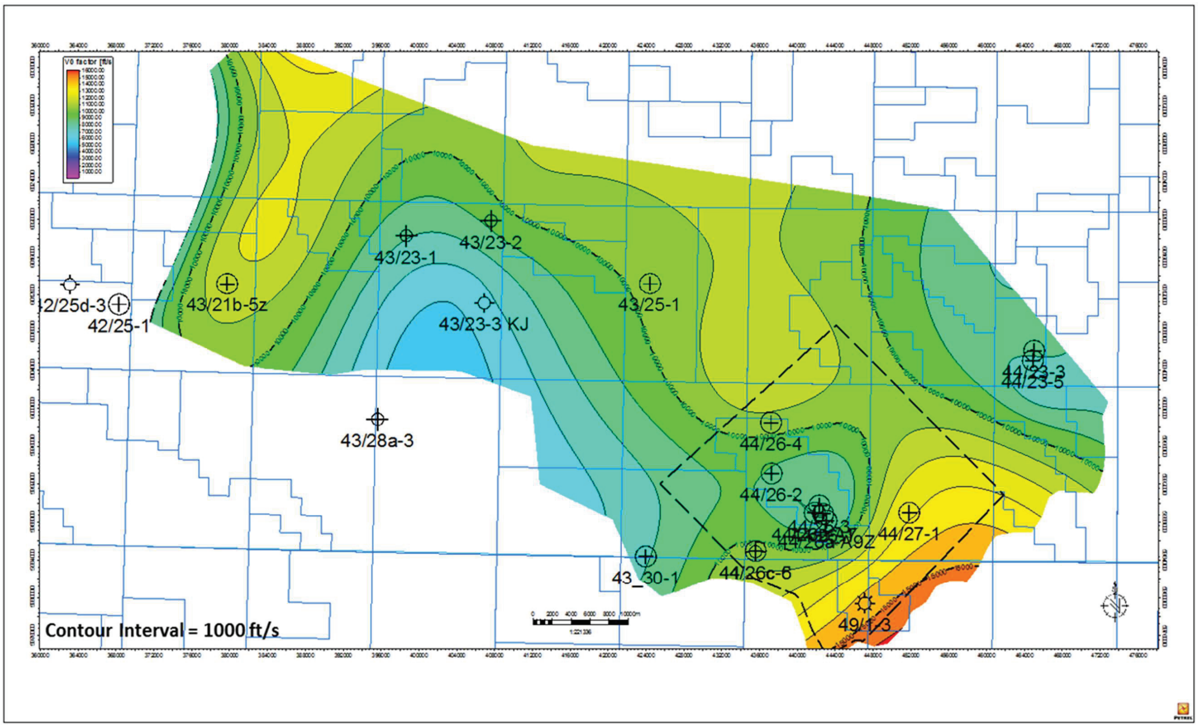
Figure 3-25 - Top Chalk V0 map



Top Chalk depth structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

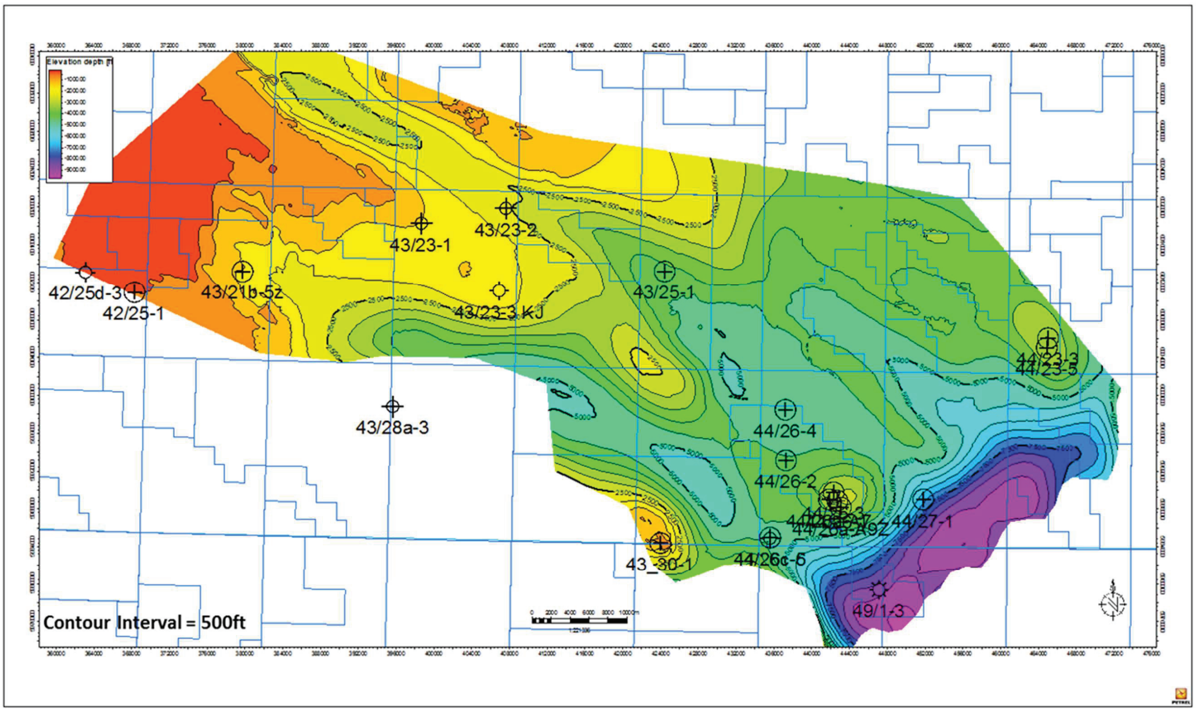
Figure 3-26 - Fairway and Closure 36, Top Chalk depth structure map



Cretaceous interval V0 map over the Fairway and Closure 36.

This is combine with a K value of 1.1 to depth convert this interval.

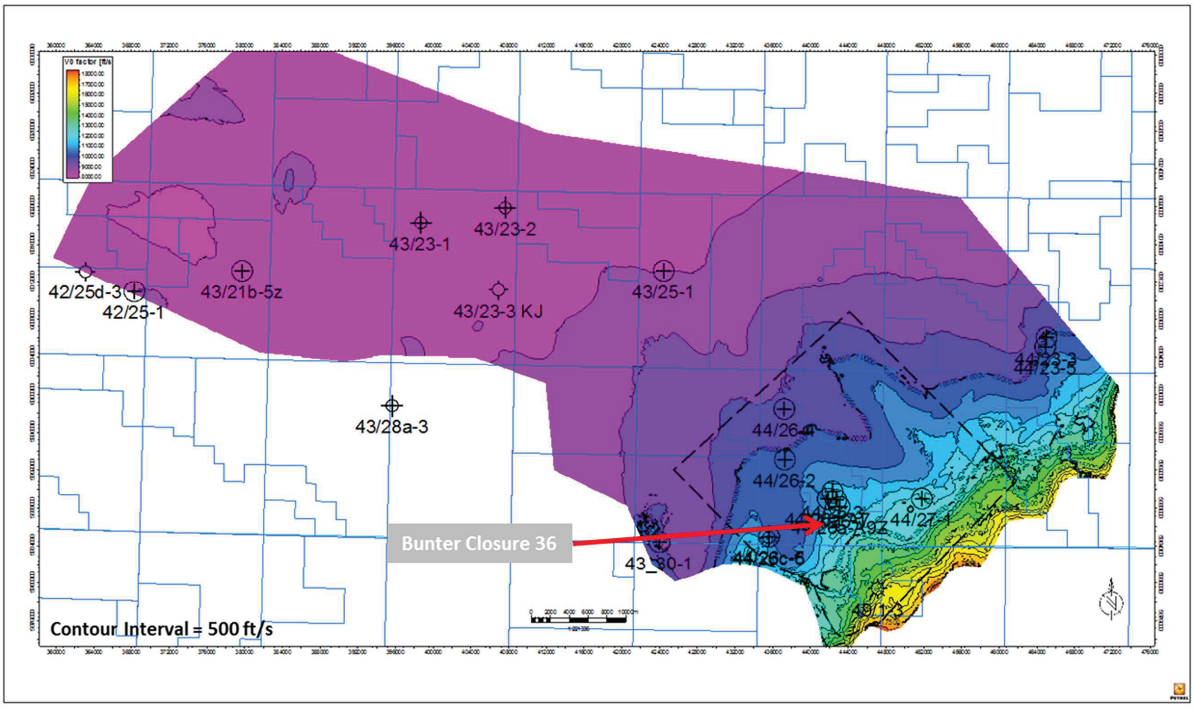
Figure 3-27 - Base Cretaceous Unconformity V0 map



Base Cretaceous Unconformity depth structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

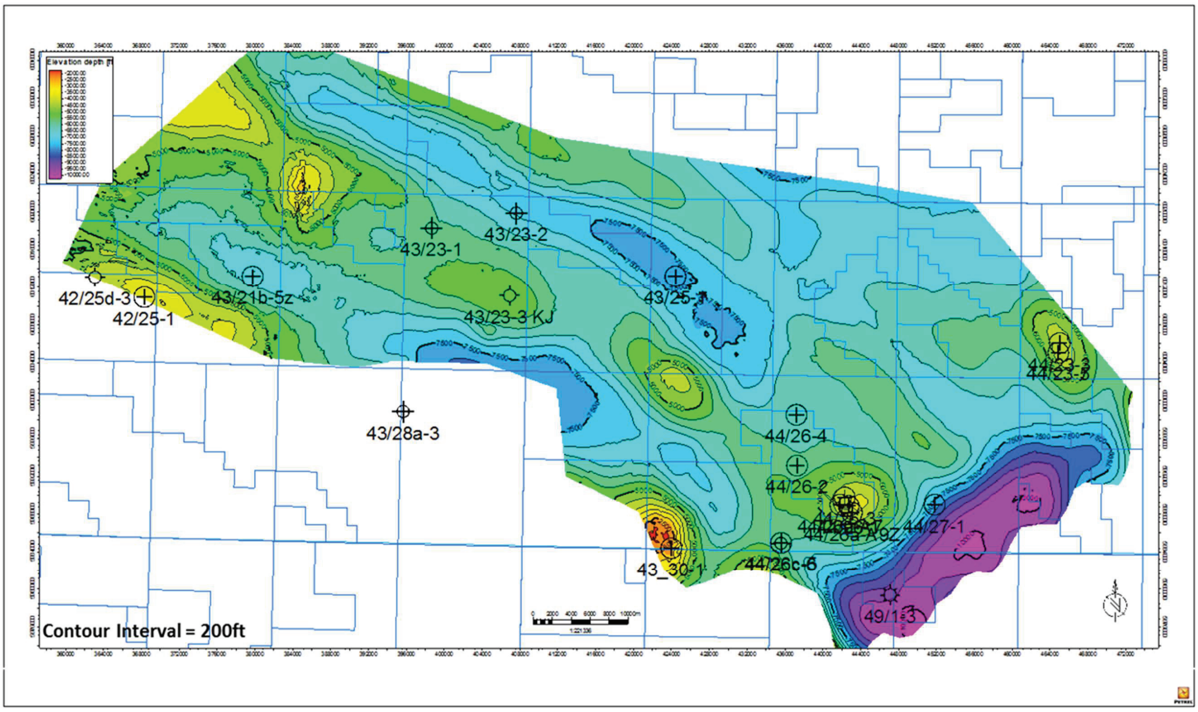
Figure 3-28 - Fairway and Closure 36, Base Cretaceous Unconformity depth structure map



Base Cretaceous Unconformity to Top Bunter Sandstone Interval Velocity Map over the Fairway and Closure 36.

This is combine with an interval time thickness to depth convert this interval. The resultant isochore is added to the Base Cretaceous depth surface to generate the Top Bunter Sandstone depth surface.

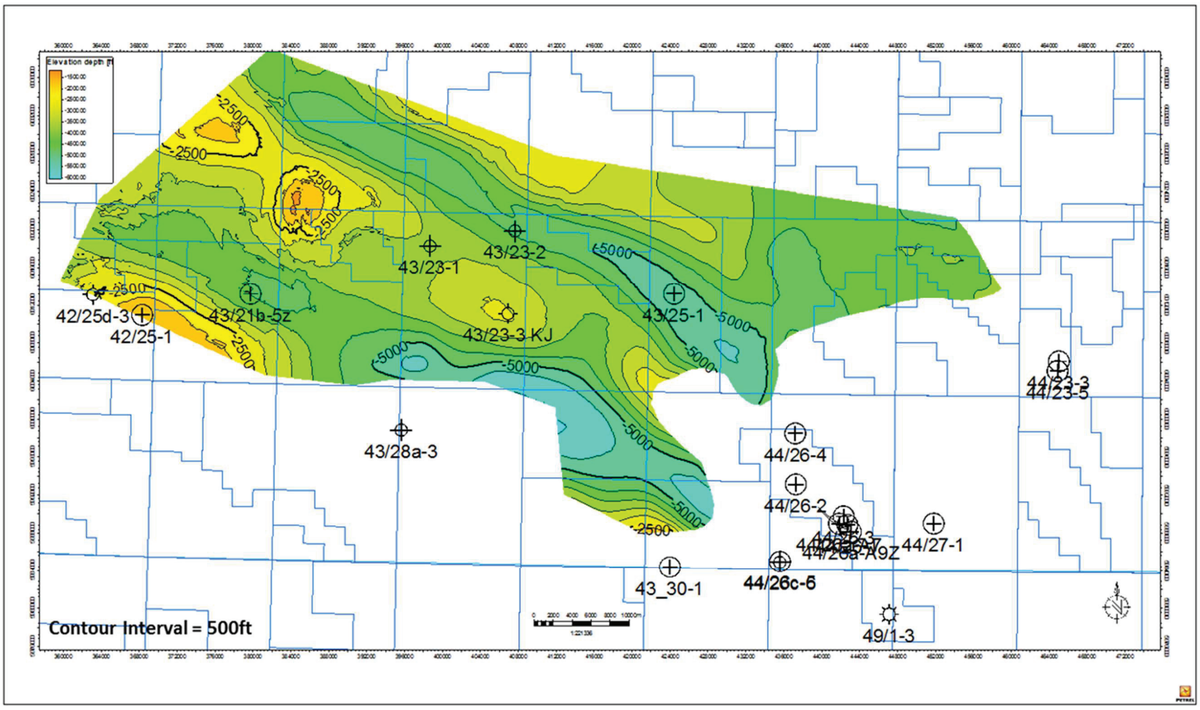
Figure 3-29 - Base Cretaceous Unconformity to Top Bunter Sandstone interval velocity map



Top Bunter Sandstone depth structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

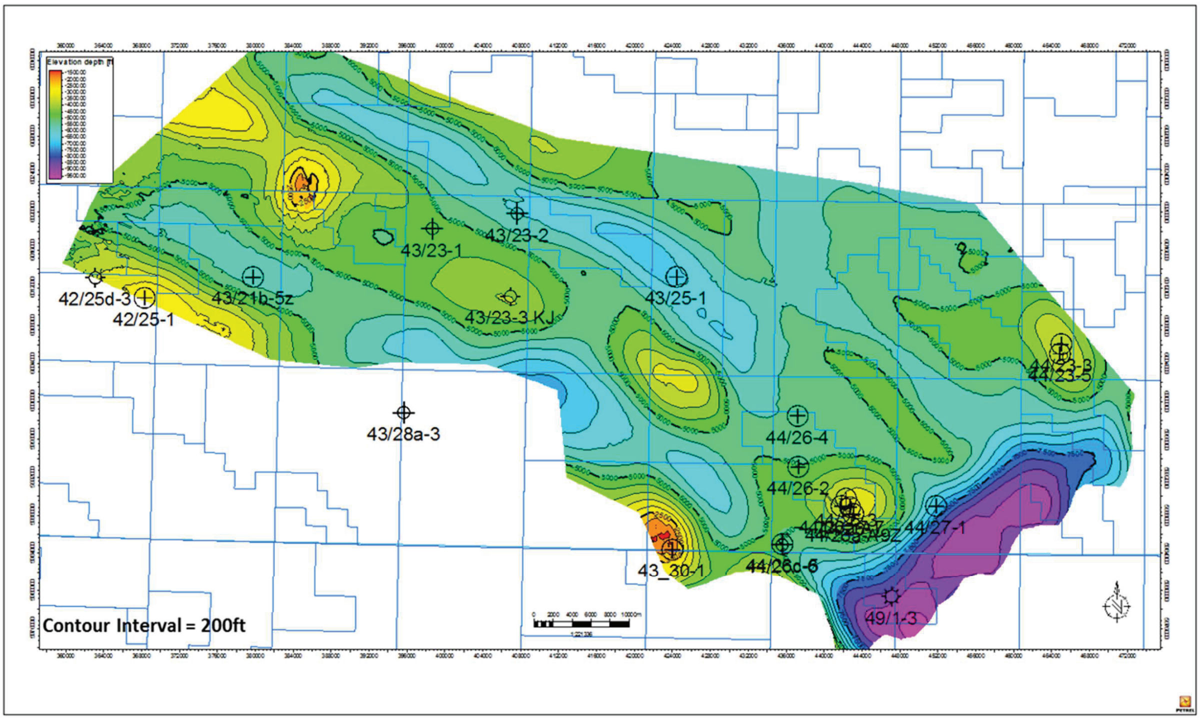
Figure 3-30 - Fairway and Closure 36, Top Bunter Sandstone depth structure map



Top Triassic/Top Haisborough depth structure map over the Fairway and Closure 36.

The seismic event is only present in the North Western part of the fairway, it is eroded to the east by the Base Cretaceous Unconformity.

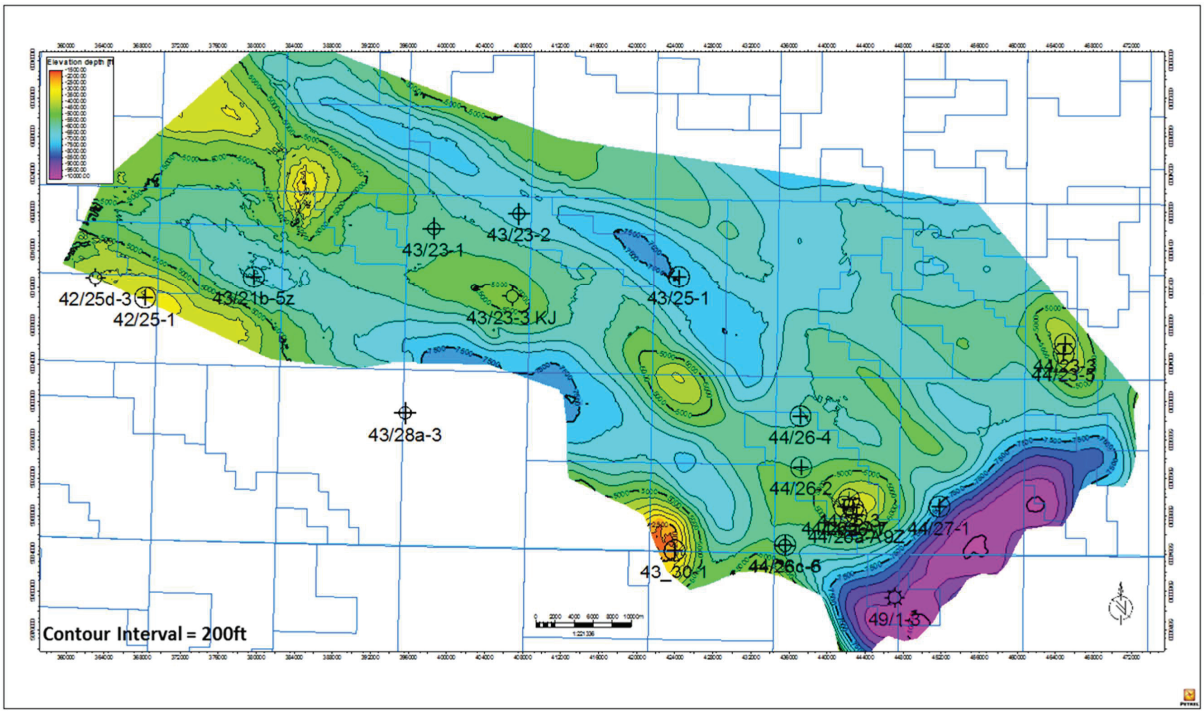
Figure 3-31 - Fairway and Closure 36, Top Triassic/Top Haisborough depth structure map



Top Muschelkalk depth structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

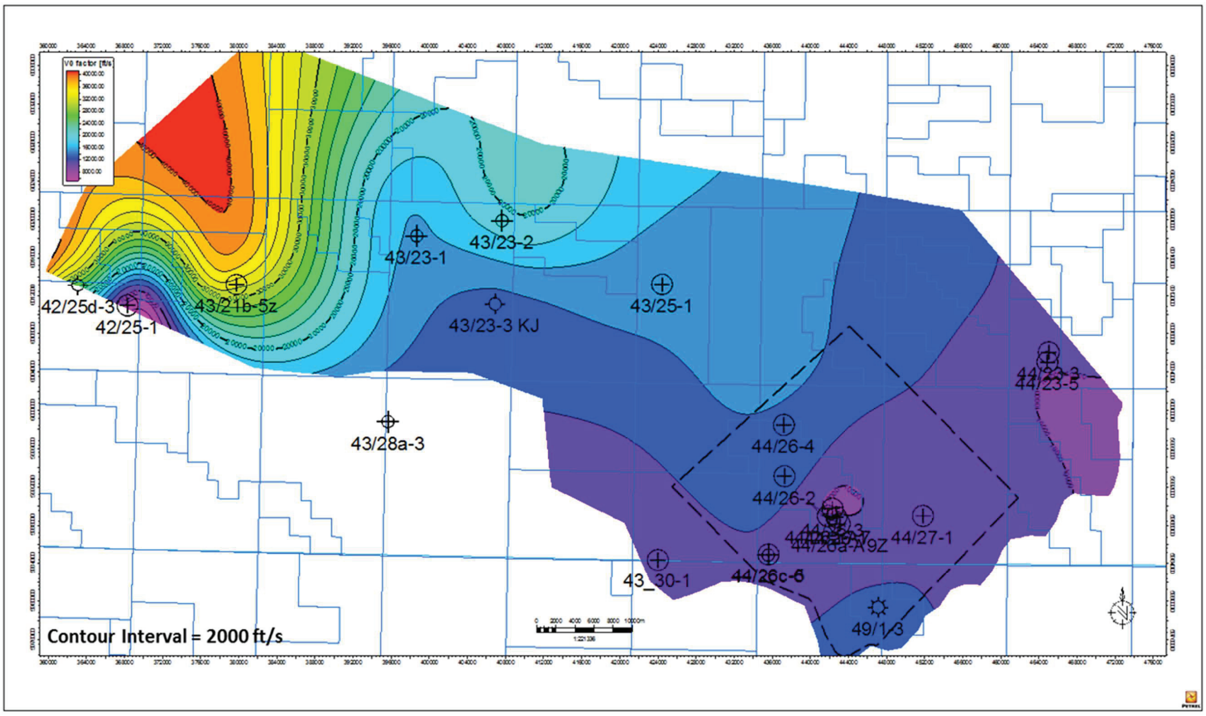
Figure 3-32 - Fairway and Closure 36, Top Muschelkalk depth structure map



Top Rot Halite depth structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

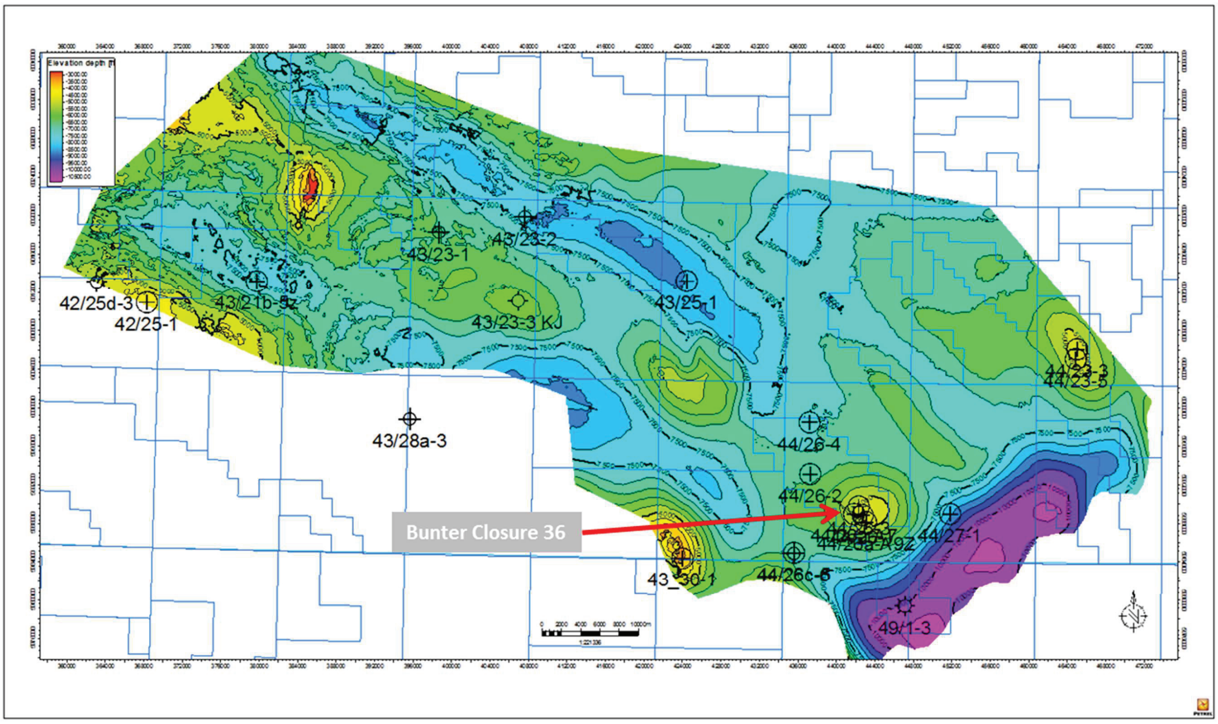
Figure 3-33 - Fairway and Closure 36, Top Rot Halite depth structure map



Bunter sandstone interval V0 map over the Fairway and Closure 36.

This is combine with a K value of 0.92 to depth convert this interval.

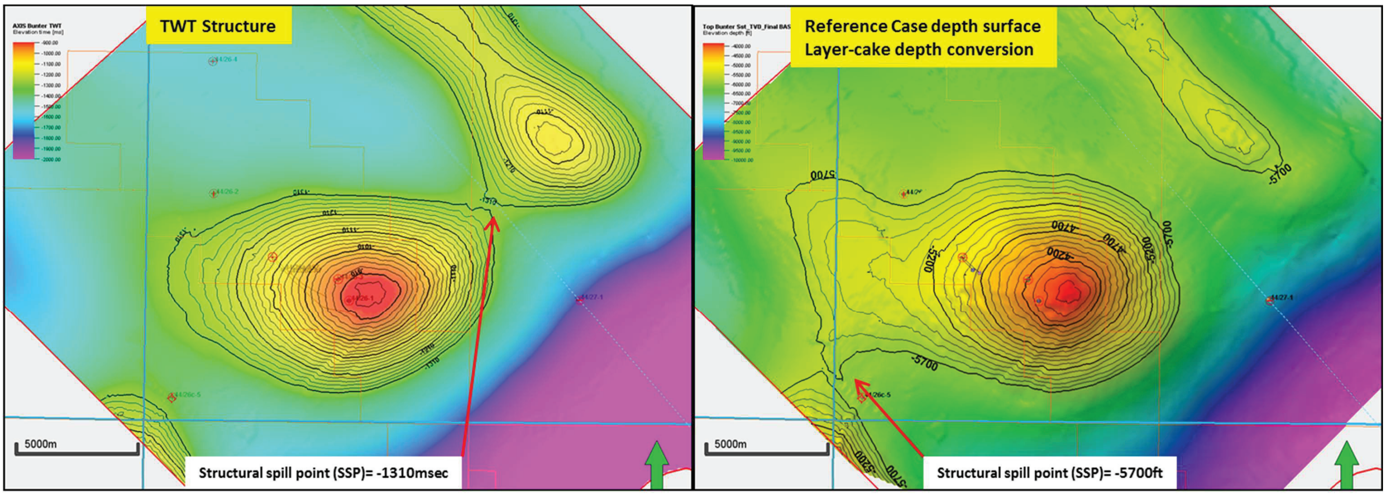
Figure 3-34 - Top Bunter Shale V0 map



Top Bunter Shale depth structure map over the Fairway and Closure 36.

Bunter 36 is a 4-way dip closure at this level.

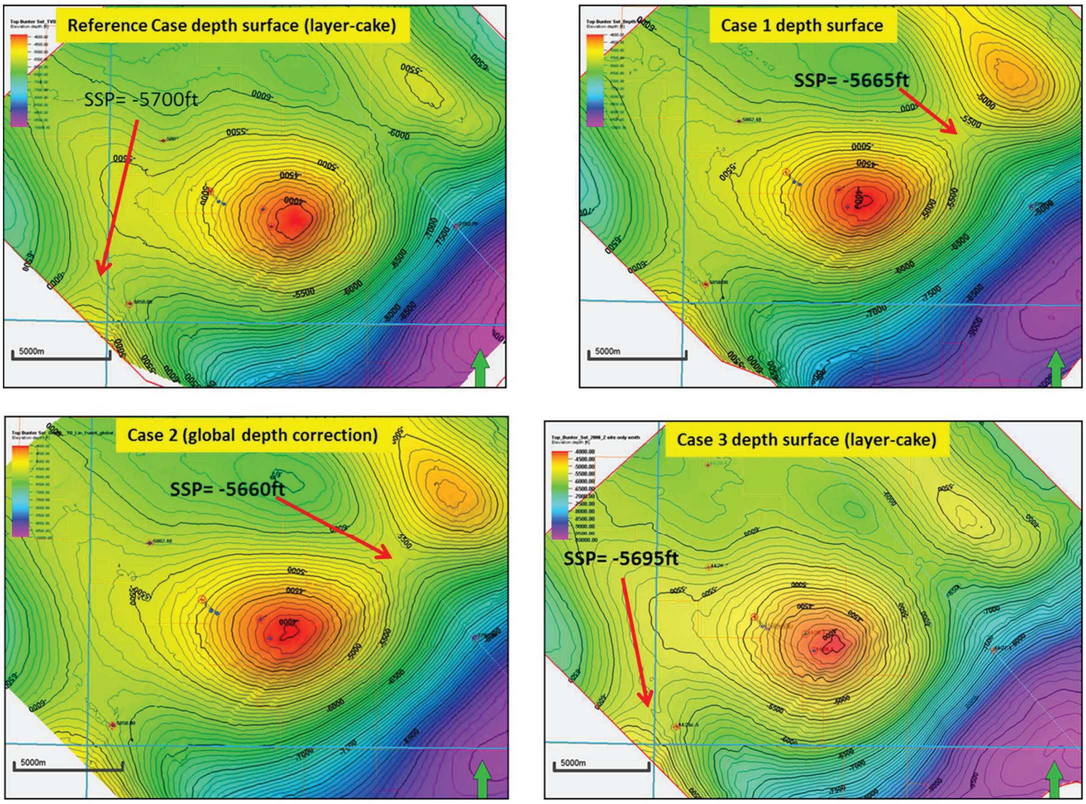
Figure 3-35 - Fairway and Closure 36, Top Bunter Shale depth structure map



Top Bunter Sandstone time and depth maps showing how the structural spill point moves from the NE to SW after depth conversion.

The layer cake depth conversion pulls up the western flank of Bunter Closure 36.

Figure 3-36 - Top Bunter time and depth surface comparison



Top Bunter Sandstone depth maps showing how the structural spill point moves depending upon the type of depth conversion applied.

Figure 3-37 - Bunter Closure 36: Top Bunter Sandstone depth structure maps

3.4.6 Seismic Attributes

Seismic attribute displays have been generated and used for a range of applications in this characterisation of Bunter Closure 36. The attributes fall into two primary application groups:

- **Supporting structural definition** - these include semblance attributes which describe the degree to which a trace in the 3D volume resembles its adjacent neighbouring traces. Where there is a strong and laterally continuous seismic reflection across an area then the semblance measure will be high. Where such a seismic reflection is broken or discontinuous then the semblance will be low. Semblance can be calculated relative to a constant time value or it can be dip adapted so that continuous, but sloping reflectors will also display high semblance. Semblance can be used to quickly identify faults and structural features in the subsurface detected by the seismic data as an important aid to interpretation. Semblance has a similar function to other attributes like Similarity, Continuity, Coherency. At Bunter Closure 36, this attribute has been used to characterise structural detail at each interpreted horizon, including the key search for small faults in the primary caprock.
- **Supporting Interval characterisation** - these include seismic amplitude which describe the magnitude of the signal peak or trough of the reflected seismic wave. This is related to the acoustic impedance contrast between the layers in the earth and can be used to infer some information about the properties of one layer relative to an adjacent layer. In ideal conditions this can be used to quantify lateral variation in overall reservoir quality. At Bunter Closure 36, amplitude has been used qualitatively to build confidence around overall reservoir quality and to understand the regional "phase reversal" at the Top of the Bunter storage reservoir interval. (Furnival, et al., 2013).

Both of these attribute groups are affected by the patchwork nature of the PGS 3D mega survey used for this project. The post stack splicing of different 3D seismic surveys with different acquisition and processing parameters makes the quantitative deployment of amplitude challenging and can result in linear artefacts in the attributes along the joins between the surveys. This is one of the motivations behind a recommendation to acquire new purpose designed 3D seismic data for the area ahead of any development.

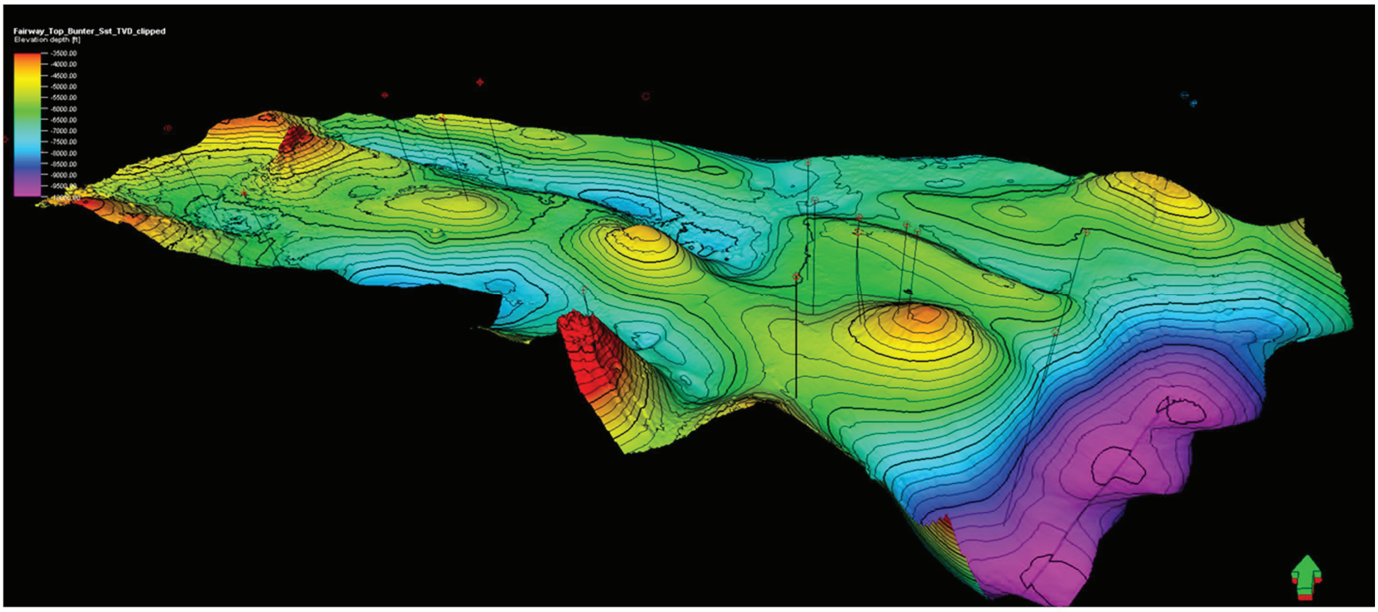
3.4.7 Conclusions

The PGS Southern North Sea MegaSurvey seismic volume which extends over the Bunter Closure 36 and the regional fairway has been interpreted. The key horizons have been identified, interpreted and mapped. Seismic data quality is considered adequate for structural interpretation.

There is no clear evidence of faulting in the reservoir or primary cap rock of the Bunter Closure 36 storage site that is considered likely to breach the primary seal (Rot Halite and Solling Claystone). The mapped time surfaces have been depth converted using a combination of a V0+k and interval velocity layer cake methods. Layer cake depth conversion was identified as the most technically robust approach due to velocity variations in the overburden units.

A limited depth sensitivity study highlights that the Bunter Closure 36 spill point could shift from the South West corner to the North East and be at a shallower depth.

Un-faulted depth structure grids have been taken forward used as input data for the site, overburden and fairway 3D static models (Figure 3-38).



3D view of Top Bunter Sandstone depth structure over the Fairway and Closure 36.

This is the un-faulted surface that is taken forward to 3D static modelling.

Figure 3-38 - Top Bunter Surface used in Static Modelling

3.5 Geological Characterisation

3.5.1 Primary Store

3.5.1.1 Depositional Model

The primary storage unit is the Triassic Bunter Sandstone Formation.

The depth to primary store at the crest of the structure is -1171m tvdss (-3841ft tvdss) and the Bunter Sandstone thickness at the site is approximately 215 m (705ft). A Top Bunter Sandstone Depth map for the site is shown in Figure 3-39.

The formation reservoir quality is good with high net to gross ratio (>80%), average porosity of 22% and average permeability of approximately 200 mD (max 1970 mD).

The Bunter Sandstone was deposited in a fluvially dominated environment, mainly as sheet floods on a broad low relief alluvial plain in an arid to semi-arid climate (Ritchie & Pratsides, 1993). The depositional model suggests fluid flow paths through the formation are continuous but tortuous due to locally preserved channel abandonment, overbanks silts, and later digenetic cements acting as baffles. The depositional system is regionally interpreted as flowing from the west and southwest, draining into a playa lake towards the north- northeast.

Whilst most of the shales and cements are not believed to be laterally extensive, baffling rather than impeding fluid flow, pressure measurements from the nearby Caister field indicate that some shales and cements are laterally extensive and can form locally effective vertical pressure barriers.

The Bunter Sandstone interval has been divided into five zones based upon an interpretation of the depositional environment, and correlated across the site and fairway using the available well log data. The correlation scheme is consistent with that published for the nearby Caister Field, a description of each zone is shown in Table 3-5. This zonation has been incorporated into both the static models.

At the Bunter Closure 36 site laterally extensive shales and cements are believed to be present at the top of both the Bunter 4 and Bunter 3 zones.

Bunter Zone	Description
Bunter 1	Sheetflood dominated floodplain; increasing shale content
Bunter 2	Sheetflood dominated floodplain; increasing shale content
Bunter 3	Distal braidplain dominated by channel units and sheetflood sands
Bunter 4	Distal braidplain with predominantly prograding sheetflood sands; high NTG
Bunter 5	Interbedded prograding sheetfloods and playa lake shale

Table 3-5 - Subdivision of Bunter Sandstone from top to bottom, Bunter Closure 36

The basal Bunter 5 zone is the poorest quality interval within the site (containing less than 50% sand), comprising interbedded playa lake shale and sheetflood sands, prograding NE into the basin replacing the playa lake shales of the Bunter Shale. In contrast the overlying Bunter 4 zone comprises predominantly prograding sheetflood sands, with occasional channels developed and a low proportion of shale (a proportion of sand greater than 90%). The top of this zone is marked by a tightly cemented layer which is thought to be laterally extensive across the site.

Bunter 3 represents the end of progradation and is interpreted as braided river channel units, with occasional sheetfloods and increased shale content. These shales have been interpreted as representing ponding within a playa margin environment. A laterally extensive, sealing shale is believed to exist at the top of this zone.

The uppermost two zones (Bunter 1 and 2) represent the onset of transgression within a distal floodplain and increasing shale content, culminating in the deposition of the overlying shale (Solling Claystone) and evaporates (Rot Halite) which form the primary seal.

A representative reservoir correlation through five wells across the Bunter Closure 36 site is shown in Figure 3-40.

3.5.1.2 Rock and Fluid Properties

The petrophysical database is outlined in Section 3.2 and was sourced from the publically available CDA database. The quality of the wireline data is generally good. Where there was some uncertainty in log quality it was possible to reference back to the composite log or final well reports for guidance. There were a small number of unresolved data quality issues, the most important being:

1. Well 44/23-5 it was not possible to resolve the apparent corrections made to the neutron porosity log. The conventional CNC log did not lie on the expected matrix line when plotted on a conventional Neutron- Density cross-plot, for this reason CN was chosen for Neutron porosity.
2. Well 44/26-1 had some depth matching concerns through the Bunter reservoir section. Although major formation changes were consistent, the finer resolution inter-bedded shales that were discriminated on the density and neutron log were offset or absent in the density log. Gamma ray clay model was excluded from the analysis in this well.

Conventional core data was available for 5 wells in total but only one within the storage complex. These core data included Grain Density, Helium Porosity, Horizontal and rarely vertical permeability. No uniaxial confined pressure measurements were available; it was assumed that a correction factor of 0.96 would be appropriate; no liquid corrected permeability measurements were available.

For depth matching the density log was used for reference. Core porosity was depth matched to this curve and all associated core measurement were then shifted to match. Bulk shifting of the core data was generally used and found to give the best results.

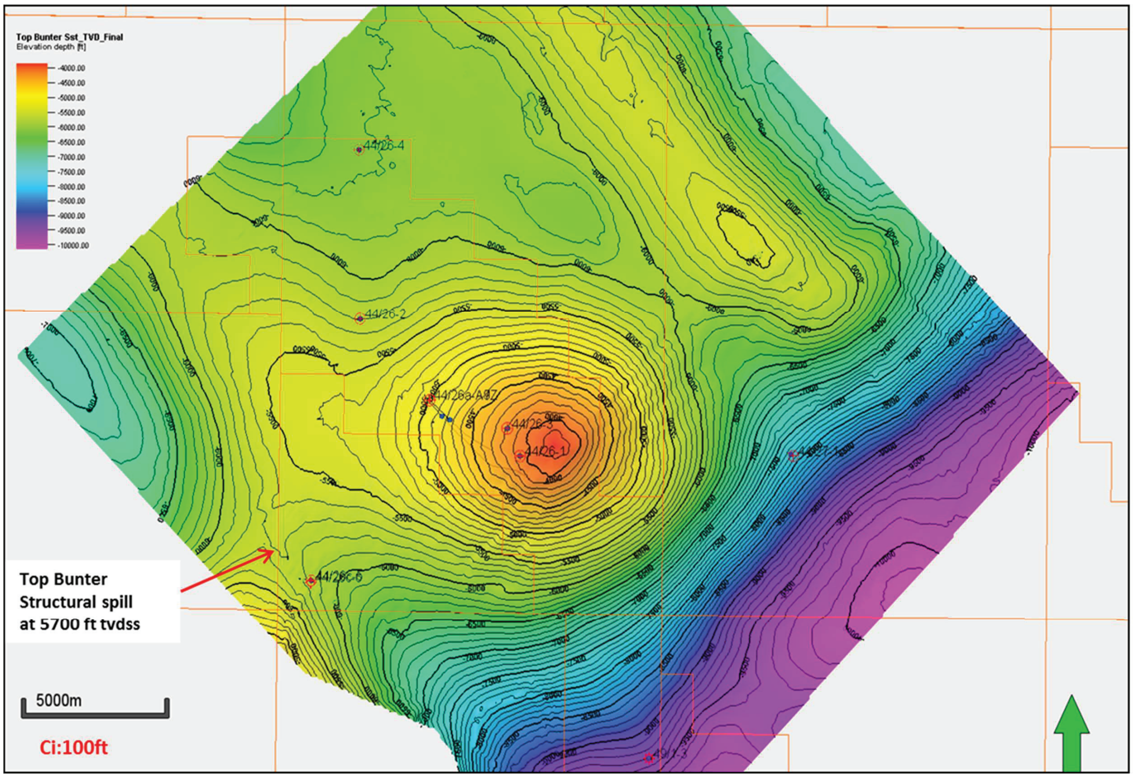
Whilst porosity logs were available for all selected wells, full density log coverage was only available for 3 out of 5 exploration wells within the storage complex. Density logs were also generally unavailable over the Bunter section in the Schooner development wells. This contributes some minor additional uncertainty to reservoir quality definition.

No SCAL data was available for this study and electrical properties were assumed to 'be standard' values with a=0.62, m=2.15 and n=2.0.

For the purposes of quantitative evaluation of reservoir rock properties from wireline logs, a standard oilfield approach to formation evaluation has been adopted. This is outlined in Appendix 11 and illustrated in Figure 3-41.

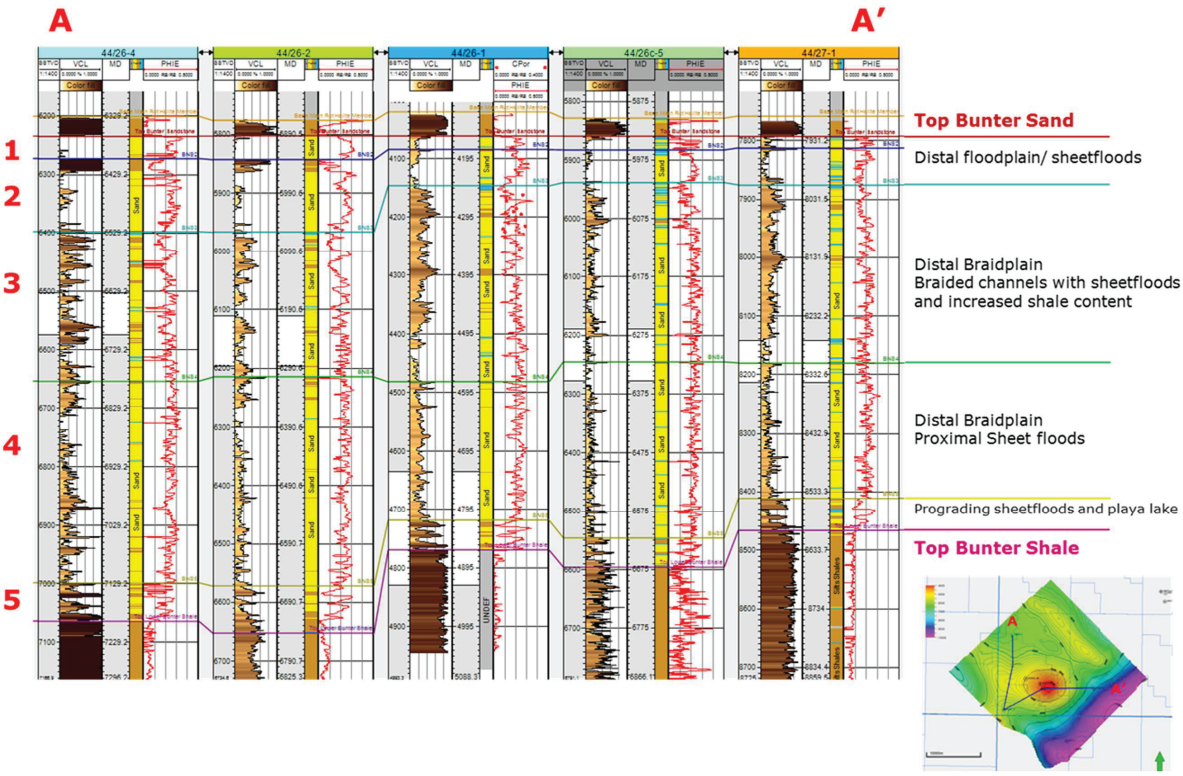
In summary, whilst there is good regional well coverage and 5 exploration wells within the storage complex area, 3 of which have full density, neutron and sonic log suites, there is remaining uncertainty associated with reservoir quality since:

1. There is only one partially cored well available within the storage complex
2. Three out of the five exploration wells in the storage complex were drilled with water based mud systems and the impact of this on the preservation of any halite cemented intervals is uncertain.
3. Of the five wells, only two are located within the closure itself leaving residual uncertainties around reservoir quality which would need to be addressed with further appraisal drilling.



Top Bunter Sandstone depth structure map for the Bunter 36 Site. Contour interval is 100ft. Depth to crest is approximately 3840ft tvdss.

Figure 3-39 - Top Bunter Sandstone depth structure map for the Bunter Closure 36 Site



Well correlation section across the Bunter 36 site showing the Bunter Sandstone zonation and dominant lithofacies.

Flattened on Top Bunter Sandstone.

Figure 3-40 - Well correlation section across the Bunter Closure 36 site

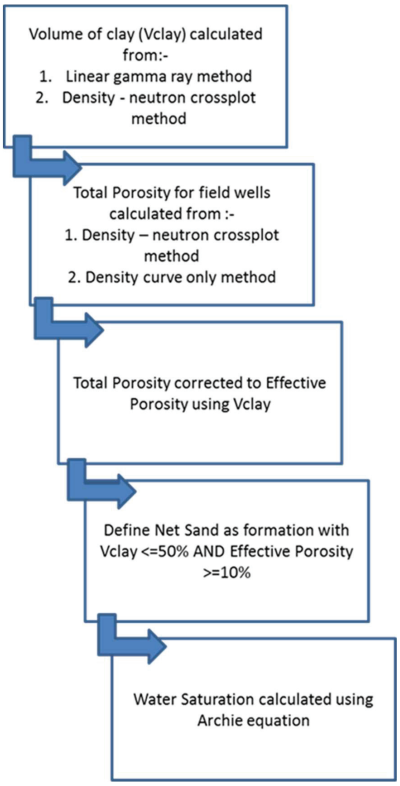


Figure 3-41 - Summary of Petrophysical Workflow

The results of the petrophysical analysis are summarised below for the full Bunter Sandstone interval, across all the wells reviewed. Computer processed interpretation plots for each analysed well showing derived calculated information are also provided in Appendix 6. Note that the input curves have been provided under a CDA license and are not reproduced in this report.

Table 3-6 is a summary of the Net Reservoir properties for the Bunter Sandstone, the reservoir is characterised as generally a thick sequence of sands with very high net to gross ratios. The wireline estimated porosity is consistent with the measurements made of the core porosity data of 20.4%.

Bunter Sandstone	Average	Minimum	Maximum	St. Deviation
Net Sand Thickness (Ft)	594	241	772	152
Net to Gross Ratio (%)	86.2	71	97	9.2
Porosity (%)	19.84	12	27	3.12

Table 3-6 - Bunter Net Reservoir Summary

Table 3-7 is a further breakdown of rock properties from the petrophysical analysis of wells within the storage complex. Permeability has not been estimated based upon wireline log data, but was computed within the Primary static model based upon core based porosity vs permeability relationship. This is detailed below in Section 3.5.4.6.

Well	Zone	Gross (ft)	Net (ft)	NTG	Porosity	Vclay	Calc Method
44/26-1	All Zones	702.7	562.9	80.1%	21.4%	26.1%	Sonic
44/26-1	Bunter 1	20.5	18.0	88.0%	20.5%	18.6%	
44/26-1	Bunter 2	58.5	53.6	91.6%	21.0%	11.8%	
44/26-1	Bunter 3	290.7	207.9	71.5%	20.2%	30.1%	
44/26-1	Bunter 4	281.3	260.0	92.4%	22.4%	26.2%	
44/26-1	Bunter 5	51.7	23.4	45.2%	23.4%	27.4%	
44/26-2	All Zones	850.0	773.3	91.0%	22.6%	14.2%	Density
44/26-2	Bunter 1	40.2	40.2	100.0%	26.1%	1.5%	
44/26-2	Bunter 2	124.1	108.1	87.1%	23.4%	6.5%	
44/26-2	Bunter 3	247.7	228.2	92.1%	20.2%	18.2%	
44/26-2	Bunter 4	357.6	352.1	98.5%	23.7%	14.5%	
44/26-2	Bunter 5	80.4	44.7	55.5%	20.4%	21.1%	
44/26-4	All Zones	829.0	600.3	72.4%	17.0%	30.4%	NDXplot
44/26-4	Bunter 1	38.0	28.0	73.7%	16.0%	28.4%	
44/26-4	Bunter 2	125.0	73.5	58.8%	17.5%	30.8%	
44/26-4	Bunter 3	317.0	212.5	67.0%	17.0%	33.3%	
44/26-4	Bunter 4	283.5	257.5	90.8%	17.1%	28.4%	
44/26-4	Bunter 5	65.5	28.8	43.9%	15.5%	29.1%	
44/26c-5	All Zones	739.5	645.8	87.3%	22.0%	16.1%	NDXplot
44/26c-5	Bunter 1	8.5	0.8	8.8%	19.5%	20.7%	
44/26c-5	Bunter 2	68.5	59.5	86.9%	22.0%	6.2%	
44/26c-5	Bunter 3	310.0	264.5	85.3%	21.8%	18.6%	
44/26c-5	Bunter 4	301.0	288.5	95.8%	22.5%	15.1%	
44/26c-5	Bunter 5	51.5	32.5	63.1%	19.9%	22.3%	
44/27-1	All Zones	676.5	636.0	94.0%	21.4%	17.9%	NDXplot
44/27-1	Bunter 1	20.0	17.8	88.7%	21.4%	14.4%	
44/27-1	Bunter 2	63.5	58.5	92.1%	18.8%	6.9%	
44/27-1	Bunter 3	263.0	250.5	95.2%	20.6%	24.0%	
44/27-1	Bunter 4	274.0	268.5	98.0%	23.1%	13.4%	
44/27-1	Bunter 5	56.0	40.8	72.8%	18.7%	27.3%	

Table 3-7 Bunter Sand Petrophysical Averages from Storage Complex

Halite Cements

The presence of halite cements is well documented within the Bunter Sandstone, however the regional distribution and the causes of these cements are not well understood. At Bunter Closure 36, whilst there is no definitive evidence of the presence of halite cemented intervals, it remains a risk factor because of the challenge associated with sampling halite in wells drilled with water based drilling mud systems. Some consideration has been given to assessment of this risk at Bunter Closure 36 and is outlined below.

A seismic phase reversal is observed close to the 5/42 saline aquifer site which is reported to correlate to the presence of a tightly halite cemented zone at the top of the Bunter Sand (Furnival, et al., 2013). Wells on the crest of 5/42 are un-cemented with an average zone porosity of 20 – 24% (e.g. 42/25-1), whereas wells on the flank (e.g. 43/21b-5z) have degraded porosity and appear tightly cemented at the top of the Bunter Closure 36 (average porosity typically less than 15%).

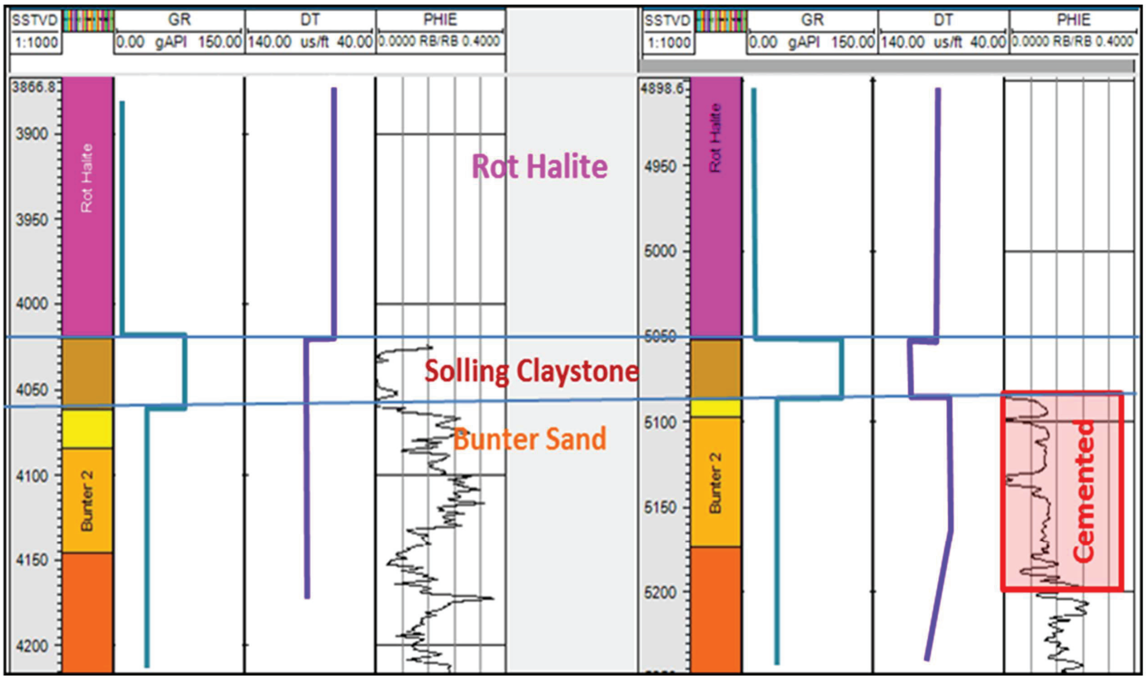
Well Review

A high level review of regional wells has been carried out to understand the regional distribution of halite cements and the risk associated with the presence of Halite cement in the Bunter Closure 36 site. The presence of halite cement at the top of the Bunter Sand can be clearly identified based on the sonic log response.

In un-cemented wells the sonic shows a fast velocity response through the overlying halite, the velocity drops as the well penetrates the Solling Claystone and then stays low in the underlying permeable, water filled Bunter Sandstone.

1. In wells with a cemented zone at the top of the Bunter Sandstone, the sonic remains the same or increases at the top of the Bunter Sand. This is due to the pore space being filled with 'fast' halite cement rather than being water filled.

This log response is shown schematically in Figure 3-42. A regional summary of wells in the area across Bunter Closure 36 and 5/42 is shown in Figure 3-43.



Schematic showing sonic response for halite cemented and un-cemented sands. A large increase in sonic values (velocity) at the top Bunter Sandstone evident when cemented.

Figure 3-42 - Log response schematic

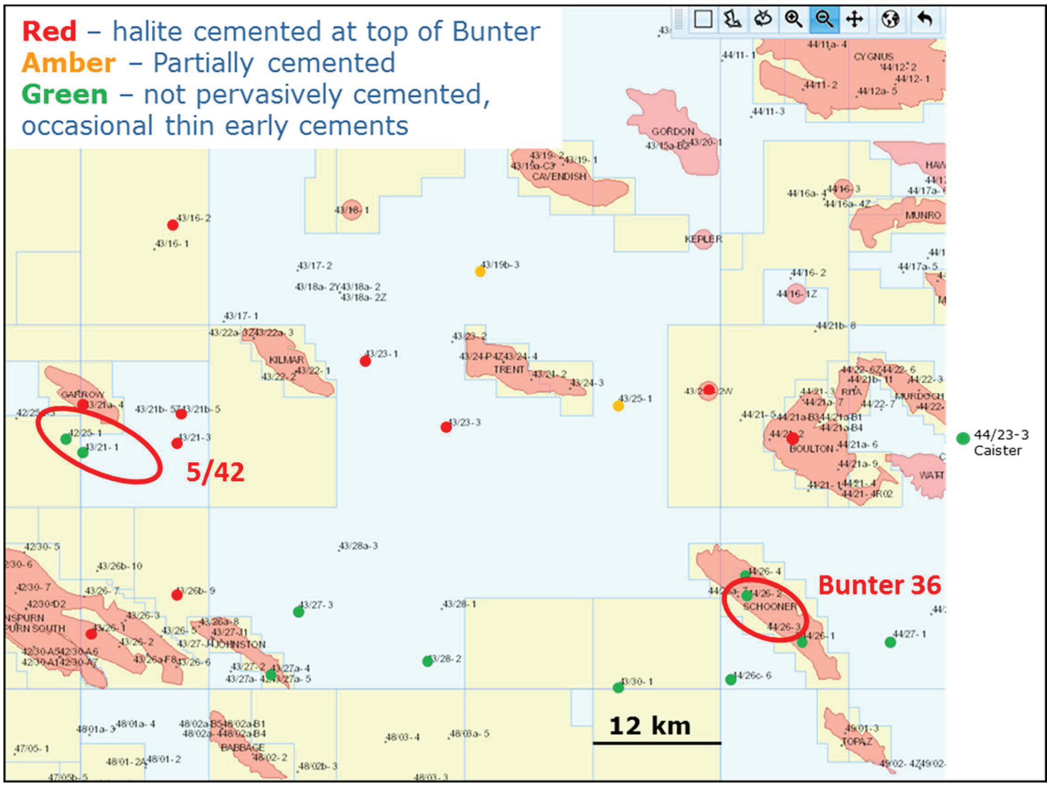


Figure 3-43 - Regional map of cemented and un-cemented wells within top of the Bunter Sandstone

Seismic Amplitude Extraction

Given the presence of halite at the top of the Bunter sand can be expected to change the acoustic properties, a map of the maximum negative amplitude at the Top of the Bunter Sandstone has been extracted across the interpreted seismic data area. It covers an interval 35 msec above and 12 msec below the Top Bunter Sandstone pick (Section 3.4). The high amplitudes correlate to higher velocity (increase in acoustic impedance) within the top of the Bunter Sand, caused by the cemented halite. This fits very well with the regional well data, except in areas of poor seismic data quality such as around 43/25-1 Figure 3-44.

The review demonstrates that there are no wells in the Bunter Closure 36 area which show significant Halite cement at the top of the Bunter Sandstone, and concludes that based on the well and seismic information that the associated risk of halite cement in the Bunter Closure 36 area is low.

3.5.1.3 Relative Permeability and Capillary Pressure

There is no special core analysis available for any of the wells in the vicinity of the Storage site. Further discussion regarding the handling of relative permeability is contained in the section on Injection Performance Characterisation.

3.5.1.4 Geomechanics

Geomechanical modelling of the primary store was conducted to clarify the strength of the storage formation and its ability to withstand injection operations without suffering mechanical failure at any point during those operations. Specifically, well information was used to ensure that the injection wells could be safely drilled, and that they could be operated without any significant sanding risk. Analysis of existing wells indicated that a minimum fracture pressure gradient of around 0.73 psi/ft is valid for the Bunter Sandstone and that no major drilling problems should be anticipated. Sanding analysis indicates that the Bunter Sandstone is a relatively strong formation and is unlikely to result in sand failure issues in the near wellbore area which might cause subsequent operational problems.

Full details of the geomechanical modelling work are included in Appendix 8.

3.5.1.5 Geochemistry

Geochemical modelling of the impact of CO_2 injection on the rock fabric and the mineral assemblage of the Bunter Sandstone reservoir was carried out to assess the risk of any geochemical consequences during either the active injection period, or the post-injection, long term storage period.

The approach and methodology used are described in more detail in Appendix 11 but were focussed on two key questions:

1. Will increasing the amount (partial pressure) of CO_2 in the reservoir/aquifer lead to mineral reactions which result in either increase or decrease of porosity and permeability of the reservoir?
2. Will elevated partial pressure of CO_2 compromise the caprock by mineral reaction?

A dataset of water and gas compositional data (from the literature as no direct measurements were available in CDA) and reservoir mineralogy (from published petrographical data from well 44/23-3 (Cade & Cubitt, 1987)) were used to establish the pre-CO_2 geochemical conditions in the primary reservoir. Equilibrium modelling was then undertaken to assess the impact of increasing amounts of CO_2 at a range (55°C – 66°C - 70°C) of temperatures to identify which mineral reactions are likely and assess the impact on the porosity of the rock. An initial kinetic study of the geochemical reactions in the reservoir was then undertaken with appropriate estimates of rock fabric and the selection of appropriate kinetic constants for the identified reactants to evaluate the realistic impact of CO_2 injection with regard to time.

Mineralogical Changes under Elevated CO_2 Concentration

The Bunter Sandstones are quartz-rich with variable carbonate, anhydrite and clay mineral cement contents (Cade & Cubitt, 1987). 'Unresolved' clay content has been equally divided between illite and chlorite for the purposes of this work. Detailed results are given in Appendix 11 but the key reactions in the reservoir sands appear to result in precipitation of dawsonite (a carbonate mineral), anhydrite and alunite (a K-Al sulphate mineral) with a modelled net reduction in porosity from an initial 20% to a final 13-14% (if the reaction were to proceed through to equilibrium).

Halite

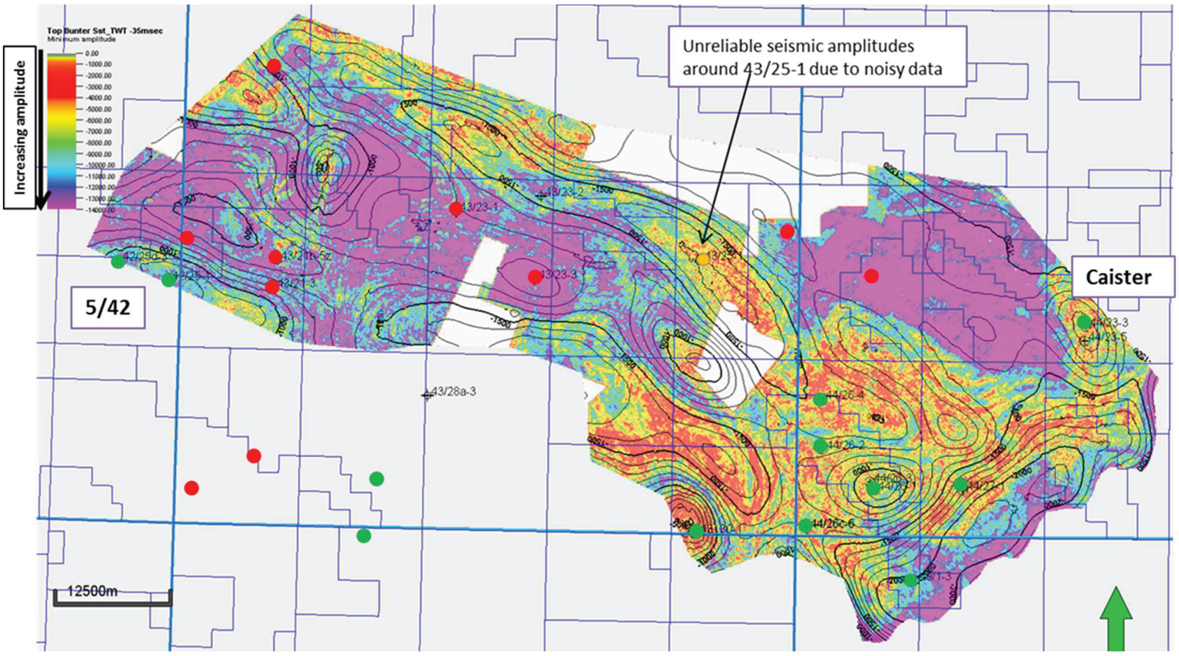
The uncertainty regarding in situ halite cements within the Bunter Sandstone reservoir and the precipitation of halite under injection conditions through near wellbore drying cannot be resolved with the data available at this time with more specific and detailed information on formation water salinity being required from an appraisal well.

Rate of Reaction: Kinetic Controls on the Geochemical Impact of CO_2 Injection

Equilibrium modelling assumes that the chemical reactions of the rock mineralogy and gas/water chemistry are simply controlled by the rate of delivery of reactive CO_2, but it is much more likely that the rate of mineral change is kinetically controlled by the rates at which mineral dissolution and precipitation occurs in the rocks, and so will be slowed down considerably:

1. If reactions are limited by rate of quartz growth, then there is unlikely to be any measurable reaction for many 10's to 100's of thousands of years since quartz precipitation doesn't seem to happen even on geological timescales at the relatively low temperatures at the injection site (<60-80°C).
2. If reactions are controlled by dissolution of illite, chlorite and K-feldspar then the dissolution rate constants for these minerals and their specific surface areas would need to be input into a specific kinetic model to evaluate rate of reaction. Dissolution rate data are poorly known but will be low at the low temperatures of the reservoir.

Overall, it is expected that the overall rate of reaction in the reservoir would be slow given the quartz-dominated mineralogy and low temperature. It is possible that the reaction would not reach equilibrium even after 10,000 years, suggesting there will be negligible impact on the injection timescale at this site. In addition, the dynamic modelling suggests that, for the development case presented, 73% of the injected CO_2 would remain structurally-trapped after 1000 years, significantly limiting the volume of dissolved CO_2 available for water-rock interaction (5% of injected volume).



Seismic amplitude map showing location of cemented and un-cemented wells.

High amplitudes equate to cemented Upper Bunter sandstone.

Figure 3-44 - Seismic amplitude map of cemented and un-cemented wells

3.5.2 Primary Caprock

3.5.2.1 Depositional Model

The thick mudstones and evaporites of the overlying Haisborough Group provide the top seal for the Bunter Sandstone. The Haisborough Group is laterally extensive and commonly over 500m thick, only being absent in the very south and north of the basin (Heinemann, Wilkinson, Pickup, Haszeldine, & Cutler, 2011). The rocks of the Haisborough Group were deposited as distal flood plain and shallow marine, alternating with coastal sabkha. Above the Bunter Closure 36 structure the total seal thickness provided by the Haisborough Group is approximately 300m (over 1000ft).

Directly overlying the Bunter Sandstone is a thin claystone (~10m) often referred to as the Solling Claystone or Rot Clay, this is overlain by approximately 60 m of the Rot Halite Member which provides the primary seal for the Bunter Sandstone.

Additional (secondary) seal is provided by the remainder of the Haisborough Group which comprises:

1. Claystones and dolomite stringers of the Dowsing Dolomite Formation (over 100m).
2. Muschelkalk Halite Member (approx. 15m or 50ft).
3. Dudgeon Saliferous Formation – approximately 90m (300 ft) of calcareous mudstones.

The formations underlying the Bunter Closure 36 site are also considered to be sealing. They are comprised of over 350m (over 1100 ft) of Bunter Shale and over 1000m (3200ft) of Upper Permian Zechstein evaporates.

3.5.2.2 Rock and Fluid Properties

Whilst there is no specific core available in the primary caprock, correlative intervals are effective seals for hydrocarbon gas in the nearby Caister gas field. Whilst it is possible than some thin sand laminations exist within the Solling Claystone, the effective porosity and permeability of the Rot halite can reasonably be assumed to be zero as the halite will flow under subsurface conditions to occlude any adjacent pore space.

3.5.2.3 Relative Permeability and Capillary Pressure

There is no direct capillary pressure measurements available on the cap rock formations of the Bunter Closure 36 site. This would be a requirement of any future appraisal programme.

A study of cap rocks from the UKCS by Mathias suggests that the permeability of evaporite sections which include halites will be exceptionally low ranging from 10-9 to 10-6 mD and that intact evaporites such as those in the Haisborough interval on the Bunter Closure 36 site can be expected to be particularly effectively low permeability seals. (a good quality seal is generally expected to have a permeability of less than 10-4 mD.

3.5.2.4 Geomechanics

Geomechanical modelling of the primary caprock interval was conducted to clarify the strength of the caprock formation and its ability to withstand injection operations without suffering mechanical failure at any point during those operations. Specifically, well information was used to ensure that the injection wells could be safely drilled, and that they could be operated without any risk of mechanical failure resulting from increasing reservoir pressure from CO_2 injection. 3D geomechanical modelling indicates that with the modelled injection scheme from 2027 to 2082 that some minor and localized uplift of the seabed

(14cm) can be expected. Furthermore, no shear or tensile failure of the overburden interval of pre-existing faults is expected. The risk of any thermally induced tensile failure in the caprock is considered to be minor, especially as the uppermost Bunter Sandstone layers are isolated from the deeper injection intervals.

Full details of the geomechanical modelling work are included in Appendix 8.

3.5.2.5 Geochemistry

A similar approach to that for the primary reservoir was undertaken to assess the geochemical impact of CO_2 injection on the Haisborough Group sediments. As no direct data for rock mineralogy were available from this site, analogue caprock mineralogies (from published Mercia Mudstone samples and onshore Netherlands Rot Formation halites) were used to establish the pre-CO_2 geochemical composition of the primary caprock.

Mineralogical Changes Under Elevated CO_2 Concentration

Two caprock lithologies were modelled. Caprock -1 is a clay-rich mudstone, while Caprock-2 is halite-dominated with minor anhydrite and calcite inclusions. To test the effect of a small amount of aluminosilicate minerals (clays and feldspars) in the top seal, e.g. in fault gouge, a geochemical model was also run with dominant halite, subordinate calcite, and minor amounts of quartz and muscovite (representing silicate fault gouge).

The diagenetic changes induced by CO_2 flooding of the mudstones (Caprock-1) sitting immediately above the Bunter Sandstone will, at equilibrium, lead to a net reduction in porosity of the rock from an initial 10% to a final 5.6 to 6.6% (as a function of temperature and the specific diagenetic reactions that occur (specifically, precipitation of dawsonite and dolomite).

The most effective top seal is the Rot Halite (Caprock-2). The equilibrium model reveals no geochemical reaction of the top seal following injection of CO_2. In general significant reactions only happen when aluminosilicate minerals (clays and feldspars) are present in the rock. There is no net creation of new porosity caused by the action of simply increasing the CO_2 partial pressure (fugacity) of the pore fluids.

Once aluminosilicates are introduced, then elevated CO_2 partial pressure does lead to reactions resulting in the precipitation of dawsonite. However the solid volume change is negligible, suggesting that even this reaction in a fault-gouge bearing Rot Halite will have little effect on seal quality.

Rate of Reaction: Kinetic Controls on the Geochemical Impact of CO_2 Injection

As the Solling Claystone is less quartz-rich than the Bunter Sandstone, it is possible that reaction rates may be controlled more by dissolution of the alumino-silicates (illite, chlorite, muscovite and K-feldspar). Although more reactive than the underlying sandstone, it is still expected that the reaction rates will be slow at the low temperatures of this site and the net product is one of porosity loss. No geochemical reaction is expected in the Rot Halite. Contact between dissolved (reactive) CO_2 and the primary seal in the crest of the structure will be limited by the predominance of structurally-trapped (and therefore geochemically 'dry') CO_2 for the initial 1000 years post-injection.

3.5.3 Secondary Store

The structural crest of the site is overlain by almost 1200m (over 3800 ft) of clay, mudstone, evaporate and chalk. No secondary storage site with any significance or containment potential has been identified within the overburden.

There is some very limited potential for storage in the underlying Carboniferous interval, although reservoir permeabilities and injectivity are likely to be very poor.

3.5.4 Static Modelling

Three static geological models have been developed as part of the characterisation effort of Bunter Closure 36.

1. **Primary Static Model** - The primary static model has been developed over an area which includes the Bunter Closure 36 site and its immediately adjacent geology covering an area of 25km by 25km. The purpose of this model is to serve as a basis for building an effective reservoir simulation model over the site.
2. **Fairway Model** - The second static model is semi regional in nature and covers a very large area from Bunter Closure 36 north and west towards the 5/42 structure and is some 100km long by 35km wide. The purpose of this model is to characterise the Bunter Sandstone fairway and its potential connectivity to other nearby hydrocarbon and CO_2 storage sites.
3. **Overburden Model** - The third static model builds upon the footprint of the Primary Static model, but extends to describe the overburden geology all the way up to the sea floor. This model is primarily used for consideration of containment issues which are detailed in Section 3.7.

3.5.4.1 Primary Static Model

Grid Definition

The static model described in this section focuses on the site geological model for the Bunter Sandstone Closure 36. A map of Top Bunter Sandstone for the modelled site area is shown in Figure 3-39.

The area selected for the site model covers a 25km x 25km, the coordinates of the site model boundary are:

X Min 425640.96	X Max 461561.98
Y Min 5974505.63	Y Max 6008588.18

Reservoir modelling has been carried out using Petrel v2014 and the geographic reference system used ED50 (UTM31).

The stratigraphic interval for the site model is from the Rot Halite down to the Top of the Bunter Shale which is approximately 200 m (700 ft) thick. The primary seal for this interval is the overlying Rot Halite. The stratigraphic definition of the Primary Static model is outlined in Table 3-8.

The Top Bunter Sandstone and Top Bunter Shale depth horizons within the static model were created from the depth surfaces interpreted from the seismic and time to depth converted (Section 3.4). Depth horizons have been tied to the well tops using an influence radius of 800m. Figure 3-45 shows a map of the Top Bunter Sandstone depth over the full interpreted area.

The top of the model is the Top Solling Claystone (Base of Rot Halite), this is impermeable and is represented in the model by a single layer. It has been generated by subtracting a well based isochore (thickness map) from the Top Bunter Sandstone depth horizon.

The internal reservoir depth horizons (Top Bunter 2 – Top Bunter 5) have been calculated from well thickness information, derived from the well correlation.

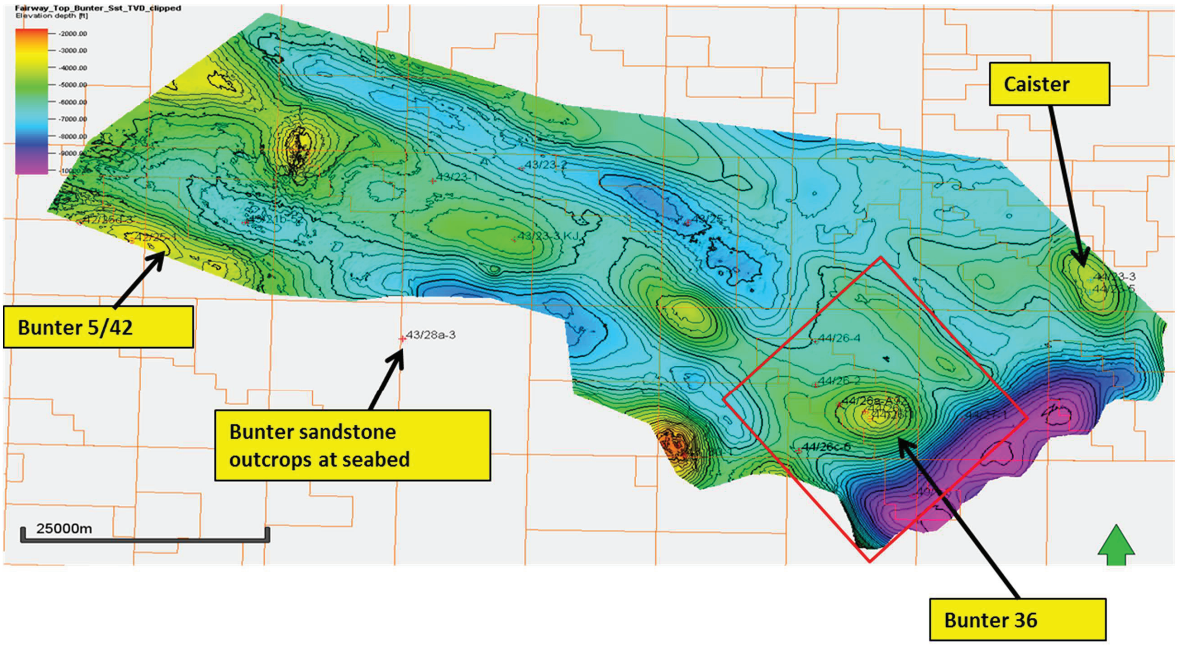
The base of the model is represented by the top 3m only of the Bunter Shale, it is impermeable and represents the underlying seal. This has been generated by adding a single cell with a thickness of 3m (10ft) to the Base Bunter Sand depth surface.

No faults have been incorporated into the model as none have been interpreted within the site model area.

A cross section through the structure showing the different zones and layering within the model through 44/26-1 is shown in Figure 3-46. The site model 3D grid was built with a rotation of 45° and grid cells of 200m x 200m in the X, Y direction.

Horizon	Zone	Source
Base Rot Halite	Solling Claystone	Built up from Top Bunter Sand using a well derived isochore.
Top Bunter Sand	Bunter 1	Direct seismic interpretation and depth conversion.
Top Bunter 2	Bunter 2	Built down from Top Bunter Sand using a well derived isochore and proportioned within the seismic envelope between Top Bunter Sand and Top Bunter Shale.
Top Bunter 3	Bunter 3	Built down from Top Bunter 2 using a well derived isochore and proportioned within the seismic envelope between Top Bunter Sand and Top Bunter Shale.
Top Bunter 4	Bunter 4	Built up from Top Bunter 3 using a well derived isochore and proportioned within the seismic envelope between Top Bunter Sand and Top Bunter Shale.
Top Bunter 5	Bunter 5	Built up from Top Bunter4 using a well derived isochore and proportioned within the seismic envelope between Top Bunter Sand and Top Bunter Shale.
Top Bunter Shale	Bunter Shale	Direct seismic interpretation and depth conversion. Only top 3m of Bunter Shale modelled.
Base Model		Top Bunter Shale + 3m (10ft)

Table 3-8 - Stratigraphy, zonation and layering for Primary Static Model



Top Bunter Sand Depth Structure for full interpreted area.

Contour interval is 250 ft.

Site model area shown by red polygon outline.

Figure 3-45 - Top Bunter Sand Depth Structure for full interpreted area

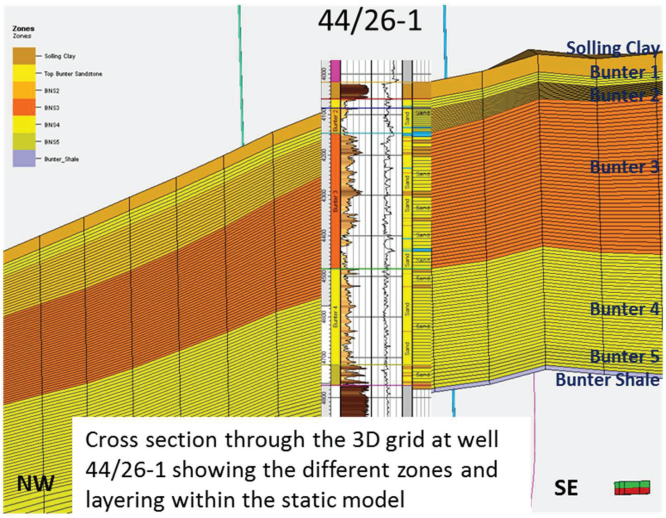


Figure 3-46 - Cross section through the 3D grid at well 44/26-1

Proportional layering has been used for all zones. The number of layers has been selected in order to effectively model the geological heterogeneity, specifically capturing the thin shales and cemented layers observed in the well data. The layering per zone is shown in Table 3-8.

The resulting grid has approximately 1.6 million grid cells.

3.5.4.2 Property Modelling

As described in Section 3.5.1.1, the Bunter Sandstone was deposited in a fluvially dominated environment, mainly as sheet floods on a broad low relief alluvial plain in an arid to semi-arid climate.

Other than the very lowest zone, Bunter 5, the Bunter Sandstone has a high net to gross of 80 – 95%. In a sandy system such as this one of the key controls on CO_2 plume migration will be impermeable thin shales and cemented sand layers which act as barriers and baffles. To allow for these barriers and baffles to be explicitly captured within the static model, a facies model has been built.

Porosity has been modelled by facies using the available interpreted Effective Porosity (PHIE) log. Permeability has been modelled within the 3D grid using the available measured core data and correlated to the modelled porosity.

3.5.4.3 Facies Log Interpretation

There is a limited amount of core data available across the Bunter Closure 36 site area. A lithology log at the wells has been calculated using wireline log cutoffs, these have then been checked manually and interpretative corrections made where required. The interpreted Vclay log has been used to discriminate between sand and shale facies. Higher Vclay values (>50%) represent either shales or fine grained silts. The density and sonic logs have been used to identify cemented layers within the sand. A summary of the cut-offs used is shown in Table 3-9.

Sand	Vclay <= 0.5
Shales/ silts	Vclay > 0.5
Cemented Sands	Clean sand with density and/ or sonic spike Vclay < 0.28 and Density > 2.5 (or Sonic < 70)

Table 3-9 - Cut-offs used to define facies log

The overall approach to the facies modelling acknowledges the sand dominated nature of the Bunter Sandstone interval. Geometric shape volumes representing the discontinuous shales and the clean but cemented sandstones are then placed into the model at random (stochastically) using a rule set which preserves the volumetric proportion, stratigraphic and geographic position trends and conditions the result to the lithologies observed in each well. Some of the key parameters used in this "object modelling" are outlined in Table 3-10.

Zone	Facies	Method	Object shape	Orientation (Degrees)	Minor width (m)	Maj/ Min ratio	Thickness (m)
Bunter 1	Cemented Sand	Object	Ellipse	25-30	400-500	2	1.5 - 3
	Silt/shale	Object	Ellipse	25-30	400	3	1.5 - 3
Bunter 2	Cemented Sand	Object	Ellipse	25-30	400	2	1.5 - 3
	Silt/shale	Object	Ellipse	25-30	800-1000	3	1.5 - 3
Bunter 3	Cemented Sand	Object	Ellipse	25-30	400	2	1.5 - 3
	Silt/shale	Object	Ellipse	25-30	1500-2500	3	1.5 - 3
Bunter 4	Cemented Sand	Object	Ellipse	25-30	400	2	1.5 - 3
	Silt/shale	Object	Ellipse	25-30	800-1000	3	1.5 - 3

Table 3-10 - Input properties used for object modelling of shales and cements in Bunter 1 – Bunter 4

Zone	Facies	Method	Orientation (Degrees)	Variogram Width (m)	Variogram Length (m)	Variogram Thickness (m)
Bunter 5	Sand	SIS	30	1000	3000	3
	Silt/shale	SIS	30	1000	3000	3

Table 3-11 - Input properties used for SIS modelling in Bunter 5

Sands and shales in Bunter zone 5 have been modelled using sequential indicator simulation (SIS), due to the more even split between proportions of sand and shale. With its lower net to gross, injection is not planned in this zone, and hence a more detailed model of the facies is not required. Sand and shale proportions have been calculated from well data, vertical proportion curves have been used to control vertical distribution. The orientation has been aligned with the depositional direction, approximately SW – NE. Variogram ranges and settings are shown in Table 3-11.

The layer at the top of Bunter 3 is assumed to be a laterally sealing shale. The layer at the top of the Bunter 4 is assumed to be a laterally sealing cemented layer.

Both the Solling Claystone overlying the site and the Bunter Shale below the site are interpreted and modelled as 100% impermeable clay or shale intervals.

Modelled facies proportions are shown in Table 3-12.

Model Results	Sand	Shale	Cement
Bunter 1	0.87	0.03	0.10
Bunter 2	0.81	0.12	0.07
Bunter 3	0.80	0.11	0.09
Bunter 4	0.93	0.06	0.01
Bunter 5	0.53	0.47	0.00

Table 3-12 - Modelled Facies Proportions

An example cross section and stratigraphic slice through the facies model are shown in Figure 3-47.

The raw lithology curve is generated at the sample rate of 0.15m (0.5ft). This has been upscaled into the modelling grid using the "most off" upscaling method. The upscaling has been weighted to ensure that a representative proportion of the thin shales and cements have been captured within the gridded model.

Facies logs have been used to control the facies modelling. These have been calculated for the following wells:

44/26-1, 44/26-2, 44/26-4, 44/27-1, 44/26c-5

An example of the lithology log from 44/26-4 and the upscaled version of the lithology log is shown in Figure 3-48.

3.5.4.4 Facies Modelling

Shales and cemented sands in Bunter zones 1 – 4 the have been modelled as objects within a background of sand. This fits with the conceptual model of a high net to gross system with barriers to vertical flow. The proportion of shales and cemented sands is calculated based on well data within the site area, for each zone in the model. The vertical distribution of these within each zone is controlled by vertical proportion curves, again calculated form the well data (Figure 3-49). Within the site there are no lateral trends interpreted or used within the modelling. The sizes of the objects used in the modelling are shown in Table 3-10. The orientation of the long axis of the shales and cemented sands has been aligned with the depositional direction, approximately SW – NE.

3.5.4.5 Porosity Modelling

The following wells were used within the site model for the modelling of porosity:

44/26-1, 44/26-2, 44/26-4, 44/27-1, 44/26c-5.

The interpreted PHIE log was upscaled to the grid scale using arithmetic averages, biased to the interpreted facies logs. This ensures that the porosity distribution (mean and standard deviation) for each facies is correct.

Porosity modelling is performed for each zone. Properties within the sand facies were distributed in the model, between wells, using a Sequential Gaussian Simulation method (SGS) and constrained to the facies model. This ensures that the property distributions (mean and standard deviation) in the original log porosity data are maintained in the final model. Due to their mixed shale and silt content the shale facies were given a very low porosity of 0.03. Cemented sands are assigned porosity values of 0%. Settings for the SGS are shown in Table 3-13.

Type	Major Axis (m)	Minor Axis (m)	Vertical (m)	Azimuth (deg)
Spherical	2000	500	3	30

Table 3-13 - Input setting for porosity and permeability SGS modelling

In addition to the well data and facies model, the spatial distribution of porosity within each zone is also controlled by depth trends where observed in the original well log data. Where present these are not significant.

The average modelled porosity is 22% which compares to the average for the site wells of 21%. The slight difference in average is accounted for by the depth trends which have been applied.

A histogram showing a comparison of the porosity well log input versus the modelled porosity for the sand facies is shown in Figure 3-50.

Average modelled porosity values by zone are shown in Table 3-14.

Zone	Average porosity in sand facies
Bunter 1	0.21
Bunter 2	0.22
Bunter 3	0.22
Bunter 4	0.23
Bunter 5	0.20
All zones	0.22

Table 3-14 - Average modelled porosity values for Sand facies in each zone

3.5.4.6 Permeability Modelling

There is a strong positive correlation observed in the available core data between the measured core porosity and core permeability. A cross plot of porosity versus permeability for both the measure core data and final modelled data is shown in Figure 3-51.

Horizontal permeability within the sand facies was modelled using a bivariate distribution method, allowing for this correlation and distribution to be used directly and ensure that the final permeability distribution matches that of the measure core data. The modelled porosity is used as a secondary property input, ensuring that the resulting permeability model also remains correlated with the modelled porosity, i.e. a cell with a high porosity will have a high permeability. The variogram settings used are the same as those used for the porosity modelling.

The average horizontal permeability from core is 202 mD which compares to the average modelled horizontal permeability of 210 mD. A histogram showing the horizontal permeability for the sand facies is shown in Figure 3-52. Average horizontal permeability values by zone are shown in Table 3-15.

The average modelled vertical permeability is 82mD which results in an average Kv /Kh ratio of 0.36.

Zone	Average Kh in sand facies
Bunter 1	233 mD
Bunter 2	219mD
Bunter 3	195 mD
Bunter 4	223 mD
Bunter 5	162 mD
All zones	210 mD

Table 3-15 - Average modelled horizontal permeability values for Sand facies in each zone

Vertical permeability is similarly modelled using a distribution method. The relationship between horizontal and vertical permeability from measure core data is used as input (Figure 3-53). The modelled horizontal permeability is used as the secondary variable to which the modelled vertical permeability is correlated. The average modelled vertical permeability is 82mD which results in an average Kv /Kh ratio of 0.36. A histogram showing the vertical permeability for the sand facies is shown in Figure 3-54.

Due to their mixed shale and silt content the shale facies were given an extremely low permeability of 0.0065 mD. Cemented sands are assigned permeability values of 0 mD.

3.5.4.7 Rock and Pore Volumetrics

Volumetric calculations for both total bulk rock volume and total pore volume in the static model have been performed for the Bunter Sandstone interval above the lowest closing contour or structural spill point of -1737 m tvdss (-5700 ft tvdss). For reference these are shown in Table 3-16.

Zones	Bulk volume (10^6 m3)	Pore volume (10^6 m3)
Bunter 1	862	169
Bunter 2	2429	433
Bunter 3	6327	1072
Bunter 4	3535	742
Bunter 5	674	83
Total	13828	2499

Table 3-16 - Gross rock and pore volumes for Bunter Closure 36 site above spill point (-1737m tvdss)

3.5.4.8 Simulation Model Gridding and Upscaling

To enable dynamic simulation models to run within a reasonable time frame, a coarser simulation grid and model was generated. Vertical coarsening from 97 layers in the primary static model to 41 layers in the dynamic model has reduced the number of cells from approximately 1.6 million to around 710,000 (approximately 600,000 active). For the dynamic model, the AOI (25km x 25km), zonation (5 Bunter zones), lateral cell size (200m x 200m), and grid orientation (45°) remain the same as in the primary static model.

A fractional layering scheme has been used for the dynamic simulation grid. This allows for the cells at the top of each zone to retain the same vertical resolution as the primary static model, with the thicker "upscaled" cells in the deeper layers only. This ensures that the heterogeneity is retained at the top of each zone where it is expected the majority of the CO_2 plume migration will take place.

A comparison of the layering between static and dynamic models is shown in Figure 3-55. The layering scheme is summarised in Table 3-17.

Zone	Static Model Layers	Dynamic Model Layers
Bunter 1	2-5	2-5
Bunter 2	6-20	6-12
Bunter 3	21-60	13-27
Bunter 4	61-90	28-37
Bunter 5	91-96	38-40

Table 3-17 - Summary of Static and Dynamic model layer equivalences

Porosity, horizontal permeability and vertical permeability have been upscaled (averaged) from the primary static model grid into the coarser scale dynamic simulation grid using the following standard hydrocarbon industry upscaling methods.

1. Porosity: Volume weighted arithmetic average.
2. Horizontal Permeability: Volume weighted arithmetic average.
3. Vertical Permeability: Volume weighted harmonic average.

A check of static model versus dynamic model pore volumes was carried out and the difference was less than 1% confirming minimal pore volume distortion resulted from the upscaling process.

3.5.4.9 Primary Static Model Sensitivity Cases

To support a range of key sensitivity cases in the dynamic modelling work, three additional deterministic static model cases have been generated capturing key static uncertainties.

Open Zones Case

Within the reference case, laterally extensive barriers have been assumed at the top of the Bunter 3 and Bunter 4 zones. These act as barriers to flow and pressure between the Bunter zones. A static model sensitivity has been generated that allows for communication between the Bunter zones. This has been done by allowing for the presence of sand at these zone boundaries.

Low Permeability Case

With limited core availability within the Bunter Sandstone aquifer and uncertainties related to reservoir quality and in particular halite cements, a case has been generated which captures a low case permeability scenario. This has been done by applying a porosity to permeability equation, which has the effect of removing the highest permeability from the model. The resulting modelled horizontal permeability average is approximately 50 mD, the modelled horizontal permeability distribution is shown in Figure 3-56.

High Net to Gross Case

There is some uncertainty both on the picking of the non-net shales and cements within the well log data, and the proportions of these barriers and baffles within the reservoir. A high net to gross (NTG) or high sand proportion case has been generated to test the sensitivity of the CO_2 migration to this. A comparison of the reference case and the high NTG case sand proportions is shown in Table 3-18.

	Ref Model Sand proportion	High NTG Sand proportion
Bunter 1	0.87	0.94
Bunter 2	0.81	0.90
Bunter 3	0.80	0.89
Bunter 4	0.93	0.95
Bunter 5	0.53	0.53

Table 3-18 - Comparison of reference case and high NTG case modelled sand proportions

Each of these cases were upscaled for the dynamic model using the same methodology as the reference case.

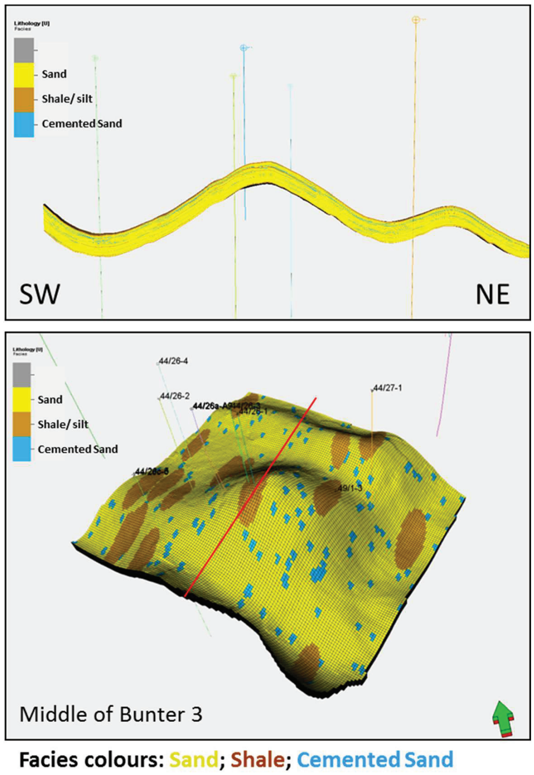
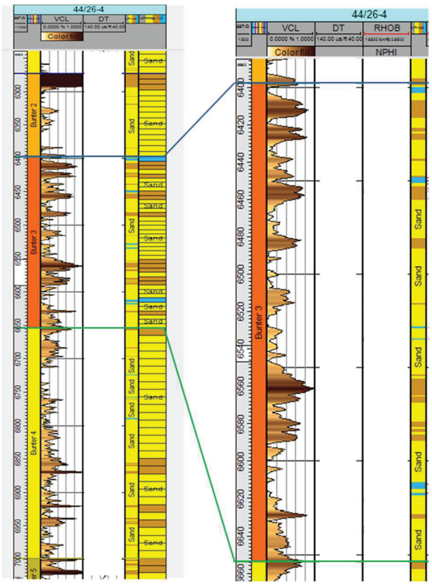


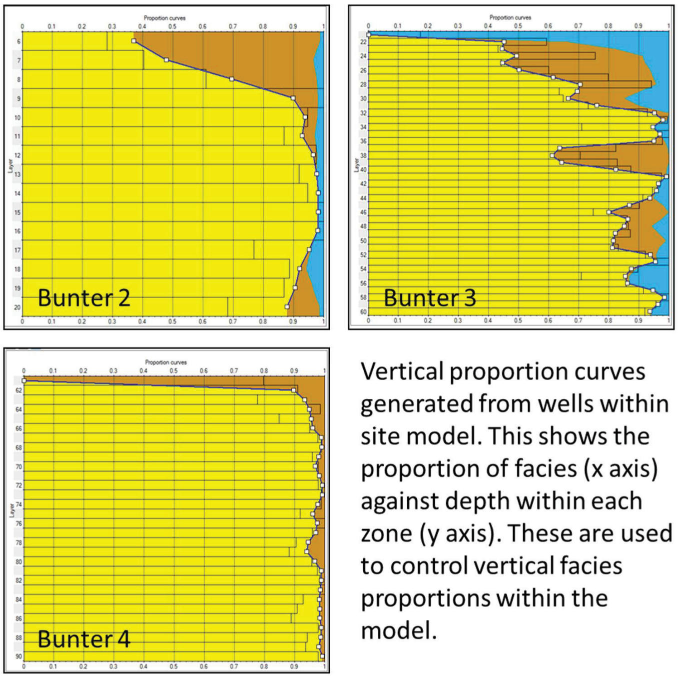
Figure 3-47 - Cross section and layer slice through the reference case facies model



Example of facies interpretation at 44/26-4
Zoomed in section shows Bunter 3 zone.
Raw log data (Density, Neutron and sonic) were used to assist with lithology interpretation but have been removed due to licensing restrictions

Figure 3-48 - Example of facies interpretation at 44/26-4

Facies colours: Sand; Shale; Cemented Sand



Vertical proportion curves generated from wells within site model. This shows the proportion of facies (x axis) against depth within each zone (y axis). These are used to control vertical facies proportions within the model.

Figure 3-49 - Vertical proportion curves

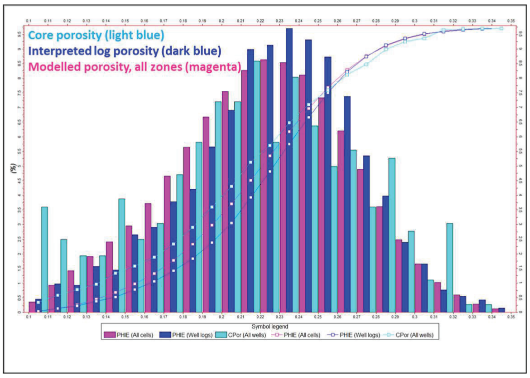


Figure 3-50 - Histogram of porosity within sand facies

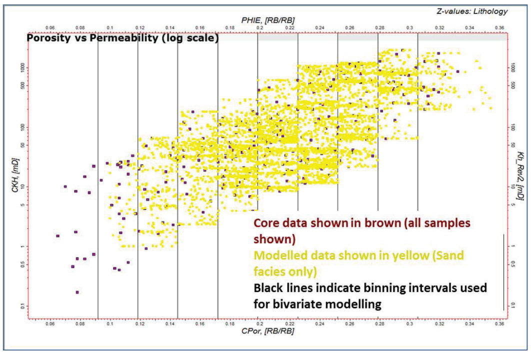


Figure 3-51 - Cross plot of porosity versus permeability (log scale)

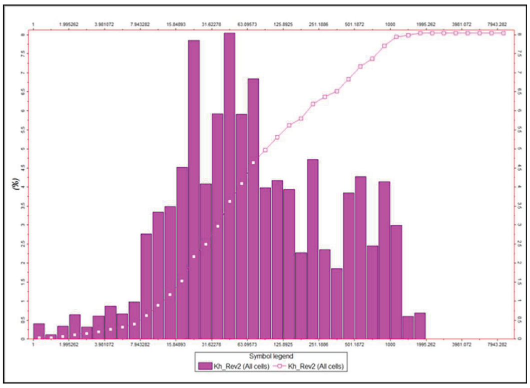


Figure 3-52 - Histogram of modelled horizontal permeability within sand facies (Log scale)

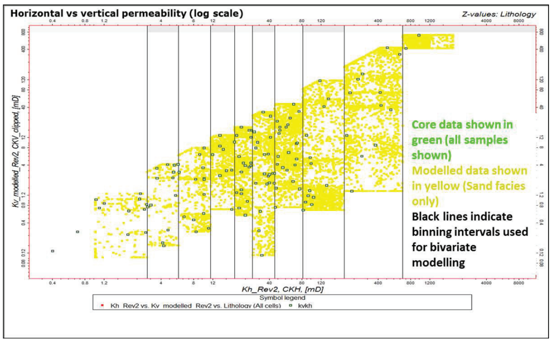


Figure 3-53 - Cross plot of horizontal versus vertical permeability (Log scale)

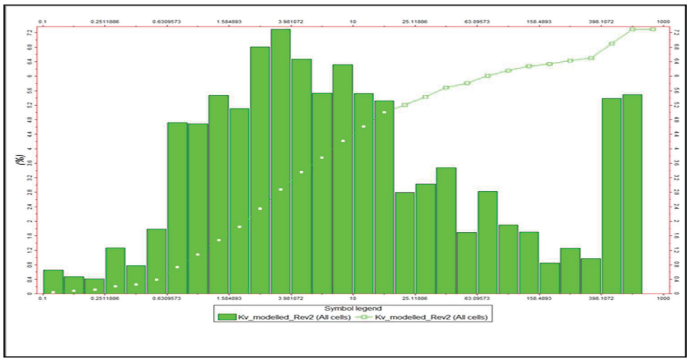


Figure 3-54 - Histogram of modelled vertical permeability within sand facies (Log scale)

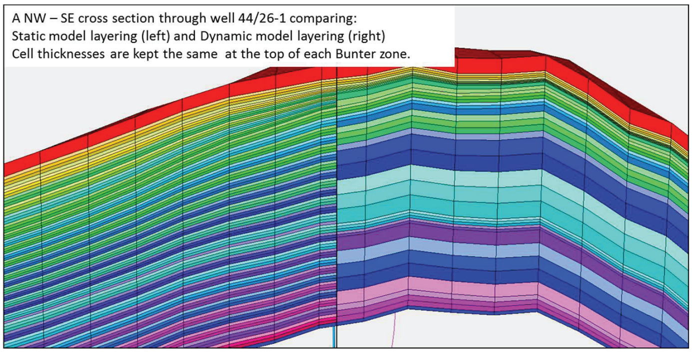


Figure 3-55 - NW – SE cross section through well 44/26-1

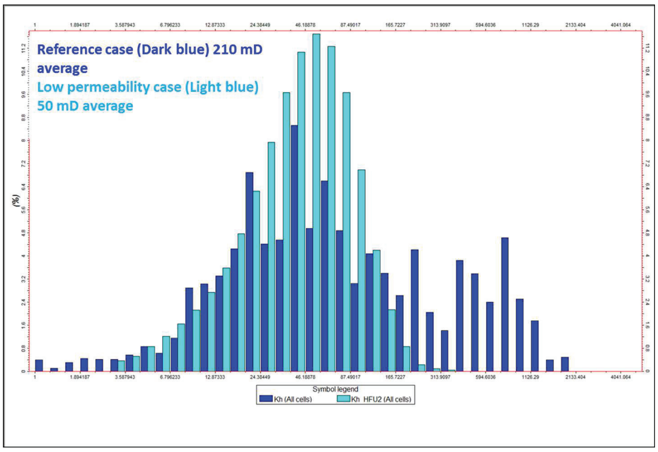


Figure 3-56 - Histogram of horizontal permeability

3.5.5 Fairway Static Model

The Fairway Static Model is semi regional in nature and covers a very large area from Bunter Closure 36 north and west towards the 5/42 structure and is some 100km long by 35km wide. The purpose of this model is to characterise the Bunter Sandstone fairway and its potential connectivity to other nearby hydrocarbon and CO_2 storage sites. It also supported containment assessment and provided a model which could be used to model the CO_2 plume had it moved beyond the primary static model limits. The fairway model covers the full area of the seismic interpretation shown in Figure 3-46 is an area of approximately 100km x 35km. Stratigraphically, the model extends from the Top of the Rot

Halite (primary caprock) to the Bunter Shale (the model includes the top 10 m of the Bunter Shale, as a basal seal to the site).

The model stratigraphy is shown in Table 3-19, it is the similar to the scheme use for the primary static model, but has fewer layers within it. Again the layering is based upon the zonation scheme defined during the well correlation. Proportional layering has been used for all zones. No faults have been incorporated into the model.

The Fairway model 3D grid was built with a rotation of 45° and grid cells of 200m x 200m in the X, Y direction. The number of cells has been kept to a minimum due to the regional scale of the model. The resulting grid has approximately 1.4 million grid cells.

At this time the fairway model has not been used to assess plume mobility into other areas outside Closure 36 as the proposed development plan has been designed to retain all the injected CO_2 within Closure 36. No migration of CO_2 into other structures is envisaged.

Horizon	Zone	Source
Top Rot Halite	Rot Halite	Built up from Top Rot Halite using a well derived isochore.
Base Rot Halite	Solling Claystone	Built up from Top Bunter Sand using a well derived isochore.
Top Bunter Sand	Bunter 1	Direct seismic interpretation and depth conversion.
Top Bunter 2	Bunter 2	Built down from Top Bunter Sand using a well derived isochore and proportioned within the seismic envelope between Top Bunter Sand and Top Bunter Shale.
Top Bunter 3	Bunter 3	Built down from Top Bunter 2 using a well derived isochore and proportioned within the seismic envelope between Top Bunter Sand and Top Bunter Shale.
Top Bunter 4	Bunter 4	Built up from Top Bunter 3 using a well derived isochore and proportioned within the seismic envelope between Top Bunter Sand and Top Bunter Shale.
Top Bunter 5	Bunter 5	Built up from Top Bunter4 using a well derived isochore and proportioned within the seismic envelope between Top Bunter Sand and Top Bunter Shale.
Top Bunter Shale	Bunter Shale	Direct seismic interpretation and depth conversion. Only top 3m of Bunter Shale modelled.
Base Model		Top Bunter Shale + 3m (10ft)

Table 3-19 - Stratigraphy, zonation and layering for Fairway Model

3.5.5.1 Property Modelling

Due to the regional focus of the fairway model, facies modelling was not required. Net to Gross (NTG) and porosity have been modelled using the interpreted well log data.

3.5.5.2 NTG and Porosity Modelling

Eleven wells have been used for the modelling of NTG and porosity in the fairway model:

> 42/25-1, 43/23-3, 43/25-1, 44/23-3, 44/23-5, 44/23a-A3, 44/26-1, 44/26-2, 44/26-4, 44/26c-5, 44/26c-6, and 44/27-1.

NTG and Porosity modelling is performed separately for each zone. NTG and Porosity in the primary caprock (Solling Claystone and Rot Halite) and the underlying Bunter Shale have been modelled as zero. Within the Bunter Sandstone the interpreted NTG and Porosity (PHIE) log data have been upscaled to the grid scale using arithmetic averages, and distributed in the model using Sequential Gaussian Simulation. This ensures that the property distributions (mean and standard deviation) in the original data are maintained in the final model. The model has also been calibrated and checked against the Primary static model for consistency.

Settings for the SGS were the same for both NTG and Porosity, and are shown in Table 3-20.

Type	Major Axis (m)	Minor Axis (m)	Vertical (m)	Azimuth (deg)
Spherical	2000	800	3	30

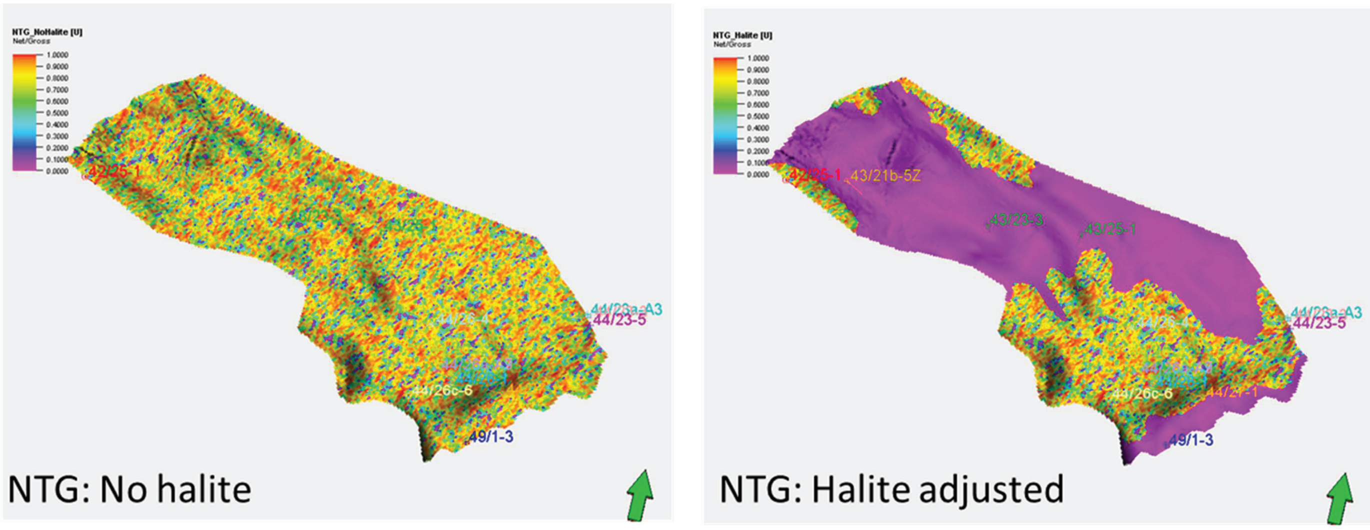
Table 3-20 - Input setting for NTG and Porosity SGS modelling

In some parts of the fairway area, halite cements can severely impact reservoir quality, particularly within the uppermost Bunter 1 and Bunter 2 zones. Areas affected by halite cements have been mapped as part of a quick regional review of well data and seismic amplitudes (Section 3.4). Within these areas properties have been adjusted to take account of the impact on NTG, Porosity and Permeability. These adjustments are based on interpreted results in 43/23-3, which is one of the wells in the fairway area impacted by Halite cements.

Adjustments made within halite affected areas:

1. NTG set to a constant 0.05 within Bunter 1 and Bunter 2.
2. Porosity reduced by 2 porosity units (2 PU) within all Bunter zones.

Figure 3-57 shows an example layer from the Bunter 2 zone, with and without the NTG adjustment.



Layer 6 in Bunter zone 2. Comparison of net to gross before (left) and after (right) model has been adjusted for halite. Halite only impacts NTG within Bunter Zones 1 and 2.

Figure 3-57 - Layer 6 in Bunter zone 2

3.5.5.3 Permeability Modelling

Horizontal permeability has been calculated using a porosity/permeability equation derived from measured core data. The equation used is shown below:

Perm=PHI^3×(1.527/(0.0314*(1-PHI)))^2

This provides a simple and effective method to populate the fairway model with realistic permeability values.

3.5.5.4 Static Model – Uncertainty Statement

Whilst both the seismic and well data used in the construction of the static models are considered to be of both adequate quantity and sufficient quality, as with all subsurface characterisation, some important uncertainties remain unresolved and should be the focus of any future appraisal activity. These include:

Reservoir Quality - whilst there are reasonably good quality logs available over the area together with some core material, they have all been acquired for the purposes of hydrocarbon exploration and not for CO_2 storage. In particular, there remains an uncertainty regarding the impact of potential halite cementation on reservoir quality. This is discussed further in Section 3.4 (phase reversal) and requires further investigation since it is poorly understood on both a local and regional scale. Further regional work is required to refine the models of reservoir quality which include the role of pore water salinity and structural evolution of the area. This will help to improve confidence in local reservoir quality assessment over Closure 36.

Hydraulic Architecture of the Reservoir - the nature and continuity of both the high permeability and low permeability intervals have a significant influence on how an injected CO_2 inventory might move in the subsurface. At the present time this has been acknowledged through using published Caister experience as an analogue and also through sensitivity studies. Further appraisal may be able to clarify the extent of baffles to vertical flow in the reservoir through careful testing and pressure measurements.

Structural Depth Model - careful depth conversion through the overburden has highlighted the importance of seismic velocity change to the depth mapping across the structure. Whilst this uncertainty will not be of first order significance, in detail it will influence the targeting of development wells and also the ultimate capacity of the buoyant trap.

Connected Aquifer Volumes - The total connected aquifer pore volume within the mapped fairway has been calculated as approximately 120 km^3. The aquifer volume within the site model has been calculated as 23 km^3.

The seismic data and interpretation for this study did not cover the complete Bunter Sandstone Formation, the maximum aquifer volume is therefore assumed to be larger than that mapped. The total aquifer volume assumed in the reference case for the purposes of dynamic simulation was estimated as 270 km^3. These aquifer volumes will significantly influence the pressure dispersion in the dynamic model and hence the ability to maintain injection below any fracture pressure limitations of the site. It is therefore very important for capacity estimation.

3.5.6 Probabilistic Volumetrics

The combination of static and dynamic modelling have through uncertainty and sensitivity analysis provided a wide range of estimates of rock volume, pore volume and dynamic CO_2 storage capacity. The complexity of the models and the number of variables conspire to make a full exploration of this uncertainty space impractical. To this end a simple probabilistic approach to estimation has been adopted to provide a context within which the specific runs from static and dynamic modelling can be considered.

The approach used has been adopted from oil and gas industry practice for the estimation of oil and gas volume estimates where:

STOIIP = GRV x NGR x PHI x (1-SW) x Bo

Where:

STOIIP - Stock tank oil initially in place.

GRV - Gross rock volume - the geometric volume of the gross reservoir interval from its top surface to the deepest level that contains hydrocarbons.

NGR - Net to gross ratio - The average vertical proportion of the gross reservoir interval that can be considered to be effective (net) reservoir.

PHI - The average effective porosity of the net reservoir volume.

SW - The average proportion of the net reservoir volume pore space that is saturated with water.

Bo - The shrinkage (oil) or expansion (gas) factor to convert the hydrocarbon volumes from reservoir conditions to surface conditions.

This equation has been modified here to be:

Dynamic Capacity = GRV x NGR x PHI x CO_2 Density x E

Where:

CO_2 Density - the average density of CO_2 in the store at the end of the injection period.

E - the Dynamic storage efficiency which is the volume proportion of pore space within the target storage reservoir volume that can be filled with CO_2 given the development options considered.

To consider probabilistic estimations of capacity, a Monte Carlo model has been developed around this equation. Each input parameter is described by a simple probability distribution function and then each of these is sampled many times to calculate a large range of possible dynamic capacity estimates.

The input to the calculation and the results are outlined below.

3.5.6.1 Gross Rock Volume

It has been shown that the depth conversion has a significant influence on the shape of the Top Bunter Sandstone depth map and in particular the depth and shape of the "lowest closing contour". These sensitivities resulted in a range of gross rock volume estimates which are described in Table 3-16. An additional assessment has been included which considers a thicker Bunter Sandstone interval across the closure. This provides a further upside case. A simple triangular distribution has been assumed.

3.5.6.2 Net to Gross Ratio

An average net to gross ratio of 85% for the closure has been extracted from the static model. This is derived from an interpolation of the petrophysics from well control through the model. An upper and lower value of 90% and 80% have been assigned from consideration of well data variability in the area. A simple triangular distribution has been assumed.

3.5.6.3 Porosity

An average porosity of 22% for the closure has been extracted from the static model. This is derived from an interpolation of the petrophysics from well control through the model. An upper and lower value of 24% and 18% have been assigned from consideration of the well data variability in the area, the precision of the porosity evaluation method from well information and also the potential for the development of some porosity occluding halite cement to be present over parts of the reservoir. A simple triangular distribution has been assumed.

3.5.6.4 CO_2 Density

This range of 0.7514 to 0.7766 to 0.7998 was established after consideration of the low and high range pressure and temperature conditions at the volume midpoint of the storage reservoir at the end of the injection phase and then using an equation of state to compute CO_2 Density. A simple triangular distribution has been assumed.

3.5.6.5 Dynamic Storage Efficiency

The range of this parameter has been assessed from a consideration of the full range of dynamic simulation sensitivity results on the primary development case static model or reservoir characterisation. This provides an ability to extract qualified dynamic storage efficiency values for each case run. The simulation results exhibited a dynamic storage efficiency range from 0.03 representing 72MT capacity through to 0.25 representing 509MT capacity. The mid case was set at 0.19 which matches the reference case capacity of 391MT. Since the dynamic modelling found a significant rate dependency, it was felt that "high rate / low capacity cases" should be accounted for but carry a small weighting, whilst those cases with moderate rates should carry a higher weighting. A custom distribution was used to capture this. It should be noted that using E derived from dynamic modelling in this way accounts for appropriate dynamic filling of the structure and the same pressure limitations as were considered in the dynamic modelling.

3.5.6.6 Probabilistic Volumetric Results

Figure 3-58 captures both the inputs and outputs of this Monte Carlo assessment. This shows a P90 value of dynamic CO_2 storage capacity (i.e. 90% chance of exceeding) of 300MT, with a P50 value of 364MT (i.e. 50% chance of exceeding) and a P10 value of 426MT (i.e. 10% chance of exceeding). These numbers provide the context for the "deterministic" estimates from the simulation work and the "development reference case" capacity of 391MT.

Whilst there is no formalised resource classification system available yet for CO_2 Storage resource assessment, the following is proposed based upon the current SPE petroleum resource classification (Society of Petroleum Engineers, 2000) thinking adapted for CO_2 storage deployment (see Figure 3-59)

There are no CO_2 storage reserves currently assessed for the Bunter Closure 36. This is largely because the resource base cannot at this time be considered commercial as FID has not been concluded nor is there a commercial contract in place with a CO_2 emitter. As a result, the assessed volumes all fall within the sub-commercial contingent resources category. The existence of the storage reservoir has been proven and there is significant evidence in the form of well and seismic data indicating that a storage site could be developed. At the moment without a matched power plant, the resource has been characterised on the basis of probabilistic assessment as:

Contingent Resources - Development unclarified (Figure 3-59

1C - 300MT – P10

2C - 364MT - P50

3C - 426MT – P90

The full scope of probabilistic dynamic CO_2 storage capacity outcomes ranges from 49MT at a P100 level to a P0 of 566MT.

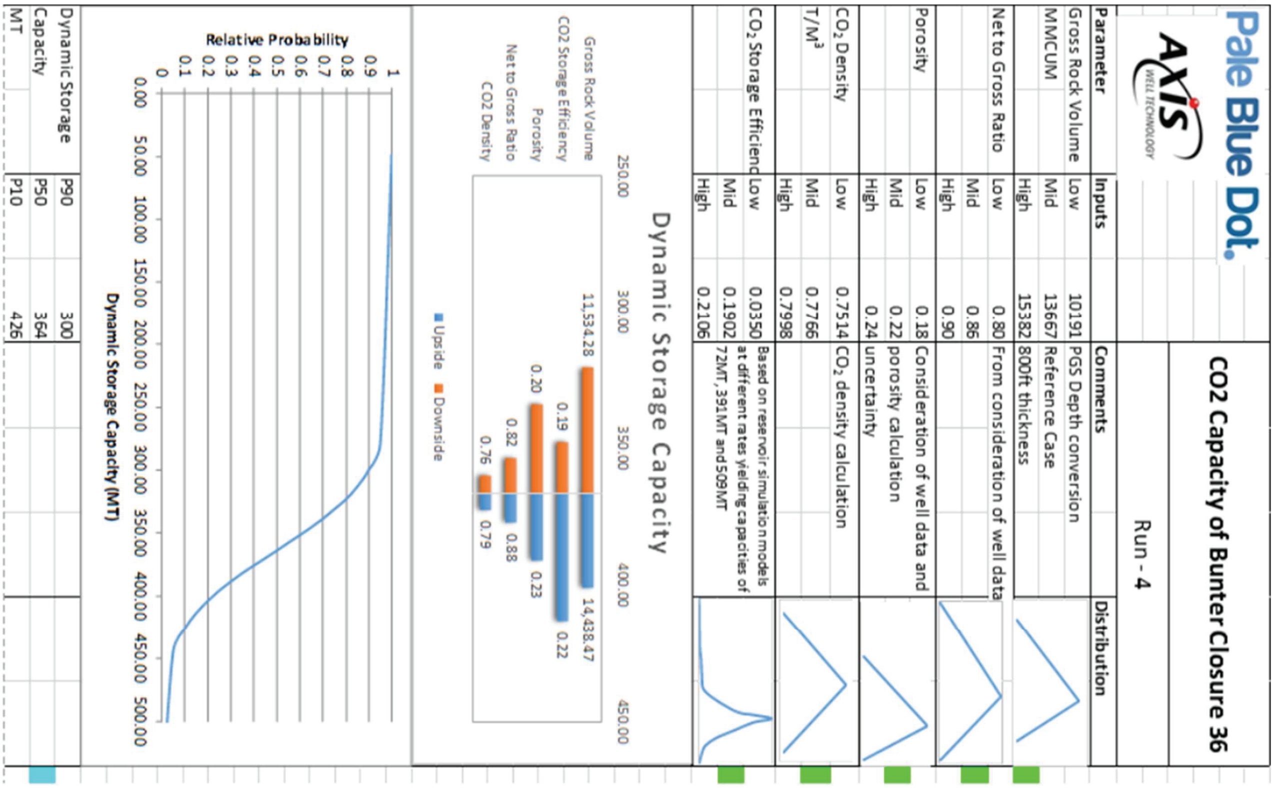


Figure 3-58 - Probabilistic storage capacity

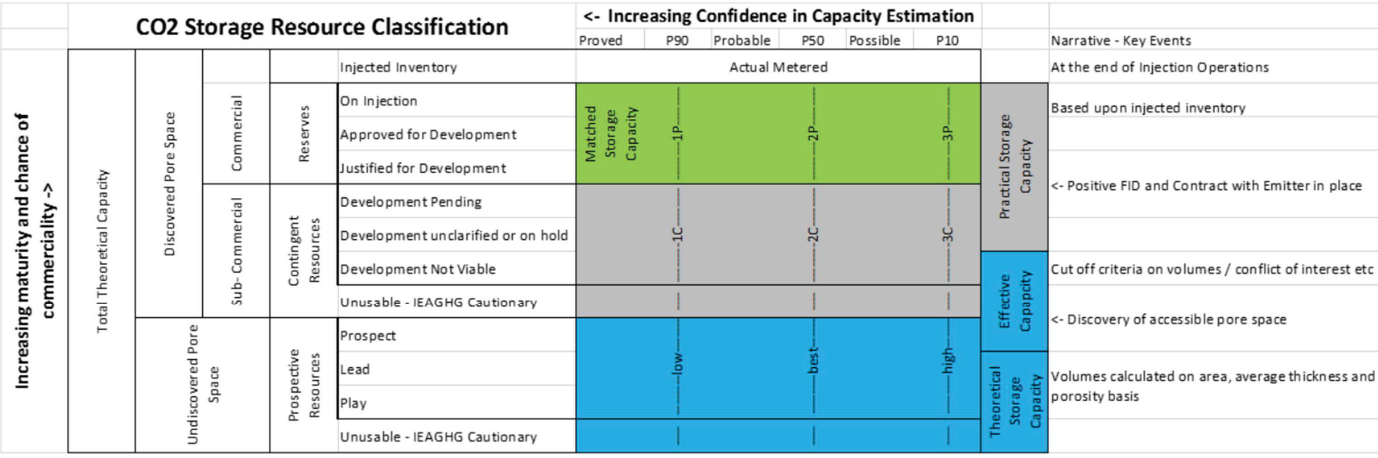


Figure 3-59 - CO_2 Storage resource assessment

3.6 Injection Performance Characterisation

3.6.1 PVT Characteristics

The PVT properties were modelled using the Peng Robinson equation of state and the CO_2 density correction within the Petroleum Experts software package for modelling CO_2 injection. The injection fluid was modelled as 100% CO_2 in compliance with project CO_2 composition limits. The PVT description used is shown in Table 3-21.

CO_2 physical properties that strongly affect tubing flow and hence transport are density (ρ) and viscosity (μ). To test the validity of the Prosper PVT model predicted in-situ CO_2 densities and viscosities were compared with pure component CO_2 properties calculated using the Thermophysical Properties of Fluid Systems from the National Institute of Standards and Technology (NIST). Comparisons were carried out for a range of temperatures and pressures (temperatures of 4 °C to 60 °C and pressures of 30 bara to 350 bara), with the following results:

1. Density differs from the NIST calculated value by a maximum of 1.1% with an average of 0.3%.
2. Viscosity differs from the NIST calculated value by a maximum of 14.3% with an average of 7.9%.

Property	Units	Value
Critical Temperature	°C	30.98
Critical Pressure	bara	73.77
Critical Volume	M3/kg.mole	0.0939
Acentric Factor	None	0.239
Molecular Weight	None	44.01
Specific Gravity	None	1.53
Boiling Point	°C	-78.45

Table 3-21 - PVT properties

3.6.2 Well Placement Strategy

The well placement strategy has been informed by considerations of geology, Bunter Closure 36 structural geometry, reservoir engineering modelling and the economics of development. Reservoir engineering results indicate that four wells are required over field life to inject the target CO_2 volumes. Four wells, located part way down the flank of the structure, towards the north west, will result in the highest storage capacity being realised while achieving target injection rates. Wells are expected to have a useful life of approximately 20 years and consequently the current plan is to re-drill all wells around this time.

To achieve the desired injection rates, wells are required to penetrate the full Upper Bunter Sand sequence. Vertical wells would result in the point of CO_2 injection lying directly below the point of caprock penetration, thereby presenting the highest integrity risk (high concentration of CO_2 at the penetration point and high injection pressures). Deviated wells are therefore preferred, as they will also maximise the sand face contact. Deviation has not been limited for wireline access in the injector wells, as regular well interventions are not planned, and well tractor technology allows access to highly deviated wells if intervention is required. The main risk to well performance is the residual uncertainty in reservoir quality and in particular the potential role of in-situ halite cements. Current understanding suggests that this presents a low risk, although further work is suggested to improve the understanding of this factor.

3.6.3 Well Performance Modelling

Well modelling was carried out using Petroleum Experts' Prosper software, which is a leading software for this type of application. The field development plan stipulates several CO_2 injection wells for Bunter Closure 36 these wells are expected to be similar and it was therefore decided to evaluate well performance using a single prototype well, Injector 1 (INJ1). The input of the well model is described in the following sections.

3.6.3.1 Reservoir Data and Inflow Performance Relationship (IPR)

IPR modelling was based an assessment of reservoir and field parameters as summarised in Table 3-22 and Table 3-23.

Parameter	Unit	Low	Mid	High
Formation Top Depth (Datum)	*ft TVDSS*		4000	
Formation Gross Thickness	*ft*	594	722	827
Formation NTG	-	0.84	0.95	1
Reservoir Pressure	*bara (psia)*		124.4 (1804)	
Reservoir Temperature	*°F*		99	
Permeability	*mD*	62	164	271
Permeability Anisotropy (K_v/K_h)	-	0.05	0.21	0.48
Formation Water Salinity	*ppm*		205000	

Table 3-22 - Reservoir Data

Parameter	Unit	Low	Best Estimate	High
Water Depth	*ft*		236	
Pressure Gradient	*psi /ft*		0.451	
Geothermal Gradient	*°F/100ft*		1.6	
Drainage Area	*acres*	3385	3385	3385

Table 3-23 - Field and Well Data

Formation water salinity data is sparse (no direct measurement available) and no sensitivities were performed. The mid estimate used was the high case from Benthem's 'An assessment of carbon sequestration' (Bentham, 2006), which quotes a salinity range of 130,000 ppm to 205,000 ppm for a number of Bunter Closures in the SNS. This is conservative in terms of storage capacity (CO_2 solubility decreases with increasing salinity, thus a higher value is somewhat conservative in terms of long-term storage capacity, with less solubility trapping) and halite scale issues. It is also a mid-range value if considering Ritchie and Pratsides' study of the Caister gas fields (Ritchie & Pratsides, 1993) as a high value (250,000). The range is consistent with data provided in Ketter's study of the Esmond, Forbes and Gordon fields (Ketter, 1991).

Using this data three IPR models were defined in Prosper to represent high, medium and low reservoir performance. These are summarised in Table 3-24.

3.6.3.2 Tubing Size Selection

Tubing selection is based on identifying the size required to achieve the desired injection rate whilst remaining within the pressure and temperature conditions anticipated in the tubing during operations. The two limiting conditions are:

1. Maximum shut-in tubing head pressure. The maximum pressure that can be applied at the wellhead without fracturing the formation at the top perforation.
2. Minimum temperature at perforation depth. The temperature below which formation water will freeze during CO_2 injection.

Parameter	Unit	Low	Medium	High
Reservoir Pressure @ top perforation depth	*bara (psia)*	147.9 (2145)	147.9 (2145)	147.9 (2145)
Reservoir Temperature @ top perforation depth	*°C (°F)*	44.2 (111.5)	44.2 (111.5)	44.2 (111.5)
IPR Model	*n/a*	Jones	Jones	Jones
Permeability	*mD*	62	164	271
Reservoir Thickness	*ft*	452	622	750
Drainage Area	*acres*	3385	3385	3385
Dietz Shape Factor	*n/a*	31.6	31.6	31.6
Perforation Interval	*ft*	452	622	750
Skin	*n/a*	20	10	0

Table 3-24 - IPR Parameter Values

Parameter	Unit	Value
Fracture Limit at Top Perforation Depth (90% of fracture pressure)	*bara (psia)*	219.4 (3182)
Maximum THP for Fracture Prevention	*bara (psia)*	85.7 (1243)
Minimum Fluid Temperature at Perforation Depth	*°C*	0
Tubing head Injection Temperature	*°C*	4

Table 3-25 - Injection Constraints

The fracture pressure at top perforation depth has been calculated using a fracture gradient of 0.7436 psi/ft and a top perforation depth of 4755 ft TVDSS. The maximum shut-in THP is difference between the Fracture Limit pressure at the perforations and the hydrostatic head of CO_2.

Three tubing sizes were evaluated against the three IPR scenarios outlined in Table 3-26. Results from these 9 sensitivity cases are summarised in Table 3-26, from which it can be seen that a tubing size of 5.5" or 7" is required in order to achieve the desired injection rate of over 2Mt/y. 5.5" tubing is preferred since it is the lowest cost (i.e. the smallest) option that can meet the required duty.

Tubing Size	IPR Case	Rate (Mt/y)
4.5'' (12.6 ppf)	High	1.47
	Medium	1.44
	Low	1.28
5.5'' (17 ppf)	High	2.56
	Medium	2.48
	Low	2.00
7'' (29 ppf)	High	4.68
	Medium	4.38
	Low	2.97

Table 3-26 - Tubing Size Sensitivity (at THP of 85.7bara)

3.6.3.3 Impact of Temperature

The seabed temperature in the Southern North Sea is affected by warmer water moving from the Channel and can cause seasonal variations. The seabed water temperature at the Bunter Closure 36 location (Block 44) could vary from 6°C to 16°C over the course of a year (Turrell, 2007).

The base case assumption is for a well head injection temperature of 4°C. To understand the potential impact of the seasonal variation a sensitivity was run at 10°C, and at maximum assumed pipeline delivery pressure (120bara). Higher temperatures lower the CO_2 density and thus reduce the mass injection rate. The increased temperature reduces the well injectivity of the 5.5" tubing by approximately 5%, from 2.00 to 1.89 Mt/y in the low IPR case.

The dynamic reservoir modelling work is not rate constrained by well delivery and therefore the effects of increased delivery temperature are not considered critical. However, it is recommended that a full system delivery temperature sensitivity be performed during the next phase of work.

3.6.3.4 Minimum Injection Pressure

The minimum injection pressure required for the CO_2 to remain in dense phase was calculated for the two temperatures using the chosen tubing size of 5.5''.

Temperature	Minimum Pressure (Bara)	Rate (Mt/y) in Low IPR case	Rate (Mt/y) in High IPR case
4°C	42.3	0.9	1.4
10°C	49.3	1.0	1.5
Difference		11%	7%

Table 3-27 - Impact of Temperature on Minimum Injection Pressure

The hydrostatic pressure gains are greater than friction losses for this tubing choice and consequently the minimum pressure and with it the minimum temperature are attained at the tubing head.

3.6.3.5 CO_2 Impurity Sensitivity

The well and tubing design work has been carried out assuming that the CO_2 is contaminant free. In practice, small amounts of other gases may be present in the CO_2 stream and affect the phase behaviour, viscosity and density of the mixture. These will affect the critical point of the fluid and therefore the operating conditions necessary to remain in dense phase as well as flow behaviour.

For small amounts of impurities, the change in minimum injection pressure is minor. To simulate the effect of possible contamination a 10% safety region has been defined around the pure CO_2 phase envelope and this region has been avoided during the well design work.

Vertical lift performance (VLP) curves were generated for the wells assuming 5.5'' tubing (Figure 3-61). To allow sensitivities to injection pressure limits and other quantities to be run in Eclipse without extrapolation, the generation of these curves was extended to pressures and rates which are outwith the limits discussed in the previous section. In particular, input parameters were as follows:

1. Tubing Head Pressures: 613 psia (42.3 bara) to 2500 psia (172.4 bara) in 10 equal steps.
2. Gas Rates: 5 MMscf/d to 250 MMscf/d in 20 equal steps. The performance envelope of the well is shown in Figure 3-60 for dense phase injection throughout the tubing and without breaching the temperature limit of 0°C.

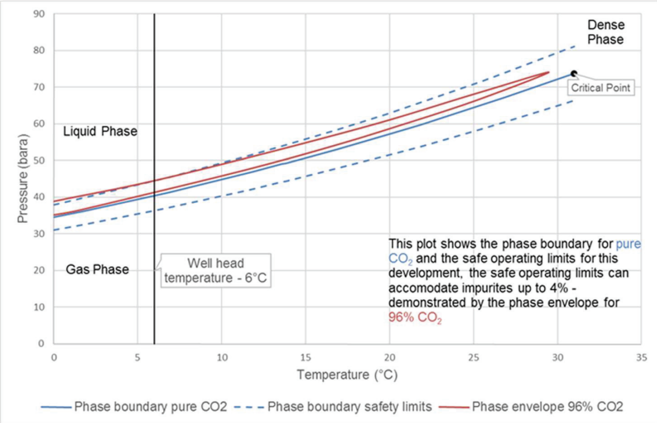


Figure 3-60- CO_2 Phase Envelopes and Impurities

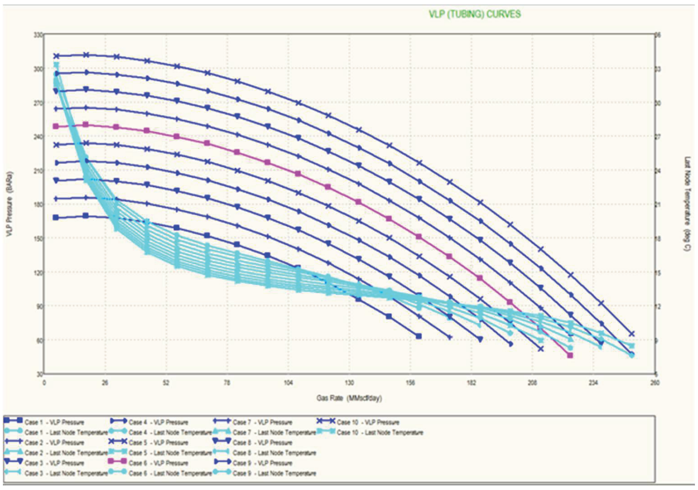


Figure 3-61 - Vertical Lift Curves for 5.5" Tubing

3.6.4 Injectivity and Near Wellbore Issues

The effects of long term CO_2 injection into a sandstone reservoir are not yet fully understood by Industry. During CO_2 injection the reservoir rock is subject to pressure and thermally induced stresses, applied in sometimes random patterns (cyclic stressing from variations in supply conditions). These stresses can lead to rock failure or damage to the rock fabric and therefore permeability changes. Interaction of CO_2 with in-place reservoir rock and fluids may also alter the ability of the rock to conduct fluids.

Some of the more recognised issues are discussed below, along with their effect on the Bunter Closure 36 storage potential.

3.6.4.1 Halite

The Bunter Closure 36 formation water is a saline brine. There is uncertainty in the composition of this brine, but some nearby fields have reported high salinity values, as discussed earlier. When CO_2 is injected into formations containing high salinity brine, the majority of the brine will be pushed away from the wellbore by the injected CO_2. However, some brine will remain in pores and adhering to rock matrix. As CO_2 and water are miscible, CO_2 will absorb the water. However, the salt in the brine is not soluble in CO_2, thus precipitating the salt out of solution. The near wellbore may become dehydrated, leaving the salts behind. The volume of solid salt crystals produced depends on brine salinity, residual brine volume (left after the 'sweep'' of CO_2), interactions at the CO_2 flood front and the propensity of the brine to re-saturate the near wellbore region during shut-in periods. Capillary pressure also plays a part in re-saturation, but is likely to be masked by CO_2 buoyancy effects.

To estimate the effect of salt precipitation during the initial injection a mobility multiplier was used in the Eclipse 100 model as a proxy for the dehydration and reduction in productivity that is expected to occur. Two scenarios were considered when salt saturation increases to 10%:

1. Mobility of injected fluid decreases by half and reduces to zero when the solid saturation reaches 0.8.
2. Mobility of injected fluid decreases to 10 % and reduces to zero when the solid saturation reaches 0.7

Both case resulted in a significant reduction in injectivity as illustrated in Figure 3-62. The results show a significant drop in injectivity after the first month of injection, resulting in higher injection bottom hole pressures or lower injection rates. The effect of halite precipitation can be mitigated by 'washing' the near wellbore with fresh or low salinity water. The wash water dissolves the salt and carries it away from the near wellbore region, where the effects of permeability reduction have most impact. It is expected that an early time water wash (after 1 to 2 months on CO_2 injection) will be required, with frequency dropping through field life, due to increased CO_2 saturation and decreased brine saturation.

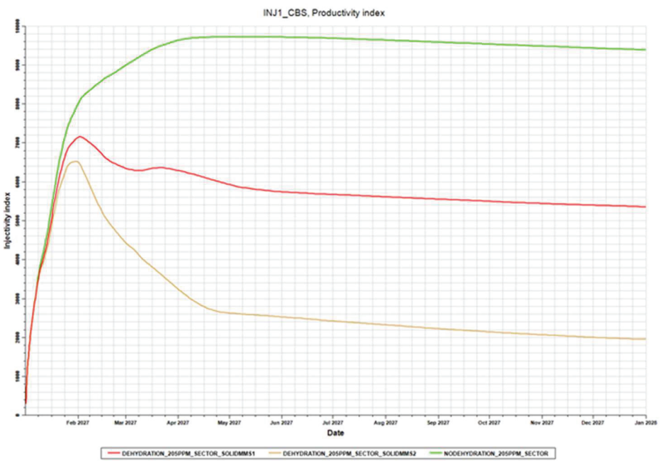


Figure 3-62 - Impact of Salt Precipitation on Injectivity

3.6.4.2 Thermal Fracturing

The CO_2 stream injected into the Bunter Closure 36 formation is colder (12 to 24°C depending on input assumptions) than the modelled ambient reservoir

Research work on the impact of halite precipitation effect by (Mathias, Gluyas, Gonzalez, Bryant, & Wilson, 2013) has suggested that despite some loss of absolute permeability, the CO_2 relative permeability can increase slightly. The consequences of this uncertainty have been managed here by designing water wash facilities into the platform services to account for these operations and this is an area that should be subject to further research and modelling in the future.

temperature (~37°C). Thermal modelling in Eclipse 100 indicates that reduced temperatures occur within 12m of the wellbore. Temperature will have an effect on the near wellbore stresses, drops will make rock more liable to fracture. The effect of this thermal effect on the fracture pressure has not been investigated in this report. However, as the magnitude of temperature drop is low and restricted in extent, it is not expected to be problematic in the Bunter Sandstone.

3.6.4.3 Sand Failure

The average critical total drawdown for sanding in offset well 44/46-2 is above 5000 psi. This indicates that the Bunter Sandstone is competent and there is minimal risk for sanding during injection operations. However, this is based on an uncalibrated rock strength so uncertainty remains.

3.6.5 Safe Operating Envelope Definition

In the context of this study, safe operating limits are those that allow the continuous injection of CO_2 without compromising the integrity of the facility, well or the geological store. Since wells are designed to cope with the expected injection pressures and temperatures, the primary risk to integrity is uncontrolled fracturing of the formation rock, leading to an escape of CO_2 through the caprock (adjacent to the wellbore or at a point anywhere in the storage complex).

In order to minimise the risk associated with the uncertainty introduced by operating wells across a phase boundary, all injection will be limited to single phase. With the reservoir pressure of Bunter Closure 36 (124 bara) being above the critical point for CO_2 (74 bara), injection will be limited to liquid or dense phase.

3.6.6 Dynamic Modelling

3.6.6.1 Dynamic Model Construction

Schlumberger's Eclipse 100TM 'Black Oil' simulator was used for the dynamic modelling. Although there are some limitations in using Eclipse100TM previous studies have shown that there is no significant loss of accuracy in using the 'Black Oil' simulator for modelling CO_2 storage in saline aquifers. (Energy Technologies Institue, 2011).

3.6.6.2 Structural Grid and Reservoir Properties

The structural grid and static property modelling has been discussed in detail in section 3.5.1.4. The site model extends over a relatively small area to allow for reasonable run times in the dynamic model. The model contains 603,394 active cells. In the horizontal grid the cell dimensions are 200m by 200m. The connected aquifer volume, beyond the site model, was incorporated into the model using pore volume modifiers in the outer cells of the grid. The connected aquifer volume in the reference case is $270x10^9$ m^3.

Permeability, transmissibility across intra Bunter Shales, and the connected aquifer volume were identified as key uncertainties. The impact of a range of values for each parameter on injectivity and CO_2 plume migration was evaluated in the sensitivity analysis and is detailed in section 3.6.6.6.

3.6.6.3 Approach to PVT Modelling

Commercial Black Oil reservoir simulators (e.g. Eclipse™) are used widely throughout the petroleum industry to model oil, water and/or gas as separate and immiscible phases whose properties and inter-phase mass transfer are averaged functions of pressure and temperature, where in reality the fluids have complex molecular compositions. This treatment involves the use of published "Black Oil" correlations and other physical relationships. Previous studies, such as those of Gammer et al. (Energy Technologies Institue, 2011) and Goater et al. (Goater, Bijeljic, & Blunt, 2013), have shown that this same approach can be applied for CO_2 storage in saline aquifers by adapting the Black Oil fluid model to the PVT behaviour of CO_2 -brine mixtures. In this way, CO_2 properties are described using the gas-phase, whereas the brine is designated as the oil-phase. This allows for mass transfer between the two phases; dissolution of CO_2 into brine using solution gas-oil ratio (Rs), and vaporisation of water into the free CO_2 phase using the solution oil-gas ratio (Rv). This approach represents the mutual solubility between the two phases and demonstrates acceptable accuracy with improved computational efficiency, as compared to the alternative compositional simulation, which requires complex equations of state describing molecular component interactions.

Eclipse100TM can only model isothermal systems with uniform salinity. The Bunter Closure 36 reservoir temperature is 45°C and the salinity is assumed to be 200000 ppm. For this study the fluid description has been further simplified and the vaporisation of water into the free CO_2 phase has not been included as the value of Rv for this system is so small, with an equilibrium mole fraction of less than 1%.

3.6.6.4 Relative Permeability

Relative permeability is a key parameter that influences injectivity performance and CO_2 plume migration. However, there is very limited data available for CO_2 - brine systems from North Sea formations. The impact of alternative functions has been evaluated within the uncertainty analysis and is discussed in section 3.6.6.10. The reference case drainage and imbibition curves are illustrated in Figure 3-63. The drainage curves represent a CO_2 charge scenario where CO_2 saturation is rising and water saturation is falling. The imbibition curves represent a scenario where CO_2 saturation is falling and water saturation is increasing, a situation that will occur post injection as the plume continues to migrate up structure.

The functions were generated using Corey functions. End points were based on the published results (Shell UK ltd., 2011) for the Captain formation within the Goldeneye field, North Sea (Burnside & Naylor, 2014). Drainage and imbibition curves are included allowing for the residual trapping of CO_2 to be modelled. The residual saturation is 0.29.

3.6.6.5 Pressure Constraint

The Bunter Sandstone formation is hydrostatically pressured resulting in an initial reservoir pressure of 119bar at a depth of 1170m TVDSS, the crest of the Bunter Sandstone structure. During the CO_2 injection phase the reservoir pressure will increase. To avoid any chance of fracturing the reservoir the maximum pressure at any point in the reservoir will be limited to 90% of the fracture pressure. The fracture pressure gradient is 0.168bar/m and the fracture pressure at 1170m TVDSS is 197bar. The maximum allowable pressure at this depth is therefore 177bar.

The model is set up so that if the pressure in any cell in the model reaches the maximum allowable pressure for the depth of that cell then injection will be stopped. No injection into the uppermost zone (Bunter 1) is planned largely because of its poor reservoir quality. This also reduces the risk of thermally induced fractures reaching the primary caprock.

In all sensitivities it was found that the maximum allowable pressure limit was reached in the crestal area of the structure but not necessarily the same cell in the crest. The location of the grid cell where the pressure limit is first met in the reference case model is shown in Figure 3-63.

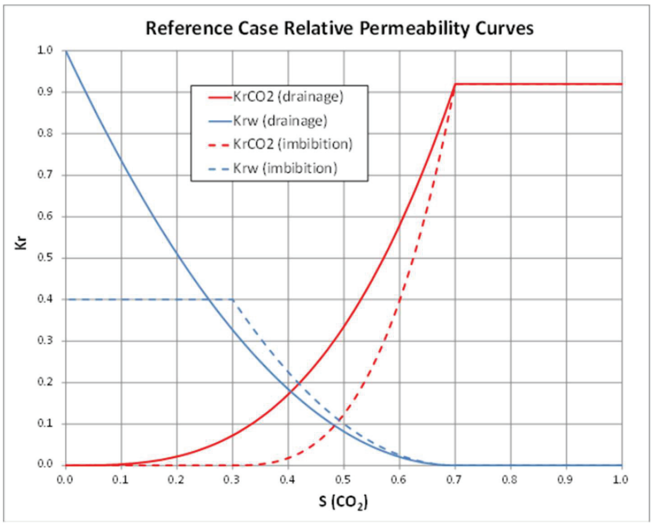


Figure 3-63 - Reference Case Relative Permeability Functions

3.6.6.6 Well Modelling

Lift curves were generated using Prosper for wells of 4 ½", 5 ½" and 7" tubing sizes. Although higher injection rates can be achieved using 7" wells, the optimised injection rate per well of less than 2MT/y only requires a 5 ½" tubing size. The optimisation of injection rate is discussed in section 3.6.7.1. The well designs and lift curve generation are detailed in Appendix 9. Whilst an injection rate of 1.8 to 2MT/yr per well appears achievable from the work completed here, further work in the near wellbore area is recommended before a development decision to refine understanding of issues such as skin factor changes from thermal or other mechanical effects.

3.6.6.7 Modelling Results and Sensitivities

Numerous sensitivities were run to evaluate the impact of development well selection criteria and subsurface uncertainties on the injectivity forecast and CO_2 storage capacity for Bunter Closure 36. An initial screening test was carried out to identify the key parameters. A reference case was then selected that is optimal for a sustained injection plateau of at least 40 years and the CO_2 storage capacity. The reference case was then validated by running addition sensitivities to confirm the impact of the key uncertainties. The results of the sensitivity analysis are outlined below.

3.6.6.8 Well Placement

Bunter Closure 36 is a 4 way dip closure considered to be close to its original natural reservoir pressure. As a result, CO_2 will be injected in dense phase. Whilst the force of injection can result in pushing CO_2 downwards locally, ultimately the buoyant CO_2 will migrate to the highest point in the structure. The injection strategy is therefore to inject as deep in the structure as possible to maximise injectivity and storage capacity but not so deep that loss of containment from the structure becomes a significant concern. Wells have been placed in model areas which have the best reservoir quality to optimise injectivity. It should however be flagged that the reservoir quality distribution within the model was a single realisation of a stochastic process and uncertainty remains regarding variation of reservoir quality across the structure.

After some testing, the planned development scenario involves 4 wells placed along the western side of the structure. If wells are located radially around the structure such that they fully enclose it, then the pressure build up in the crestal area is rapid as there is no mechanism for pressure relief. This has a significant impact upon estimated storage capacity, reducing it by 60%. The western side is preferred to the eastern side as the structure is more steeply dipping to the east and requires a greater injection force and therefore pressure build up rate to inject the same mass of CO_2. With a shallower dip to the west and a bigger connected volume the pressure is dissipated more effectively resulting in a slower pressure build up and an extended injection life. Figure 3-64 illustrates the 4 well open pattern used in the reference case and an alternative 8 well closed pattern.

The comparison of the injection forecasts for the open and closed well placement pattern is shown in Figure 3-65.

3.6.6.9 Well Depth

As CO_2 is more buoyant than saline water the well placement strategy is to locate the wells as deep in the structure as possible without risking the loss of containment within the structure. Sensitivities were run to optimise injection well depth. The deeper well scenario (average depth 1600m TVDSS) allowed for higher injected rates and higher total mass injection volumes but the CO_2 migrated beyond a desired containment boundary towards the Storage Complex boundary, in both low and high injection rate scenarios.

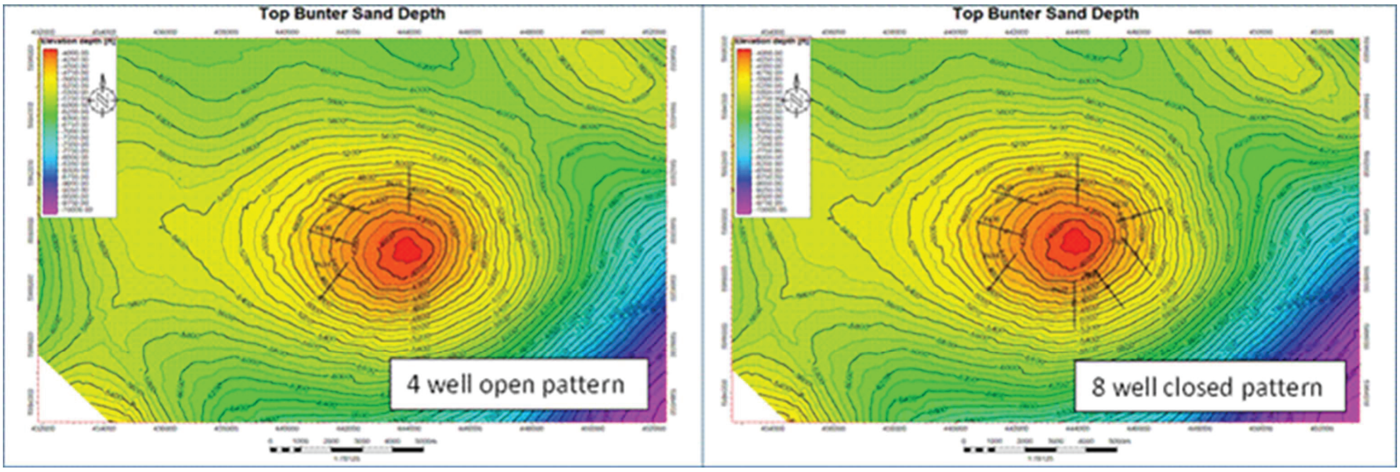


Figure 3-64 - Well locations for open and closed well pattern sensitivity

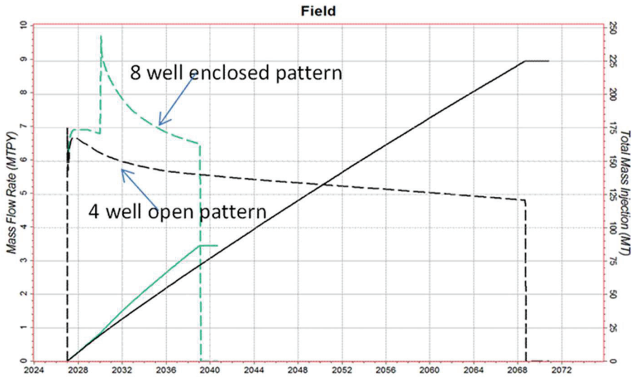


Figure 3-65 - Injection Forecasts for open and closed well pattern sensitivity

The desired containment boundary is shown in red in Figure 3-66 and the definition is detailed in section 3.5. The wells were then moved up to an average depth of 1400m TVDSS and these wells have been proposed for the development scenario reference case. The plume development pattern for the deep well scenario is illustrated on the CO_2 concentration map in Figure 3-66. In this case 240MT was injected into the structure and the plume is not contained within the desired containment boundary.

3.6.6.10 Well Number

Sensitivities were run to evaluate the impact of adding additional wells to increase the injection rate potential. New wells were located in areas where the model contained the thickest and best quality sands and distances between injectors was maximised to try to limit interference between the wells. The incremental benefit of adding each additional well declined as more wells were added due to the pressure interference between the wells. In addition, with higher field injection rates, the pressure build-up rate is much faster and the pressure constraint is reached earlier resulting in a shorter injection life and a reduced storage capacity. The injection forecast for the 7 well and the 4 well cases is shown in Figure 3-67. In this case the capacity is reduced by 45% relative to the reference case.

3.6.6.11 Relative Permeability

Significant uncertainty exists in understanding the relative permeability properties of the reservoir. Three relative permeability curve sets were tested as part of the uncertainty analysis to evaluate the impact on both injectivity and CO_2 plume migration. Endpoint inputs were based on available published experimental values for Set 1 and Set 2. A third set was generated to capture the guidance provided by a project developer (National Grid Carbon, 2015). Drainage curves for the three sets are compared in Figure 3-68 and the Corey exponents and end points used to generate the curves are shown in Table 3-28.

	Drainage			Imbibition		
Relative Permeability Set	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
Ng	2.8	3	2.5	4	3	2.5
Nw	1.7	2	4.5	2.1	2	4.5
Krw @ SGWCR	1.000	1.000	1.000	0.365	0.400	0.400
Krg @ SWCR	0.2638	0.920	1.600	0.2638	0.920	1.600
SWL	0.423	0.300	0.070	0.423	0.300	0.070
SWCR	0.423	0.300	0.280	0.423	0.300	0.280
SGWCR	0.000	0.000	0.000	0.297	0.290	0.300
SWU	1.000	1.000	1.000	0.703	0.710	0.720

Table 3-28 - Corey exponents and end point inputs for the relative permeability curves

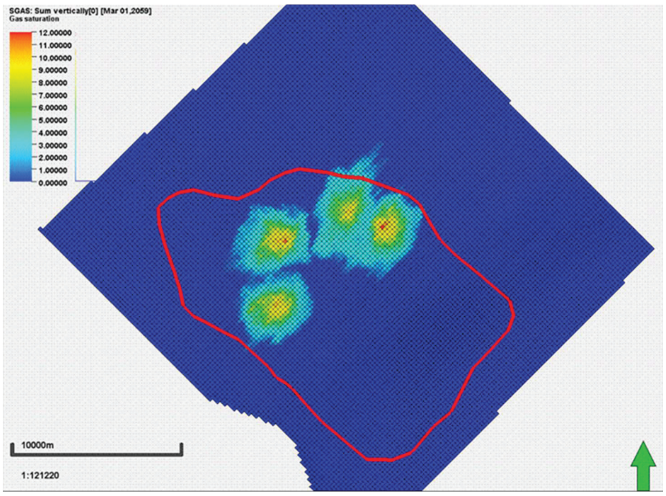


Figure 3-66 - CO_2 concentration during injection for deep well sensitivity

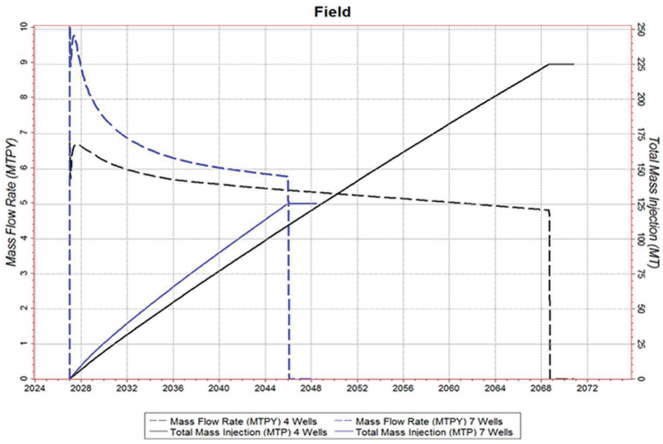


Figure 3-67 - Injection Forecasts for well number sensitivity

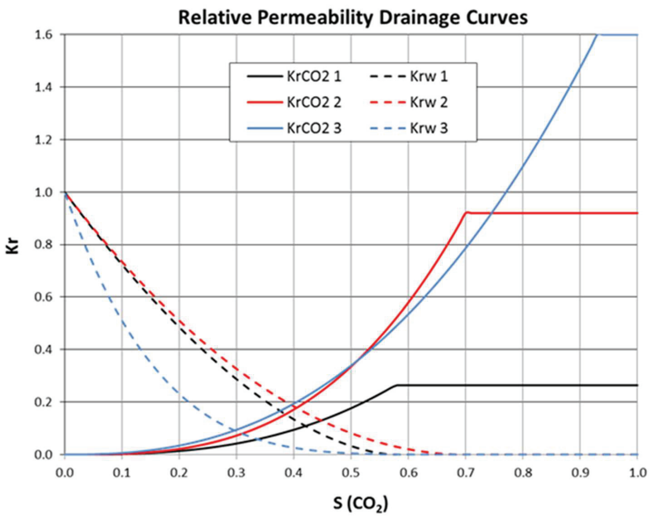


Figure 3-68 - Range of relative permeability drainage curves

The maximum Krg value is an indication of CO_2 mobility in the system, the higher the value the more mobile CO_2 will be. The values range from 0.26 in Set 1 to 1.6 in Set 3. The low mobility case is representative of relatively low permeability system (~20mD). This is based on the published results from the (Bachu, et al., 2013) study for the Viking#2 formation, Alberta Canada (Burnside & Naylor, 2014). This is considered to be too low for the Bunter Closure 36 system. Set 2 includes a maximum Krg value of 0.92. This is based on the published results (Shell UK ltd., 2011) for the Captain formation within the Goldeneye field, North Sea (Burnside & Naylor, 2014). Guidance from National Grid Carbon (NGC) after their experience with their 5/42 work suggested that the CO_2 is much more mobile than previous experiments have indicated and that maximum Krg values of 1.6 are possible. This has been incorporated into Set 3.

The impact of increasing the maximum Krg value is to increase the CO_2 mobility resulting in increased injection rates.

The mobility of water is also an important factor of injectivity potential since the injected CO_2 must displace that water. Sets 1 and 2 have similar water relative permeability trends. However, Set 3, based on guidance from NGC, has significantly reduced water mobility. As CO_2 injection into the saline aquifer relies on water displacement, reduced water mobility results also in a reduction in CO_2 mobility.

The three alternative relative permeability sets were evaluated using the reference case model, with no rate constraint applied, and the impact on the injection forecast is shown in Figure 3-69:

The forecasts show an increased injection rate resulting from using Set 2 relative permeability input compared to Set 1. This is mainly attributable to an increased maximum Krg from 0.26 to 0.92. The Set 3 forecast shows a reduced injectivity rate compared to Set 2. In this case, although the maximum Krg is increased further, the effective mobility of CO_2 is reduced due to the reduced water mobility.

As has been shown for Bunter Closure 36, increasing the injection rate results in a faster pressure build up leading to the pressure limit being reached earlier. Hence the higher injection rate cases have a shorter injection life. The capacity associated with the relative permeability cases is 380MT, 391MT and 338MT for Set 1, Set 2 and Set 3 respectively.

Set 2 was selected for the reference case as Set 1 is considered to be too low in terms of mobility for Bunter Closure 36 and Set 3 data has not yet been validated.

3.6.6.12 Connected Aquifer Size

There is significant uncertainty associated with the size of the aquifer that is connected to the Bunter Closure 36 site. The connected aquifer volume, beyond the site model, was incorporated into the model using pore volume modifiers in the outer cells of the grid. The connected aquifer volume in the reference case is $270x10^9$ m^3. A sensitivity was run to evaluate the impact on injectivity and capacity of a much smaller aquifer being connected. The size of the aquifer was reduced to $120x10^9$ m^3. A smaller connected aquifer results in a faster pressure build up, which leads to a shorter injection life. The capacity, in this case, was reduced by 48%.

3.6.6.13 Vertical Connectivity across the Intra Bunter Barriers

The reference case model includes laterally extensive barriers at the top of Bunter 3 and Bunter 4 zones resulting in no pressure communication or CO_2 migration across the barriers in the model. The injection strategy in this case is to perforate the Bunter 3 and the Bunter 4 zones only resulting in no injection.

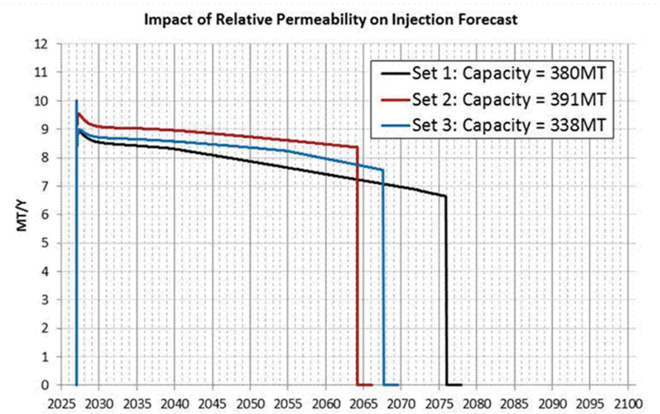


Figure 3-69 - Field Mass Injection forecasts for relative permeability sensitivity

into the Upper Bunter zones. A sensitivity was run to evaluate the impact of there being some connectivity across the barriers. In this case there is a small uplift to injection rate potential (~3%) and the capacity is increased by 34%. This is the direct result of increasing the connected volume to the injection wells within the site and improving pressure dissipation.

An additional sensitivity was run to evaluate the benefit of injecting into the full Bunter section, including the Upper Bunter zone. The results of this case are rate dependent. In the higher rate case there is an uplift in injection rate and the capacity is reduced by 5%. In the lower rate case the capacity is increased by 8%.

In both of the above scenarios there will be a higher chance of fractures reaching the cap rock if thermal fracturing does occur at the wells. The reference case perforation strategy, of not injecting into the Upper Bunter zones, has been selected to reduce the risk of this occurring.

3.6.6.14 Permeability

There is considerable uncertainty in the absolute permeability values and also the permeability distribution within the site. An alternative low case permeability scenario was tested in the dynamic model (section 3.5). For the 4 well development case the capacity is reduced by >40%. This is due to the well injectivity being reduced to <1.5MT/y compared to 2.5MT/y in the reference case. In this case more wells could be drilled to improve the site injection rate and storage capacity.

3.6.6.15 Net to Gross

The uncertainty associated with NTG was evaluated in the dynamic model. The average NTG was increased from 0.85 to 0.91. This effectively increased the connected volume within the site resulting in an increase in capacity of 11%.

3.6.7 Reference Case and Development Plan Injection Forecast

A reference case was selected based on the results of the sensitivity analysis. The reference case model inputs are summarised in Table 3-29.

Reference Case Input Parameters	
Connected aquifer size	270 x 10^9 m^3
Intra Bunter sealing shakes	Sealing
Permeability	210 mD
Kv/Kh_{low}	0.36
NTG	0.85 (average)
Relative permeability dataset	Set 2
CO_2 endpoint Kr_{CO2}	0.92
Corey exponent Nw	2
Initial pressure	119 bar @ 1170m TVDSS
Initial temperature	45°C
Fracture pressure gradient	0.168 bar/m
Well placement	Open pattern
Well depth	Shallow (~1400m TVDSS)
Well number	4
Injection rate	7MT/y
Tubing size	5.5"
Injection zones	Bunter3 + Bunter 4

Table 3-29 - Reference Case Model Inputs

The reference case includes 4 development wells. The well locations are shown in Figure 3-70.

3.6.7.1 Development Forecast Injection Rate Selection

The dynamic modelling has clearly shown that the storage capacity is dependent on the rate of injection. This is mainly due to higher injection rates leading to a more rapid pressure build up and reaching the maximum allowable pressure limit earlier in the injection phase. At this point injection is stopped to ensure reservoir and caprock integrity are maintained. The capacity is therefore directly related to the pressure build up rate.

One of the criteria set for the development forecast is that a plateau rate has to be sustained for at least 40 years. Rate sensitivities were therefore carried out to determine the maximum rate that could be confidently sustained. The injection forecasts for the tested rate cases are shown in Figure 3-71.

The cumulative injection after 40 years and the storage capacity for each case is shown in Table 3-30.

	Target Rate (MT/y)	Initial monthly average	Cumulative @ 40 years (MT)	Capacity	
				(MT)	Injection Life (years)
REF 6MT/y	6	6.0	240	433	72
REF 7MT/y	7	7.0	280	391	56
REF 8MT/y	8	8.0	320	349	43
REF 10MT/y	10	9.2	328	328	37

Table 3-30 - Initial rates and storage capacities for the rate sensitivity cases

7MT/y was selected as there is a higher risk that the 8MT/y scenario might not achieve a 40 year injection life. In this case the CO_2 mass injected over the 40 years injection life is 280MT. 7MT/y can be sustained for a total of 56 years before the pressure limit is violated. The injected mass at this time, which is equivalent to the storage capacity of the reference case is 391MT.

3.6.7.2 Well Forecasts

The 4 selected wells have a similar injection performance over the injection period. Although initial injection potential rates are 2.5MT/y these rates cannot be sustained. In the constrained 7MT/y site injection rate case the wells inject at 1.8MT/y. The flowing tubing head pressure (FTHP) increases from 87bar at the start of injection to a maximum of 106bar at the end. The injection rates and the FTHP for each well is shown in Figure 3-72.

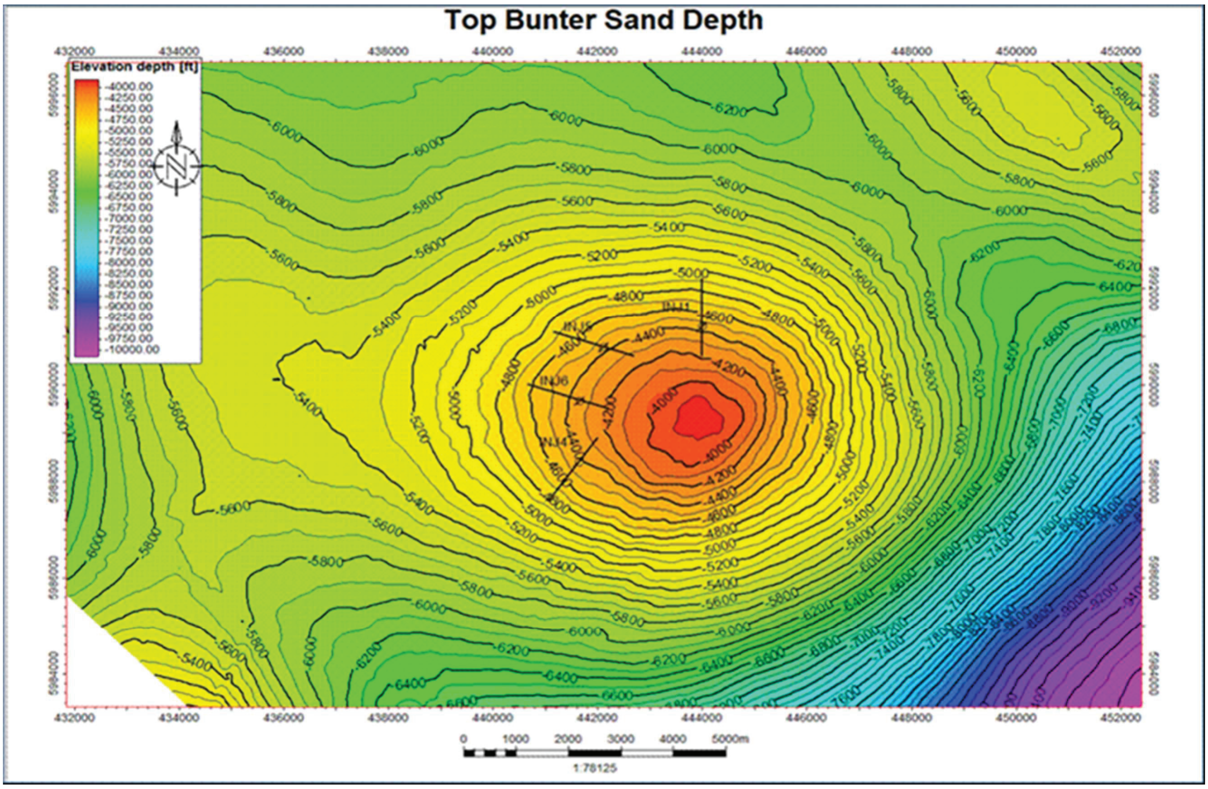


Figure 3-70 - Development Scenario injector locations

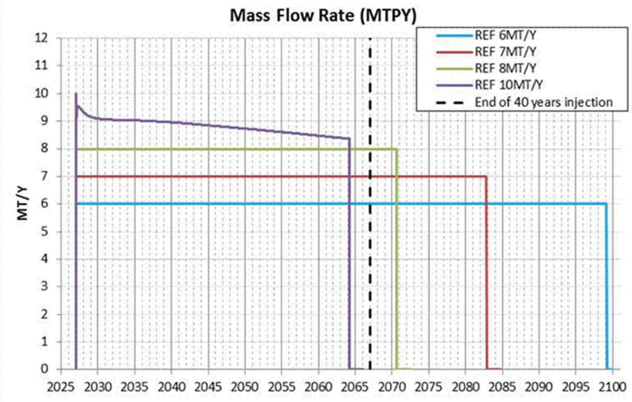


Figure 3-71 - Reference case forecasts for the rate sensitivity

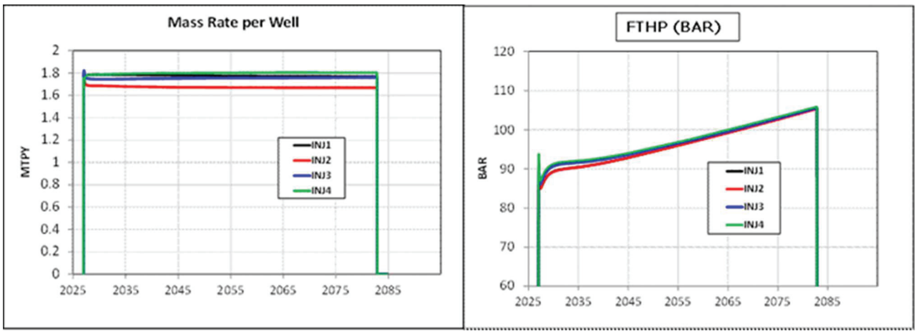


Figure 3-72 - Injection rates and FTHP per well

3.6.7.3 CO_2 Migration

CO_2 will be injected in the dense phase into the Bunter Closure 36 site. Under the force of injection the CO_2 can be pushed downwards but ultimately the CO_2 will migrate to the highest point in the structure, as it is less dense than saline water. Selected cross sections showing the CO_2 plume migration at the end of the 40 years injection period is shown in Figure 3-73.

The CO_2 migrates vertically from the injection site and then migrates laterally in the upper layers below adjacent permeability barrier.

At the end of injection all the injected CO_2 is contained within the desired containment boundary as shown in Figure 3-74.

It is important that the reference case is capable of retaining the injected CO_2 inventory within the site indefinitely. To provide confidence of this, the model was run into the future for a period of 1000 years after injection ceased. So, after 40 years of injection at 7MT/y the injection wells were shut in and the model was run for a further 1000 years. After this time (3067) the CO_2 velocity was below 0.1m/y in all cells and the injected CO_2 can be considered to be contained. By this time the CO_2 had migrated to the crest of the structure, as shown in Figure 3-75 and Figure 3-76.

3.6.7.4 Trapping Mechanism

In the reference case model, 73% of the CO_2 injected mass is structurally trapped as is expected as Bunter Closure 36 is a 4 way dip closure, a structural trap within the aquifer system. 22 % is residually trapped and 5% is dissolved into the aquifer. This is illustrated in Figure 3-77.

3.6.7.5 Dynamic Storage Capacity

It has been shown that the storage capacity is dependent on the selected development strategy for the site with the capacity ranging from 72MT to 509MT for the scenarios tested with this study. For the proposed development scenario reference case the estimated dynamic storage capacity is 391MT. This relates to 7MT injected per year for 56 years, at which time the pressure constraint is reached and injection stopped.

3.6.7.6 Impact Upon Other Subsurface Users

The injection of CO_2 into the Bunter Closure 36 reservoir is envisaged starting in 2027. By this time, work commissioned by this study from Wood Mackenzie suggests that all of the existing Bunter gas fields in the vicinity of Bunter Closure 36 will have already reached the limit of their economic life. Furthermore, the underlying Schooner gas field is estimated to reach the end of its economic life in 2021 (Table 3-31).

Gas Field	Estimated COP Date	Reservoir Age
Caister	2021	Triassic
Esmond	1995	Triassic
Hunter	2010	Triassic
Forbes	1993	Triassic
Gordon	1995	Triassic
Schooner	2021	Carboniferous

Table 3-31 - Bunter Closure 36 - Nearby gas field economic limits

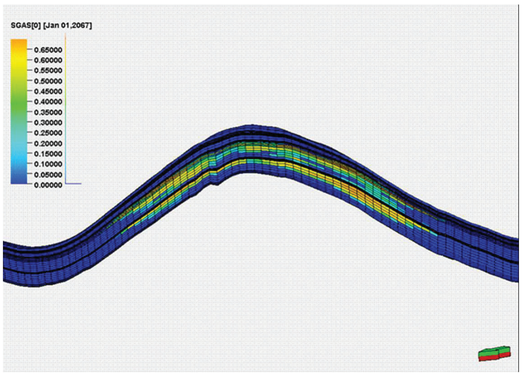


Figure 3-73 - Cross section showing CO_2 plume migration

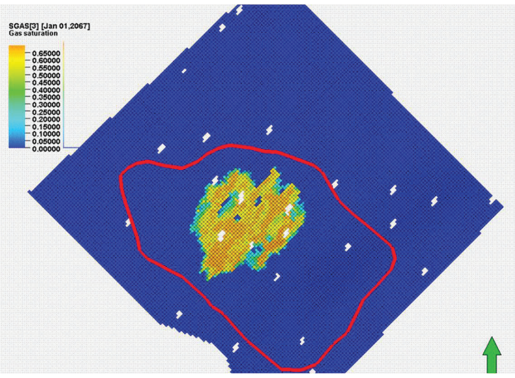


Figure 3-74 - CO_2 plume migration

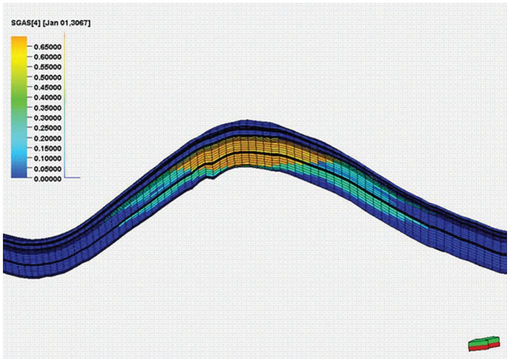


Figure 3-75 - Cross section showing CO_2 concentration 1000 years after injection has stopped

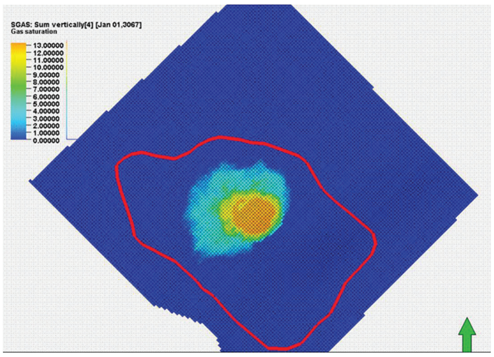


Figure 3-76 - CO_2 concentration 1000 years after injection has stopped

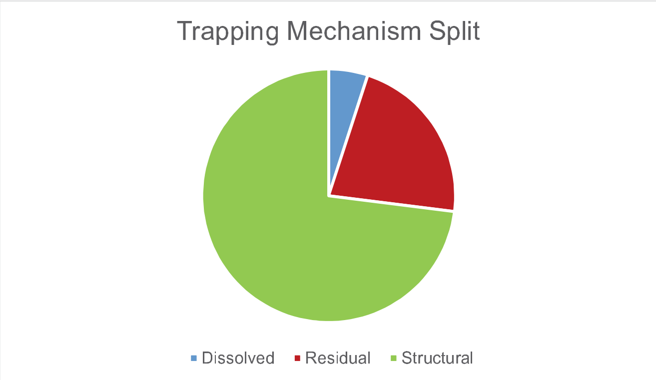


Figure 3-77 - Bunter Closure 36 CO_2 Storage Trapping Mechanism

It is acknowledged that a significant amount of as yet unpublished work has been completed on the Bunter closure known as 5/42 or Endurance. To assess the potential interactions between both of these sites injecting CO_2, a specific reservoir simulation run was devised. As the 5/42 area is outside the area of the dynamic model, its influence under injection was assessed by introducing a pressure boundary on the north-west side of the dynamic model which was elevated from the initial pressure to a point 50% of the way to the maximum allowable pressure. This might be the impact of another injection source at 5/42.

This case was run and the capacity estimate fell from the reference case by 38% to 242MT highlighting the potential significance of injection site interference.

The Shale Revolution has clarified once and for all that it is not possible to completely write off the petroleum prospectively of an area, however there are no other subsurface users currently known who might be impacted by CO_2 injection at Bunter Closure 36.

3.6.7.7 Dynamic Model Uncertainty Statement

Dynamic reservoir simulation and sensitivity analysis has indicated that there are some significant uncertainties which influence the performance of the Bunter Closure 36 CO_2 injection site. The reference case developed has been optimised to a degree against these uncertainties through the design of the development plan. This has revealed the following factors have the potential to significantly increase or decrease the effective storage capacity of the site.

Potential Significant Negative Factors include:

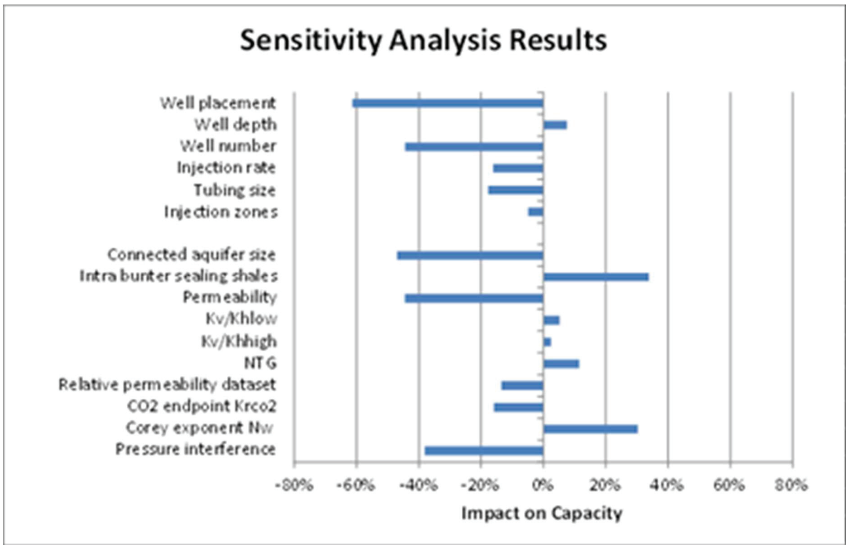
1. **Well Placement** - a peripheral placement of injection wells limits pressure dispersal and the capacity as a result.
2. **Well Number** - scenarios with larger numbers of injection wells perform worse as well interference effects choke back injection rates.
3. **Connected Aquifer Size** - this is a significant influence of how rapidly the elevated pressure around injection wells can be safely dissipated into the aquifer volume. Smaller connected aquifer volume limit this pressure dissipation and limit injection volumes.
4. **Permeability** - Lower permeabilities reduce injectivity and the rate at which pressure can be dissipated from injection wells. This significantly limits injected volumes.
5. **Pressure Interference** - Injection at other sites within the Bunter may create pressure interference effects that will ultimately limit injected volumes at Bunter Closure 36.

Potential Significant Positive Factors include:

1. **Non Sealing Intra Bunter Baffles** - this has the effect of providing access to more pore space above the injection zones for pressure dissipation to occur into. This enables a prolonged injection period before the maximum allowable pressure limit is reached and an enhanced capacity estimation.
2. **Corey Exponent Nw** - this uses a higher Nw Corey exponent controlling relative permeability of the reservoir. In effect this reduces the mobility of the water phase moving ahead of the CO_2. This slightly reduces the CO_2 injection rate at the wells, which slows down the pressure build up at the weak spot at the crest of the structure. This in turn allows injection to continue for longer leading to a higher potential capacity estimate.

These factors are detailed further in the results section and are summarised in Figure 3-78.

The plot on the left of Figure 3-78 shows the impact as a percentage change to storage capacity by changing from the parameter value in black to the value highlighted in red, as shown in the table in Figure 3-78. The key parameters are well placement and connected aquifer volume. The injection rate is also important as higher injection rates result in a faster pressure build up which leads to an earlier shut in date and a shorter injection life. The results are discussed in more detail in the following sections.



Parameter	Parameter value range
Well placement	open pattern / closed pattern
Well depth	shallow / deep
Well number	4 / 7
Injection rate	7MT/y / 10MT/y
Tubing size	5.5" / 7"
Injection zones	(Z3+Z4) / all
Connected aquifer size	Large / small
Intra bunter sealing shales	Sealing/ non sealing
Permeability	Base / Low
Kv/Kh_{low}	0.4/ 0.1
Kv/Kh_{high}	0.4/1.0
NTG	Base / High
Relative permeability dataset	Set2/Set3
CO_2 endpoint Kr_{co2}	0.92/1.6
Corey exponent Nw	2/4.5
Pressure interference	5/42 injection

Figure 3-78 - Sensitivity analysis results

3.7 Containment Characterisation

3.7.1 Storage Complex Definition

The Bunter Closure 36 storage complex is a subsurface volume who's upper and lower boundaries are the Base Cretaceous and Top Zechstein depth surfaces. The lateral limits of the proposed storage complex are guided by the lowest closing structural contour on the Top Bunter Sandstone map, within which the injected CO_2 inventory is designed to remain indefinitely with the proposed development plan.

This storage complex definition included the storage reservoir and its primary and secondary caprock together with the Bunter Shale interval floor which is considered an effective barrier to vertical flow.

The proposed storage complex is illustrated in Figure 3-79.

3.7.2 Geological Containment Integrity Characterisation

3.7.2.1 Hydraulic Communication between Geological Units

One of the key attributes of the Bunter Sandstone as a CO_2 storage reservoir is that it is generally overlain by laterally extensive mudstone and halite intervals of the Haisborough Group which provide an excellent primary caprock. Furthermore, the base of the Bunter Sandstone is underlain by thick impermeable Bunter Shale and then Zechstein evaporites. This stratigraphy provides effective top and base seal for the interval effectively eliminating the possibility to hydraulic communication to deeper or shallower formations under normal circumstances. The Bunter Sandstone is a depositionally extensive interval however and so laterally connectivity across the region is anticipated. The quantum of this connectivity is important to the performance of the site as a CO_2 store. It is more difficult to fully characterise at this time because the hydrocarbon development of the Bunter Sandstone for gas extraction in this area has been limited to a small number of minor gas fields to the north and northwest of Bunter Closure 36.

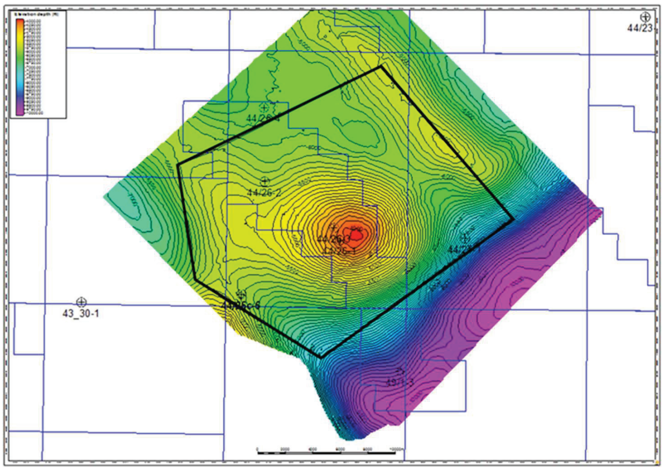


Figure 3-79 - Map of Storage Complex

Whilst there is anecdotal, but currently unpublished information suggesting good hydraulic connectivity from the 5/42 structure north to Esmond gas field, there is no similar information available for Bunter Closure 36 and so whilst good connectivity between Bunter Closure 36 and other parts of the Bunter Sandstone is anticipated, it is not proven at this time.

All the currently producing Bunter gas fields in the local region are expected to have ceased economic production by the time that Bunter Closure 36 injection starts.

3.7.2.2 Top and Base Seal

Sitting immediately on top of the Bunter Sandstone is approximately 30ft (10m) of Solling Claystone. Regional wells show that this mudstone can be slightly silty in places and may not be a perfect top seal. Therefore, the overlying Rot Halite Rot Halite Formation has been chosen as the primary caprock interval (Figure 3-80). This varies in thickness (Figure 3-81) across the storage site from 100ft to 250ft (30-75m). This halite forms an excellent impermeable seal. Interpretation of the seismic and semblance volumes (section 3.4) show that there are no detectable faults breaking the Bunter Closure 36 primary top seal. The minimum detectability threshold is considered to be approximately 10m which is significantly less than the thickness of the halite over the structure. As no faults were detected at this horizon, the implication is that the primary caprock is not breached by faulting.

The secondary seal is provided by the overlying Haisborough Group shales and Muschelkalk Halite (Figure 3-80). Interpretation of the seismic and semblance volumes (section 3.4) show that again there are no obvious faults breaking the Bunter Closure 36 secondary top seal.

30-40km to the north west of Bunter Closure 36 are two small gas fields, Caister and Hunter, with gas trapped in Bunter Sandstone and sealed by the Rot Halite. A small fault in the Rot Halite is clearly seen on seismic over the Hunter field but the continued presence of gas in the field indicates that the primary caprock has not been compromised by this fault (Williams, Holloway, & Williams, 2014)

Base seal to the Bunter Sandstone primary storage reservoir is provided by the underlying Bunter Shale which is approximately 1000ft (350m) thick and continuous over the whole region.

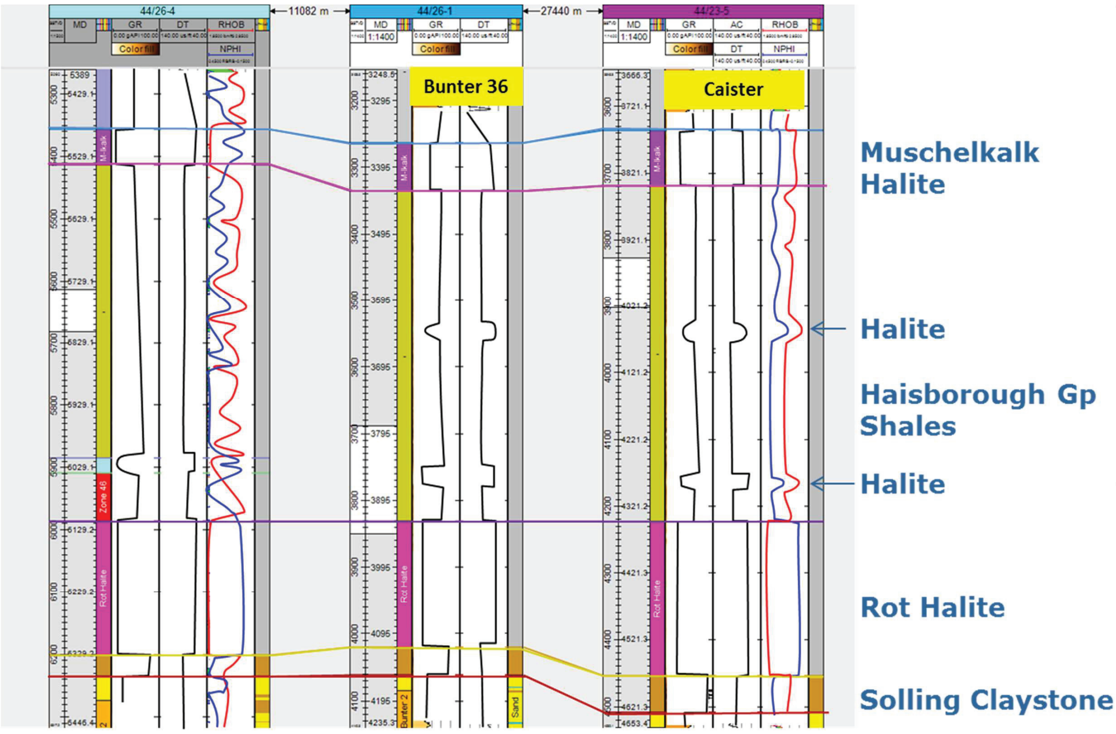
3.7.2.3 Overburden Model

A simple overburden model was built covering the same area of interest as the site static model. Section 3.4 summarises the seismic horizons which have been used to build the overburden model. No faults have been included within the overburden model. As the purpose of the overburden model was to help and inform the discussion on geological containment, no petrophysical analysis or property modelling have been carried out within the overburden.

A cross section through the overburden model is shown in Figure 3-82.

3.7.2.4 Bunter Sandstone Gas Charging

Well 44/26-1 was drilled very close to the top of the Bunter Closure 36 structural crest and did not contain gas. Whilst the possibility of a very small gas column updip from this well cannot be discounted, it has been assumed for this study that the structure is entirely water bearing with no gas. The nearby Caister and Hunter Fields do contain thin gas columns in the Bunter Sandstone, which proves the primary top seal is effective for methane gas. The obvious question of why the "Bunter Closure 36 does not contain any gas?" arises. This could have been either because it was gas charged and then leaked due to a breaching of the seal or because it was never charged with gas.



Well correlation showing Primary and Secondary Seals. Correlation from composite logs and wireline logs. Rot Halite provides primary seal – proven at Caister and Hunter Fields. Haisborough shales and halites provide additional containment.

Note: Log data shown schematically due to CDA license restrictions.

Figure 3-80- Primary and Secondary Top Seal

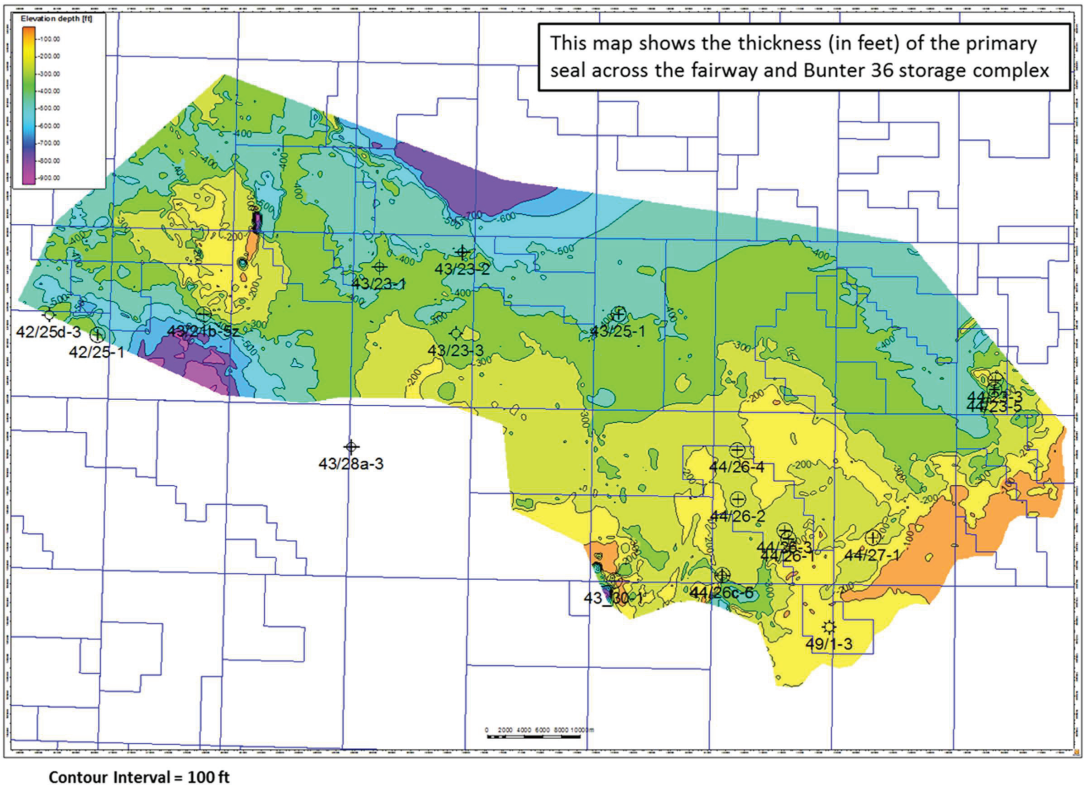


Figure 3-81 - Fairway and Closure 36, Rot Halite to Top Bunter Sandstone Isochore

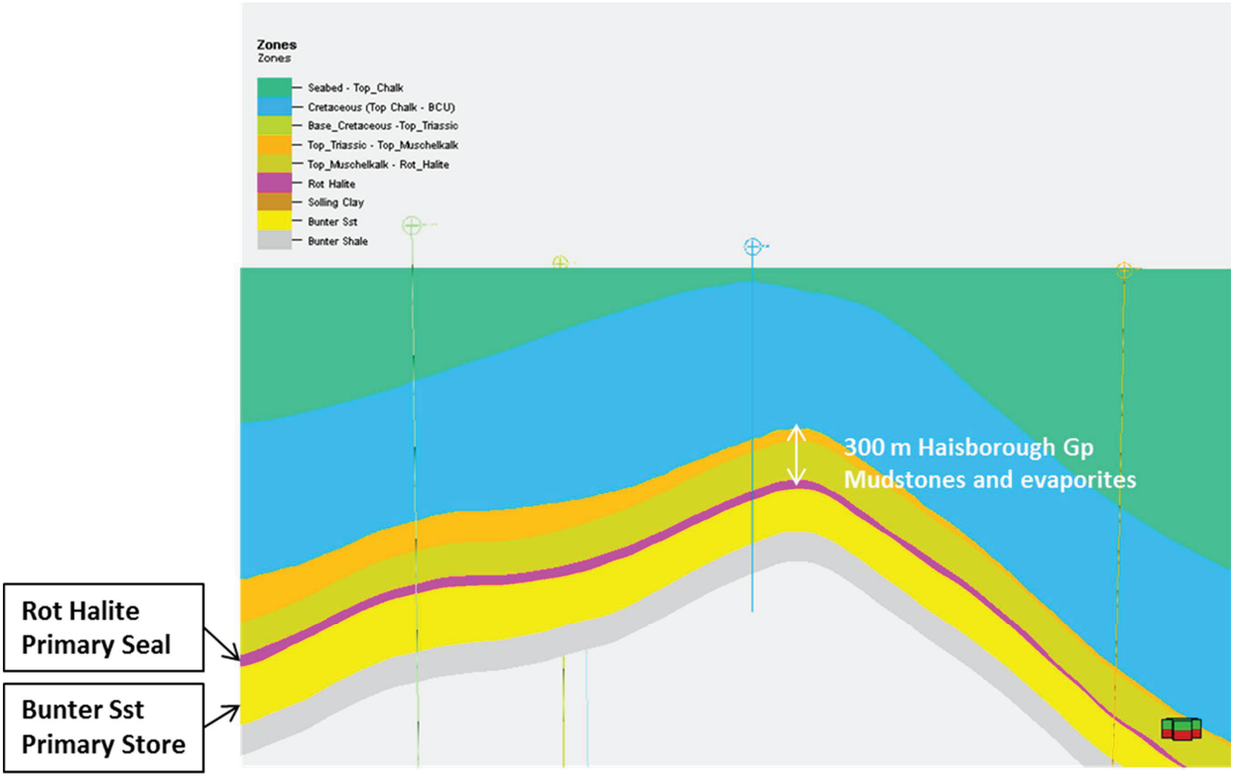


Figure 3-82 - W – E cross section through the overburden model

The source rocks for the gas in the Southern North Sea are the Carboniferous coal measures (section 3.3). The gas migration route into the Bunter Sandstone is tortuous and generally precluded across most of the Southern North Sea by thick Upper Permain Zechstein evaporites and Triassic Bunter Shales. In order to reach the Bunter Sandstone, the gas has to migrate out of the Carboniferous and through the overlying Silverpit mudstones, thick Zechstein evaporites and Bunter Shales. The halite in the Zechstein evaporite interval is mobile and over millions of years the pressures of deep burial has caused the salt to "flow". As a result of this "halokinesis", it has become very thin or absent in some places.

A regional Zechstein isochron (two way time thickness) derived from the seismic data (Figure 3-83) shows a significant thinning of the Zechstein immediately to the east of Caister and Hunter gas fields. The seismic derived cross section in Figure 3-84 illustrates today's subsurface structure and shows that the Zechstein salt is possibly missing and that the Carboniferous is juxtaposed directly against the Bunter Sandstone at a fault providing a present day potential easy gas migration route into the Bunter Sandstone. There may have been other locations where such juxtaposition occurred in the past as the structure evolved. If this migration route was effective, then the gas would migrate up dip to Caister and Hunter and then continues further to the North West to Gordon, Esmond and Forbes. None of the gas fields are full to their current structural spill points indicating that only a limited amount of gas was available or that the structures have continued to “grow” as a result of further salt movement after they were charged. There is no gas in the structure immediately to the south of the Zechstein thin (structure 44/29 in Figure 3-83) as the Rot Halite top seal has been eroded by the Base Cretaceous Unconformity.

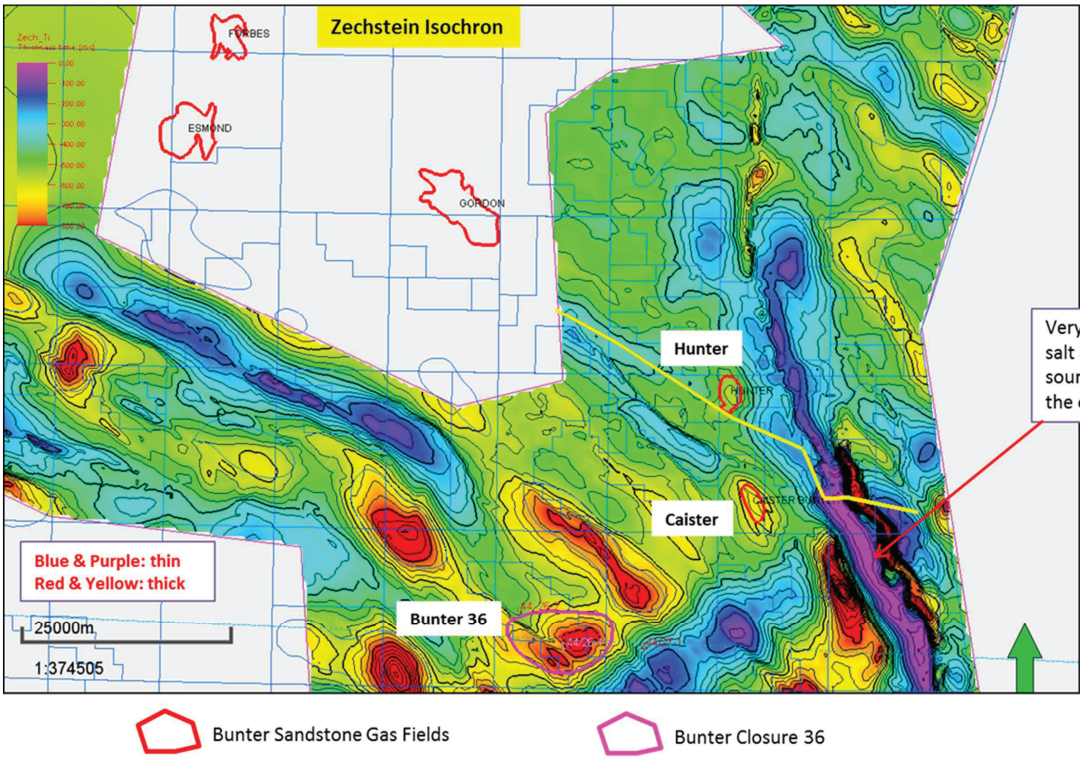
Although it cannot be conclusively ruled out, it is probable that Bunter Closure 36 has never been charged with gas. Further regional work exploring the Carboniferous to Bunter migration pathways through thin or absent Zechstein would contribute further to understanding in this area.

3.7.2.5 3D Geomechanical Analysis and Results

A 3D geomechanical model was constructed to investigate the possibility of seal breach and/or fault reactivation on the crest of the Bunter Closure 36 structure during injection. The process involves creating a small strain finite element model (i.e. the grid is not deformed) that allows elastic stress/strain relations and plastic failure effects to be investigated as a response to the proposed injection scheme. The reported output parameters include the following:

1. Displacement vectors to assess degree of overburden uplift
2. Failure criteria thresholds (shear or tensile) in the Bunter Sandstone or overburden
3. Matrix strains
4. Fault reactivation strains
5. Total and effective stress evolution
6. Stress path analysis (elastic response to pore pressure changes)

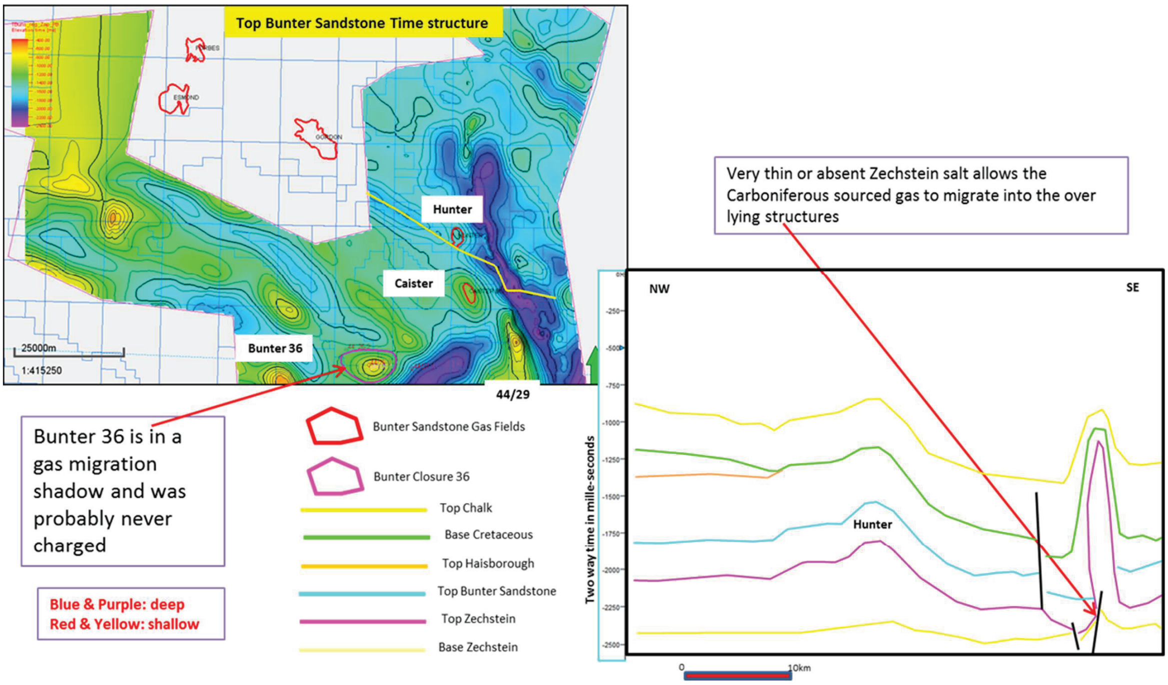
The Bunter Closure 36 Static model has been used as a basis for building a simplified 3D geomechanical model (Figure 3-85). The various steps required to construct, initialise, run and analyse a 3D geomechanical model with specific reference to Bunter Closure 36 are included in Appendix 8.



This map shows the regional time thickness (milliseconds) of the Zechstein salt interval

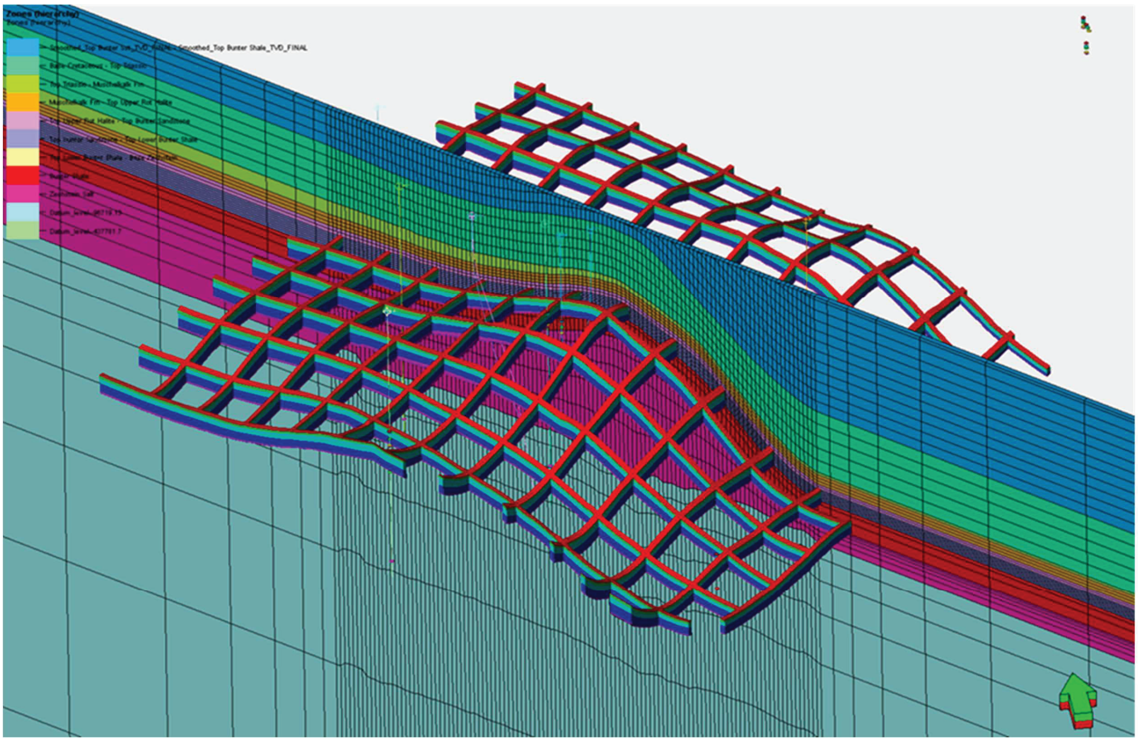
It is used to identify areas where the salt is very thin and these may provide pathways for gas to migrate up from the underlying Carboniferous source rocks.

Figure 3-83 - Regional Zechstein isochron



Maps shows the Bunter Sandstone gas fields in relation to Bunter 36 closure. Cross section is based on a seismic line which runs SE-NW from the Zechstein thin area and illustrates that the salt is very thin or absent allowing the Carboniferous sourced gas to migrate into the over lying structure and move up dip towards the Bunter gas fields.

Figure 3-84 - Possible Bunter Sandstone gas charging route



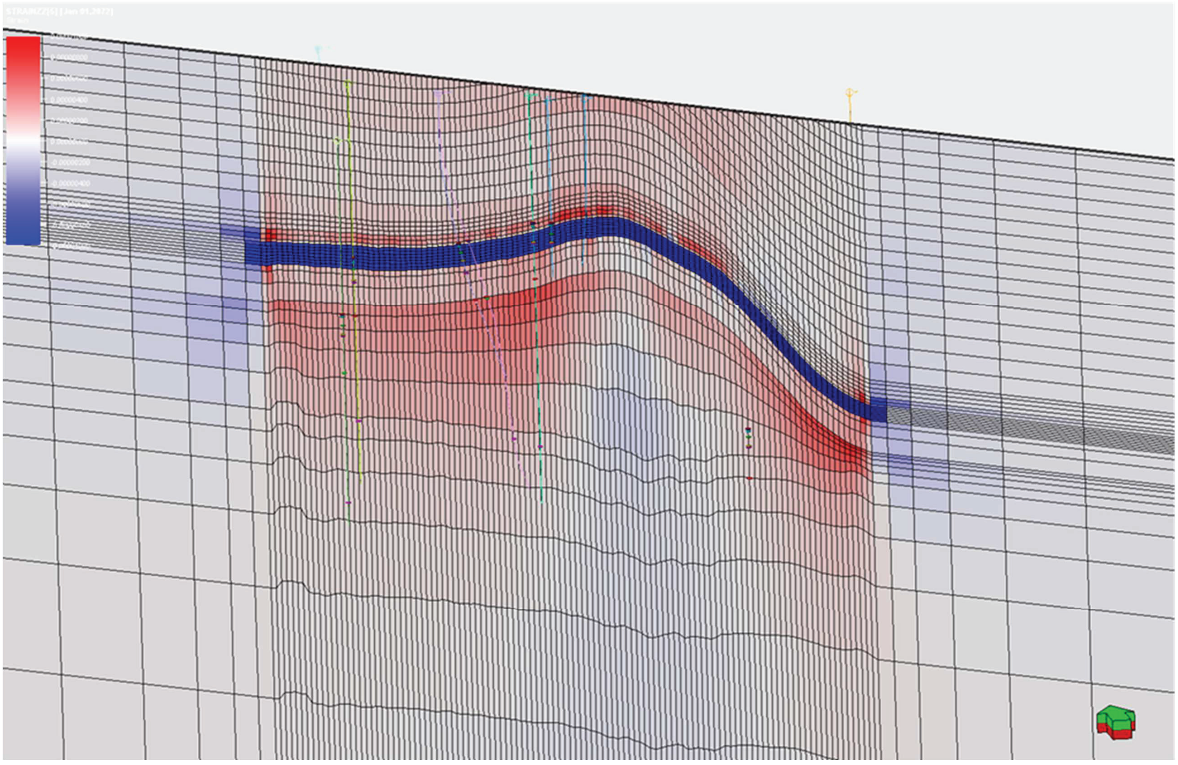
Multisection view of simulation grid (displayed with geomechanics grid (NW-SE cross section). The geomechanics grid includes the overburden and additional side and underburdens. The grids intersect within the Bunter Sandstone (purple zone on cross section).

Figure 3-85 - Bunter Closure 36 structure and geomechancis grid

The weak halite model was preferred and an explicit stress initialisation was used after approximately matching the SHmin gradient in the Bunter Sandstone and other units to 0.73 psi/ft and setting the halite stresses to lithostatic (isotropic). Seven pressure steps were used from the Eclipse runs in the Bunter Sandstone (2027, 2032, 2042, 2052, 2062, 2072 and 2082). These cases were run in linear and non-linear modes and the following observations can be made.

1. Whilst the injection is in multiple well locations and perforation intervals within the Bunter Sandstone, the pressure evolution is effectively homogeneous with equilibration over the full model area over the time steps modelled.
2. Maximum vertical displacement (uplift) at the end of injection is about 0.14 m in the Rot Halite and 0.13 m at the Seabed (see Figure 1.10). The uplift is smoothly distributed around the main Bunter Closure 36 structure with no obvious changes associated with fault reactivation. Note the slight downward displacement on the flanks within the Bunter Shale and Zechstein. This is probably a result of the response of the compliant salt to the injection.
3. Strains are very low with some minor dilational (negative) strains seen in the Bunter Sandstone and even smaller contractional (positive) strains seen in the overburden (Figure 3-86). Low elastic strains are also observed in the faults that have been introduced into the model to test if sub seismic faults might be reactivated. This is partly because the introduced faults only extend into the top 1-2 layers of the Bunter Sandstone and the modelled pressures do not increase in these layers because the injection is below an intra Bunter Sandstone sealing shale. The contractional strains in the underlying Bunter Shale and Zechstein (and associated downward displacement) probably reduce the amount of contractional strain and uplift in the overburden.
4. The non-linear run produced no plastic strains in the model indicating all deformation is elastic. Therefore, failure thresholds have not been reached in the matrix or the faultrocks. As a result it is very unlikely that any existing faults would be reactivated during injection operations as long as the model injection assumptions are honoured.
5. CO_2 injection related temperature properties were not available for this project and cooling within the CO_2 plume may cause tensile failure in the Rot Halite. However, this is likely to be minor and wouldn't occur in the current Bunter Sandstone model because the Upper Bunter Sandstone layers are isolated from the injection intervals.
6. There are some boundary condition effects at the edge of the area of interest due to the pressures stepping down to hydrostatic. These are not regarded as material to the main conclusions but can be reduced or removed by extrapolating the injection related pressures throughout the Bunter Sandstone layers in the side-burden areas.

In conclusion the 3D geomechanical modelling indicates that with the modelled injection scheme there will be minor uplift and some minor elastic strains with no shear or tensile failure of the overburden or faults.



Modelled vertical strain at 2072 in a NW-SE cross section through the Bunter Closure 36 Structure crest. Dilational strains are blue and contractional strains are red

Figure 3-86 - Vertical Strain in Bunter Closure 36

3.7.2.6 Geochemical Degradation Analysis and Results

The results of the considerations of geochemical degradation of the reservoir and caprock system in the presence of CO_2 and formation brine have been outlined in sections 3.5.1.5 and 3.5.2.5 with the methodology for the assessment detailed in Appendix 11.

As the Solling Claystone is less quartz-rich than the Bunter Sandstone, it is possible that reaction rates may be controlled more by dissolution of the alumino-silicates (illite, chlorite, muscovite and K-feldspar). Although more reactive than the underlying sandstone, it is still expected that the reaction rates will be slow at the low temperatures of this site and the net product is one of porosity loss. No geochemical reaction is expected in the Rot Halite. Contact between dissolved (reactive) CO_2 and the primary seal in the crest of the structure will be limited by the predominance of structurally-trapped (and therefore geochemically 'dry') CO_2 for the initial 1000 years post-injection.

3.7.3 Engineering Containment Integrity Characterisation

All active wells that are part of the CO_2 injection system (injectors, observation, pressure maintenance) should be designed and constructed not to leak in service and will satisfy the well integrity requirements set out in the governing legislation and guidance (Cooling, Kennai, & Martin) (Kenneth Ross, Rice Engineering Corporation , 2001). Wells will also be designed to facilitate the most secure abandonment when they are taken out of service.

Abandoned wells that penetrate the storage reservoir pose a leak risk because they provide a direct pathway to the surface. There are three abandoned well types to consider:

Pre-existing, still operational, wells in the overlying Schooner field will be abandoned before injection starts. The relevant authorities should require the petroleum operator to deploy the latest standards and practices to make them safe for a CO_2 storage environment, bearing in mind that the well construction itself was almost certainly not designed to be suitable for a CO_2 environment (e.g. material selection for corrosion resistance).

CO_2 injection wells (or related observation or water abstraction wells), which are decommissioned during the life of the storage facility, will be designed to be abandoned using the latest standards and practices. Both well types that provides confidence in the long-term containment.

Previously abandoned wells (exploration and appraisal wells from earlier hydrocarbon development) may have been abandoned in a way that is inadequate for a CO_2 storage environment because of their outdated construction design and abandonment practices (Appendix 9). In addition, record keeping for abandoned wells is not always complete and it may not be possible to determine how a particular well was abandoned. Crucially, these wells will have been cleared to approximately 15ft below the seabed; the wellhead and all casing strings close to the seabed will have been cut and recovered, access into an abandoned well is very complex and expensive. It is unlikely that this would be attempted to remediate a perceived risk, but only in the event of a major loss of containment.

Following a detailed risk review, 2 of the 3 wells reviewed showed higher risk than initially assumed. The status of the other two abandoned wells is not known. As per the initial methodology for risk assessment, the risk score for this site increases considerably (to 0.0396 for 100yr probability of a leakage and overall containment risk assessment score of 0.0078), but still remains low due to the small number of wells. However, the actual risk of loss of containment in well 44/26-1 is considered high, taking into account cement degradation. Whether this loss of containment results in a leak to surface is difficult to determine. Specific monitoring and contingency plans should be considered for this well as part of the FEED study.

3.7.3.1 Degradation Modelling

It has been shown that long term exposure of well construction materials to CO_2 (and its by-product when combined with water – carbonic acid) leads to a process of degradation. Cement used to seal the well casing annuli (and for creating barrier plugs) can degrade over time, with chemical reactions creating an increase in porosity and permeability of the cement and decreasing its compressive strength. However, cement has a 'self-healing' mechanism (carbonate precipitation) that reduces the rate of this degradation in the short term. If a cement is fully integral at the outset of exposure to CO_2, degradation is likely to be an infinitely slow process. However, if a weakness (fracture, micro-annulus or flow path) exists in the cement, the subsequent degradation process may be accelerated. Further work is required to identify the rate of cement degradation under all conditions in order to establish a minimum height of integral cement to prevent leakage in the storage time frame and to produce a range of potential leak rates. This should then be applied to all legacy wells.

Carbon steel casing (as used in legacy wells) is also subject to degradation through exposure to CO_2. Corrosion rates are more predictable (up to and around 9mm/yr in carbon steel for Bunter conditions, when exposed to the flow of CO_2 / water). Under static conditions, the corrosion rate reduces significantly. A leak path (or constant flux) adjacent to the casing is therefore required to cause degradation concern. Note that, for the new injector wells, the corrosion rate for 13%Cr material is up to and around 0.025mmyr. As the legacy wells are likely to be exposed to a flux of CO_2 during the 40 year injection period, it can be assumed that all casing strings in the reservoir section that are not protected by cement will be subject to significant corrosion. Casing strings above the reservoir will only be affected if a leak path is initiated.

3.7.3.2 Well Containment Risk Inventory

Pre-existing wells are assumed to not be designed for CO_2 injection or any other role in a CO_2 storage project and will be unsuitable for conversion to that purpose and will, therefore, be abandoned.

The possible well containment failures are:

- Flow through paths in poor casing cement sheaths or cement plugs.
- Flow through paths in casing cement sheaths created by pressure cycling.
- Flow through a cement sheaths or plugs degraded by contact with CO_2 or carbonic acid.
- Corrosion of tubulars, metallic well components or wellhead by carbonic acid.
- Degradation of elastomers by contact with CO_2 or carbonic acid.
- Blowout whilst drilling an injection/observation well.
- Blowout whilst conducting a well intervention on an injection/observation well.

3.7.3.3 Well Remediation Options

For each key risk event a remediation option (or options) is defined and an associated high level cost is estimated. Options to improve the integrity status are identified.

Table 3-32 catalogues the well containment failure mode and the associated effect, remediation and estimated cost (it is assumed that the wells are offshore). The remediation options available will be specific to the well and depend on:

- The type of failure.
- The location of the failure.
- The overall design of the well.

3.7.4 Containment Risk Assessment

A subsurface and wells containment risk assessment was completed and the results are detailed in Appendix 2. The workflow considered ten specific failure modes or pathways for CO_2 to move out of the primary store and/or storage complex in a manner contrary to the development plan. Each failure mode might be caused by a range of failure mechanisms. Ultimately, pathways that could potentially lead to CO_2 moving out with the Storage Complex were mapped out from combinations of failure modes. For each pathway, the likelihood was taken as the lowest from likelihood of any of the failure modes that made it up and the impact was take as the highest. The pathways were then grouped into more general leakage scenarios. These are outlined in Table 3-33 and displayed in a risk matrix plot in Figure 3-87.

The key containment risk perceived at the present time involved escape of CO_2 from existing legacy wells leading to seabed release of CO_2. This risk can be mitigated significantly through careful well abandonment of the wells to the underlying Schooner gas field as they are abandoned after the cessation of economic production in 2021.

Risk Event	Remediation
Blowout during drilling	Standard procedures: shut-in the well and initiate well control procedures.
Blowout during well intervention	Standard procedures: shut-in the well and initiate well control procedures.
Tubing leak	Tubing replacement by workover.
Packer leak	Packer replacement by workover.
Cement sheath failure (Production Liner)	Repair by cement squeeze (possible chance of failure). Requires the completion to be retrieved and rerun (if installed).
Production Liner failure	Repair by patching (possible chance of failure) or running a smaller diameter contingency liner. Requires the completion to be retrieved and rerun (if installed). Will change the casing internal diameter and may have an impact on the completion design and placement. Repair by side-track.
Cement sheath failure (Production Casing)	Repair by cement squeeze (possible chance of failure). Requires the completion to be retrieved and rerun (if installed).
Production Casing Failure	Repair by patching (possible chance of failure). Requires the completion to be retrieved (if installed). Will change the casing internal diameter and may have an impact on the completion design and placement.
Safety critical valve failure – tubing safety valve	Repair by: installation of insert back-up by intervention or replacement by workover
Safety critical valve failure – Xmas Tree valve	Repair by valve replacement.

Risk Event	Remediation
Wellhead seal leak	Possible repair by treatment with a replacement sealant or repair components that are part of the wellhead design. Highly dependent on the design and ease of access (dry tree or subsea). May mean the well has insufficient integrity and would be abandoned.
Xmas Tree seal leak	Possible repair by specific back-up components that are part of the wellhead design. Highly dependent on the design and ease of access. May mean the Xmas Tree need to be removed/recovered to be repaired. This is a time consuming process for a subsea tree.

Table 3-32 - Well containment risks and remediation options

Leakage scenario	Likelihood	Impact	Matrix Position
Vertical movement of CO_2 from Primary store to overburden through caprock	1	3	
Vertical movement of CO_2 from Primary store to overburden via existing wells	1	3	
Vertical movement of CO_2 from Primary store to overburden via injection wells	1	3	
Vertical movement of CO_2 from Primary store to overburden via caprock & wells	1	3	
Vertical movement of CO_2 from Primary store to upper well/ seabed via existing wells	3	4	
Vertical movement of CO_2 from Primary store to upper well/ seabed via injection wells	2	4	
Vertical movement of CO_2 from Primary store to upper well/ seabed via caprock & wells	1	4	
Lateral movement of CO_2 from Primary store out with storage complex within Bunter	2	3	
Vertical movement of CO_2 from Primary store down to Zechstein or lower via existing wells	3	3	
Vertical movement of CO_2 from Primary store down to Zechstein or lower via store floor	1	3	

Table 3-33 - Bunter Closure 36 - Leakage Scenarios

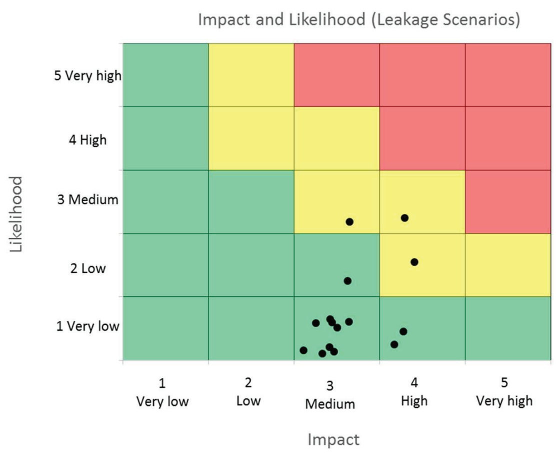


Figure 3-87 - Bunter Closure 36 Risk Matrix of leakage scenarios

3.7.5 MMV Plan

Monitoring, measurement and verification (MMV) of any CO_2 storage site in the United Kingdom Continental Shelf (UKCS) is required under the EU CCS Directive (The European Parliament And The Council Of The European Union, 2009) and its transposition into UK Law through the Energy Act 2008 (Energy Act, Chapter 32, 2008). A comprehensive monitoring plan is an essential part of the CO_2 Storage Permit.

The four main purposes of monitoring a CO_2 storage site are to:

1. Confirm that the actual behaviour of the injected CO_2 conforms to the modelled behaviour.
2. Confirm that there is no detectable leakage from the storage reservoir and defined storage complex.
3. Confirm that the storage site will permanently contain the injected CO_2.
4. Acquire data to update reservoir models to refine future CO_2 behaviour predictions.

The storage site has been carefully selected to ensure secure containment of the CO_2 and so loss of containment is not expected. A site monitoring plan needs to prove that the integrity of the store has not been compromised and build confidence that the store is behaving as predicted.

The monitoring plan is based on a risk assessment of the storage site and is designed to prevent risks, or mitigate them, should they occur. The plan is also dynamic, meaning that it will be updated throughout the life of the projected as new data are acquired, or perhaps as new technologies become commercial.

The two elements of the monitoring plan are discussed in the following sections:

- Base Case monitoring plan.
- Corrective measures plan.

3.7.5.1 Base Case Monitoring Plan

The base case plan is one that is scheduled and consists of baseline, operational and post-closure monitoring activity.

Baseline monitoring is carried out prior to injection and provides a baseline against which to compare all future results to. Since all future results will be compared to these pre-injection data, it is very important to ensure a thorough understanding of what the baseline is so that any possible deviations from it can be detected with greater confidence.

Operational monitoring is carried out during injection and to ensure that the CO_2 is contained and that the injection process and performance of the store is as expected. Data acquired from this monitoring phase will be used to update and history match existing reservoir models. The data will also be used to revise and update the risk assessment. Data such as flow, pressure and temperature at injection wellheads will be used for quantification of the injected CO_2 for accounting and reporting under the EU Emissions Trading Scheme (The European Parliament and the Council of the European Union, 2012).

As part of the Storage Permit application, the monitoring plan should include surface facilities and equipment process monitoring to demonstrate that the pipeline and facilities are operating as designed.

Post-closure monitoring takes place after cessation of injection with the primary purpose to confirm that the storage site is behaving as expected. Within the UK the anticipated requirement is for 20 years of post-closure monitoring, after which time the Department of Energy and Climate Change (DECC), or their successor will take on the storage liabilities, assuming the site shows conformance. A post-closure baseline will be carried out prior to post-closure monitoring for all future results to be compared against.

Post-handover monitoring may be required in the UK by DECC following handover of the storage liabilities. This would likely be negotiated between the CO_2 Storage Operator and DECC during the post-closure monitoring phase.

As discussed above, the monitoring plan is dynamic and will be updated and revised with data collected and interpreted from the monitoring activities. The plan will also be updated if new CO_2 sources are to be injected into the storage site or if there are significant deviations from previous modelling as a result of history matching.

Annual reporting to DECC will include information about site performance and may include commentary around any site-specific monitoring challenges that have occurred.

3.7.5.2 Corrective Measures Plan

The Corrective Measures Plan is deployed in case of detection of a 'significant irregularity' in the monitoring data, or leakage, and includes additional monitoring to further identify the irregularity and remediation options should they be required.

A 'significant irregularity' is defined in the CCS Directive as: *any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health*.

'Corrective measures' are defined in the CCS Directive as: *any measures taken to correct significant irregularities or to close leakages in order to prevent or stop the release of CO_2 from the storage complex*.

The four main parts to the Corrective Measures Plan are:

1. Additional monitoring to understand the irregularity and gather additional data.
2. Risk assessment to understand the potential implications of the irregularity.
3. Measures to control or prevent the irregularities.
4. Potential remediation options (if required).

If any corrective measures are taken, their effectiveness must be assessed.

3.7.5.3 Monitoring Domains

Within the storage site and complex there are several monitoring domains, which have different monitoring purposes (Table 3-34).

Monitoring domain	Monitoring purpose
Storage reservoir	Confirm that the CO_2 is behaving as predicted
Injection wells	Ensure safe injection process, collect data to update reservoir models for CO_2 prediction and detect any early signs of loss of containment
Storage complex (including P&A wells)	Detection of CO_2
Seabed/ atmosphere	Detection of CO_2 Quantification of CO_2 leakage

Table 3-34 - Monitoring domains

3.7.5.4 Monitoring Technologies

Many technologies which can be used for offshore CO_2 storage monitoring are well established in the oil and gas industry.

Monitoring of offshore CO_2 storage reservoirs has been carried out for many years at Sleipner and Snohvit in Norway and at the K12-B pilot project in the Netherlands. Onshore, Ketzin in Germany has a significant focus on developing MMV research and best practice.

A comprehensive list of existing technologies has been pulled together from NETL, 2012 (National Energy Technology Laboratory, US Department of Energy, 2012) and IEAGHG, 2015 (IEAGHG, 2015). This list of monitoring technologies and how they were screened is provided in Appendix 7.0 MMV Technologies.

3.7.5.5 Bunter Closure 36: seismic response of CO_2

With the significant cost of seismic surveys, it is essential to understand if they can detect and delineate CO_2 in the storage site. During injection, the CO_2 replaces and mixes with in-situ brine, changing the density and compressibility of the fluid in the pore space, which may change the seismic response enough to be detected.

This can be modelled prior to injection using a technique known as 1D forward modelling. A 1-dimensional model of the subsurface is built from well-log data and fluid substitution is carried out over the injection interval, substituting CO_2 for brine. The seismic response of this new fluid mixture is modelled via a synthetic seismogram and any visible changes give an indication that seismic will be able to detect the stored CO_2 at the site.

High level screening 1D fluid substitution modelling was carried out for well 44/26-1, in the crest of Bunter Closure 36, using Kingdom software. The Kingdom 1D modelling package is simple but gives an indication of the detectability of CO_2 in the reservoir using seismic.

3.7.5.5.1 Modelling Inputs

The Bunter 3 sand (~4150ft to 4480ft) was modelled, with the in-situ case having bulk mineral density of 2.704g/cc (from petrophysics), brine density of 1.22g/cc (corresponding to a salinity of 300,000ppm), Vp and Vs from well logs and a constant density of 2.3g/cc due to absence of a density log. The fluid substitution case modelled 60% CO_2 saturation with a density of 0.8g/cc, which corresponded to a reservoir temperature of 45^{o}C and a maximum reservoir pressure of 197 bar (taken from dynamic model). This is broadly in line with the saturations modelled for buoyant trapping. A 30Hz North Sea (reverse SEG) polarity Ricker wavelet was used to generate the synthetic seismogram.

The software uses low-frequency Gassmann equations, which relate the saturated bulk modulus of the rock (Ksat) to its porosity, the bulk modulus of the porous rock frame, the bulk modulus of the mineral matrix and the bulk modulus of the pore-filling fluids. The saturated bulk modulus can also be related to P-wave velocity (Vp), S-wave velocity (Vs) and density (rho) and so this data can be taken from well logs.

The software takes Vp, Vs and rho from well logs to determine the bulk modulus of the saturated rock over the modelled interval and then determines the mineral matrix and bulk modulus of the pore fluid from specified user inputs. It then essentially "removes" the in-situ fluid to calculate the bulk modulus of the rock matrix only and substitutes the pore fluid with the desired fluid to be modelled (in this case CO_2). Once the desired fluid is substituted it calculates the bulk modulus of the rock saturated with the new fluid and, as mentioned above, a new Vp, Vs and density can be determined from the saturated bulk modulus. This new Vp, Vs and density is then used with the synthetic wavelet to generate a synthetic seismogram.

3.7.5.5.2 Results

Figure 3-88 shows the results with 0% CO_2 model and 60% CO_2 saturation on the seismic response.

As seen in Figure 3-88, a general decrease in acoustic impedance over the whole Bunter 3 sand due to the presence of CO_2 can be seen, which is as expected. An increase in amplitude is visible at the Top Bunter 3, which is due to the magnitude of acoustic impedance contrast between the faster Bunter 2 sands and the slower, less dense CO_2-filled Bunter 3 sand. No AVO (amplitude versus offset) response is seen.

Amplitude dimming is also seen at the base of the modelled area, which is the top of the Bunter 4 sand, since the acoustic impedance contrast between the CO_2-filled Bunter 3 and Bunter 4 sand is reduced with CO_2 in the pore space. Note that Bunter 4 was kept brine-filled during the modelling, but will be used during injection and so this dimming may not be present if both Bunter 3 and Bunter 4 sands are saturated with CO_2.

From the quick-look modelling carried out, the increase in amplitude at Top Bunter 3 with 60% CO_2 saturation gives an indication that CO_2 may be detectable within the Bunter Closure 36 site using seismic and therefore seismic surveying will form part of the base case monitoring plan.

Further work on the sensitivity of the detection limit (column height and saturation) should be carried out during FEED.

3.7.5.6 Outline Base Case Monitoring Plan

The outline monitoring plan has been developed to focus on the leakage scenarios as identified in Appendix 2, with the most applicable technologies at the time of writing.

49 technologies that are used in the hydrocarbon industry and existing CO_2 storage projects were reviewed and 35 were found to be suitable for CO_2 storage offshore. A list and description of the offshore technologies is in Appendix 7.

The plan below is based on using technologies from a general offshore UKCS Boston Square (see Appendix 7), which plots a technology's cost against its value of information, and are from either the "just do it" (low cost, high benefit) or "focussed application" (high cost, high benefit) categories.

Other technologies that are in the "consider" (low cost, low benefit) category require additional work during FEED to more fully assess the value for the Bunter Closure 36 site. Note that some of the "consider" technologies are less commercially mature, but may move to the "just do it" category over time.

Figure 3-89 maps the selected technologies to the leakage scenarios discussed in Appendix 2. Note that whilst almost all of the relevant over and underburden are shales or evaporites, there are some occasional thin sands present. 4D seismic is one of the few technologies that might be able to detect CO2 ingress into such intervals.

The base case monitoring plan for Bunter Closure 36 in Figure 3-90 and outlined in the subsequent tables.

A dedicated monitoring well has not been included in the plan, but instead a redundancy injection well, which will monitor when not in use.

The surface facilities include an unmanned platform with occasional personnel carrying out inspections and maintenance. There will be a requirement for some atmospheric CO_2 monitoring, perhaps using optical CO_2 sensors, to ensure the safety of these personnel.

Monitoring of pipeline wall thickness and valve seal performance will be carried out as part of routine maintenance and the pipeline has been designed to receive pigs.

3.7.5.7 Outline Corrective Measures Plan

The corrective measures plan will be deployed if either leakage or significant irregularities are detected from the monitoring, measurement and verification plan above.

Some examples of significant irregularities and their implications are shown in Table 3-38.

Once a significant irregularity has been detected, additional monitoring may be carried out to gather data which can be used to more fully understand the irregularity. A risk assessment should then be carried out to decide on the appropriate corrective measures to deploy, if any. It may be that only further monitoring is required.

Depending on the implication of the significant irregularity, some measures may be needed to control or prevent escalation and remediation options may be required.

The Appendix 1 Risk Matrix contains examples of mitigation actions (controls) and potential remediation options. For the leakage scenarios discussed in Appendix 2 and mapped to MMV technologies in Figure 3-89, some examples of control actions and remediation options are shown in Figure 3-91.

It should be noted that re-entry into long abandoned wells can be extremely difficult. The challenge of simply locating the cut casing several metres below the seabed and re-entering it can be so difficult that a relief well is a more straightforward remediation option.

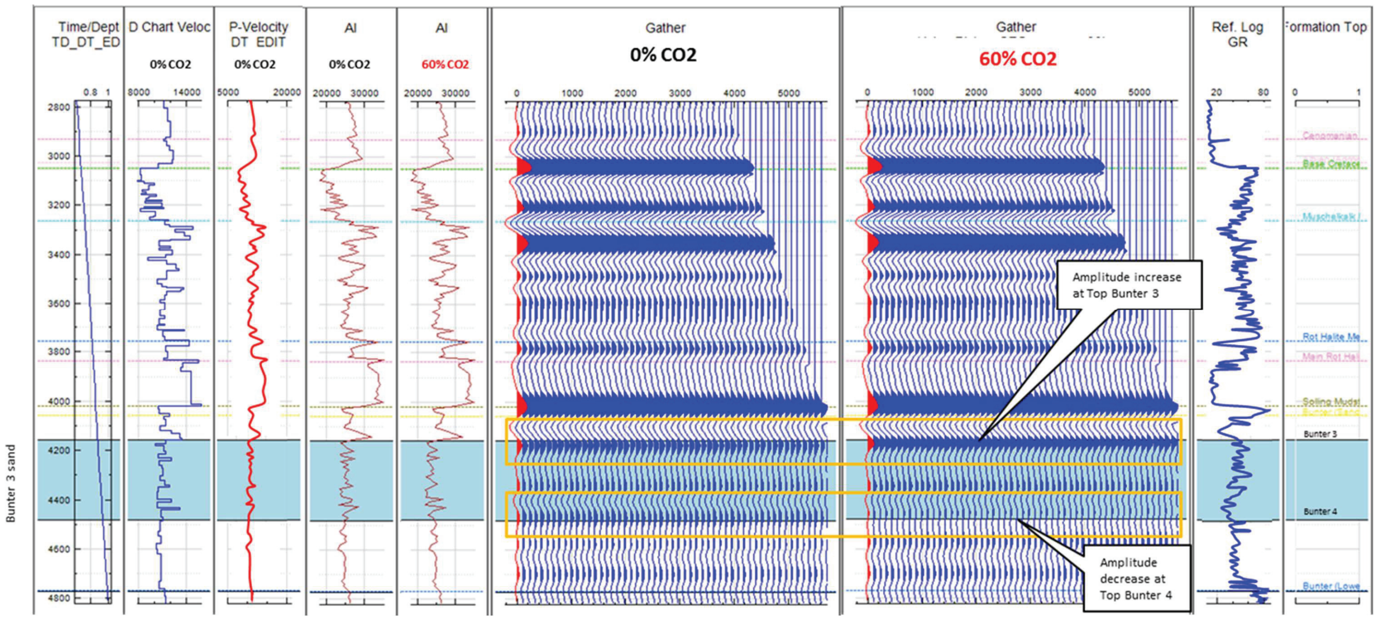


Figure 3-88 - 1D forward modelling: 0% and 60% CO_2 saturation

- Critical
- Serious
- Moderate
- Minor

Leakage Scenario			Risk ranking			Monitoring Technology				
			Likelihood	Impact	Ranking	Seabed sampling, ecosystem response monitoring, geochemical analyses of water column	Sidescan sonar survey, chirps, boomers & pingers	4D Seismic	Wireline logging	Permanently installed wellbore tools (DTS), downhole and wellhead P/T gauge and flow meter
Leakage Scenario	Overburden	Vertical movement of CO2 from Primary store to overburden through caprock	1	3	Minor			X		X
		Vertical movement of CO2 from Primary store to overburden via pre-existing wells	1	3	Minor			X		
		Vertical movement of CO2 from Primary store to overburden via injection wells	1	3	Minor			X		X
		Vertical movement of CO2 from Primary store to overburden via both caprock & wells	1	3	Minor			X		X
	Seabed	Vertical movement of CO2 from Primary store to seabed via pre-existing wells	3	4	Moderate	X	X			
		Vertical movement of CO2 from Primary store to seabed via injection wells	2	4	Moderate	X	X		X	X
		Vertical movement of CO2 from Primary store to seabed via both caprock & wells	1	4	Minor	X	X	X	X	X
	Lateral	Lateral movement of CO2 from Primary store out with storage complex w/in Bunter	2	3	Minor			X		
	Underburden	Vertical movement of CO2 from Primary store down to Zechstein or lower via pre-existing wells	3	3	Moderate			X		
		Vertical movement of CO2 from Primary store down to Zechstein or lower via store floor	1	3	Minor			X		

Figure 3-89 - Mapping between leakage scenarios and monitoring technologies

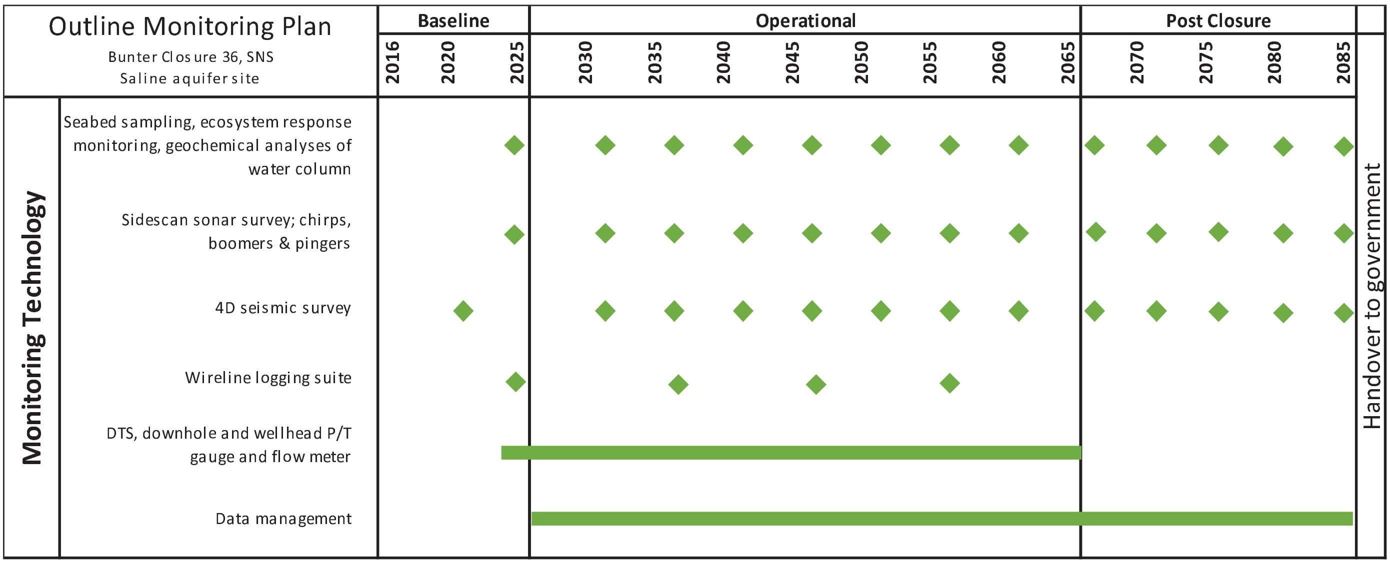


Figure 3-90 - Base case monitoring, measurement and verification (MMV) plan for Bunter Closure 36

Monitoring technology/ workscope	Rationale	Timing
Seabed sampling, ecosystem response monitoring, geochemical analyses of water column	Baseline sampling to understand background CO_2 concentrations in the sediment and water column to benchmark any future surveys against.	1-2 years prior to injection
Sidescan sonar survey **Chirps, boomers & pingers**	Baseline sidescan sonar survey to benchmark future surveys. Looking to detect any pre-existing bubble streams on seabed or around abandoned wellheads and map pock-marks.	1-2 years prior to injection
Seismic survey	Baseline survey required for 4D seismic.	1-2 years prior to injection
Wireline logging suite (incl well bore integrity)	Part of the drilling programme to gather data on the reservoir, overburden and wellbore for baseline update to reservoir models.	During drilling programme
Installation of Distributed Temperature Sensor (DTS), downhole and wellhead P/T gauge and flow meter	DTS for real-time monitoring of temperature along the length of the wellbore, which can indicate CO_2 leakage through tubing. Downhole pressure and temperature monitoring is considered essential to ensure injection integrity & required under EU Storage Directive; flow meter for reporting.	Permanent installation once wells drilled

All surveys to be carried out over the storage complex.

Table 3-35 - Baseline monitoring plan

Monitoring technology/ workscope	Rationale	Timing
Wireline logging suite (incl well bore integrity)	Gather data on the reservoir, overburden and wellbore integrity to ensure injection integrity and update reservoir models.	Every 10 years
4D seismic survey	Used to detect plume extent and update geological and dynamic models. Also looking for any early-warning signs of loss of containment, such as unexpected lateral or vertical migration of CO_2 within the storage complex.	Every 5 years
Sidescan sonar survey **Chirps, boomers & pingers**	Used to detect any bubble streams around abandoned wellheads, on the seabed or around pock-marks, which could indicate loss of containment to seabed.	Every 5 years
Seabed sampling, ecosystem response monitoring, geochemical analyses of water column	Used to detect any evidence of elevated CO_2 concentrations in sediment or water column which may indicate loss of containment.	Every 5 years
DTS, downhole and wellhead P/T gauge and flow meter readings	DTS for real-time monitoring of temperature along the length of the wellbore, which can indicate CO_2 leakage through tubing. Downhole pressure and temperature monitoring is required under EU Storage Directive, can be used to update models and is considered essential to ensure injection integrity. Flow meter for reporting.	Continuous
Data management	To collate, manage, interpret and report on monitoring data.	Continuous

All surveys to be carried out over the storage complex

Table 3-36 - Operational monitoring plan

Monitoring technology/ workscope	Rationale	Timing
4D seismic survey (dependent on modelling results)	Detect plume extent at end of injection operations and monitor to show site conformance prior to handover.	1 year post injection, then every 5 years
Seabed sampling, ecosystem response monitoring, geochemical analyses of water column	Used to detect any evidence of elevated CO_2 concentrations in sediment or water column which may indicate loss of containment	1 year post injection, then every 5 years
Sidescan sonar survey **Chirps, boomers & pingers**	Looking to detect any bubble streams around abandoned wellheads, seabed or pock-marks and set a baseline for post-closure and post-handover monitoring.	1 year post injection, then every 5 years
Data interpretation, management and reporting	To collate, manage, interpret and report on monitoring data.	Continuous

All surveys to be carried out over the storage complex.

Table 3-37 - Post closure monitoring plan

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Monitoring technology	Example of significant irregularity	Implication
Wireline logging suite (incl well bore integrity)	Indication that wellbore integrity compromised	Injection process at risk
4D seismic survey	CO_2 plume detected out with the storage site or complex (e.g. laterally or vertically)	Potential CO_2 leakage or unexpected migration
Sidescan sonar survey **Chirps, boomers & pingers**	Bubble stream detected near P&A wellbore	Potential CO_2 leakage to seabed via P&A wells
Seabed sampling, ecosystem response monitoring, geochemical analyses of water column	Elevated CO_2 concentrations above background levels detected in seabed	Potential CO_2 leakage to seabed
DTS, downhole and wellhead P/T gauge and flow meter readings	Sudden temperature drop along tubing Sudden pressure or temperature drop in reservoir	Potential CO_2 leakage from injection wellbore Storage site integrity compromised (e.g. caprock fractured) - CO_2 potentially

Table 3-38 - Examples of irregularities and possible implications

Leakage Scenario		Outline Corrective Measures: Control/ mitigation actions	Outline Corrective Measures: Potential Remediation Options
Overburden	Vertical movement of CO2 from Primary store to overburden through caprock	Invesitgate irregularity, assess risk, update models if required, increased monitoring to ensure under control	Increased monitoring to ensure under control (CO2 should be trapped by additional geological barriers in the overburden)
Overburden	Vertical movement of CO2 from Primary store to overburden via pre-existing wells	Invesitgate irregularity, assess risk, update models if required, increased monitoring to ensure under control	Increased monitoring to ensure under control. Consider adjusting injection pattern if can limit plume interaction with pre-existing wellbore. Worst case scenario would require a relief well (re-entry into an abandoned well is complex, difficult and has a very low chance of success)
Overburden	Vertical movement of CO2 from Primary store to overburden via injection wells	Stop injection, investigate irregularity, acquire additional shut-in reservoir data, update models	Replacement of damaged well parts (e.g. tubing or packer) by workover. Worst case scenario would be to abandon the injection well.
Overburden	Vertical movement of CO2 from Primary store to overburden via both caprock & wells	Invesitgate irregularity, assess risk, update models if required, increased monitoring to ensure under control	Increased monitoring to ensure under control (CO2 should be trapped by additional geological barriers in the overburden)
Seabed	Vertical movement of CO2 from Primary store to seabed via pre-existing wells	Stop injection, investigate irregularity via additional monitoring at seabed and acquisition of shut-in reservoir data, assess risk, update models	Re-entry into an abandoned well is complex, difficult and has a very low chance of success. A relief well is required.
Seabed	Vertical movement of CO2 from Primary store to seabed via injection wells	Stop injection, shut in the well and initiate well control procedures, investigate irregularity via additional monitoring at seabed and acquisition of shut-in reservoir data, assess risk, update models	Replacement of damaged well parts (e.g. tubing or packer) by workover. Worst case scenario would be to abandon the injection well.
Seabed	Vertical movement of CO2 from Primary store to seabed via both caprock & wells	Stop injection, investigate irregularity via additional monitoring at seabed, assess risk	If injection well - replacement of damaged well parts (e.g. tubing or packer) by workover. Worst case scenario would be to abandon the injection well. If P&A well - a relief well may be required.
Lateral	Lateral movement of CO2 from Primary store out with storage complex w/in Bunter	Invesitgate irregularity, assess risk, update models if required, increased monitoring to ensure under control	Reduce injection rates and volumes, alter injection pattern, licence additional area as part of Storage Complex, continue to monitor
Underburden	Vertical movement of CO2 from Primary store down to Zechstein or lower via pre-existing wells	Invesitgate irregularity, assess risk, update models if required, increased monitoring to ensure under control	Continue to monitor, licence additional area as part of Storage Complex. Worst case scenario: a relief well may be required (re-entry into an abandoned well is complex, difficult and has a very low chance of success)
Underburden	Vertical movement of CO2 from Primary store down to Zechstein or lower via store floor	Invesitgate irregularity, assess risk, update models if required, increased monitoring to ensure under control	Continue to monitor, licence additional area as part of Storage Complex. Worst case scenario: a relief well may be required (re-entry into an abandoned well is complex, difficult and has a very low chance of success)

Figure 3-91 - Leakage scenarios and examples of corrective measures

4.0 Appraisal Planning

4.1 Discussion of Key Uncertainties

All subsurface resource targets are subject to uncertainty. Most of this is associated with the consequences of having an incomplete knowledge of the underground geology and how this might impact upon the commercial aspects of the development. This "subsurface uncertainty" is a fact of life in all oil and gas and mining developments. Furthermore, whilst uncertainty generally falls as more experience of the site is obtained, it persists throughout the whole life of a subsurface asset. In CO_2 Storage this extends into the post injection phase.

Whilst the complete elimination of uncertainty is simply not possible, the reduction of uncertainty through a combination of careful data acquisition and focussed analysis and modelling (appraisal effort) can be effective in reducing uncertainty to a level at which project investment decisions can be confidently made.

Bunter Closure 36 has good existing 3D seismic coverage together with a range of well penetrations and well information. However, since very few of the wells were designed to specifically investigate the Bunter Sandstone reservoir and its caprock, there is some key data missing. This includes:

- Caprock core material to assure integrity.
- Reservoir core material to confirm reservoir quality and flow properties (such as relative permeability data).
- Full high quality log suites over all key intervals to clarify reservoir quality and magnitude / distribution of halite cement issue.
- Detailed reservoir hydraulic architecture to confirm how the reservoir will perform under injection and how the CO_2 will migrate away from the injection well.
- Good geographic sampling of reservoir quality in the area of the closure itself. In particular an additional control point in the east of the closure would be very useful to limit the uncertainty resulting from existing well locations.

Of key importance is information relating to the dynamic performance of the site under injection. These include reservoir pressures and flow rate tests under a range of conditions. Good quality dynamic data may even be able to identify reservoir connectivity across much of the site and assist to specifically identify and eliminate any sites with limited dynamic capacity estimates.

4.2 Information Value

The work conducted to date has highlighted that some significant remaining uncertainties exist. Whilst uncertainty cannot be eliminated, there are some key uncertainties that can be significantly reduced through further data acquisition and appraisal activity. This additional appraisal effort will improve the confidence and robustness of any final investment decision. Specifically, high value information can be acquired in the following areas:

1. Reservoir quality and hydraulic continuity across the site. This impacts the well injectivity and the well count, but also the estimation of pore volume and storage efficiency (vertical and areal sweep efficiency) which are key attributes to capacity estimation.

2. The large scale pressure interaction between the local injection site and the regional Bunter Sandstone aquifer. This will impact the longer term injectivity and the capacity estimation.
3. Seismic velocity field from the seabed down to the Top Bunter Sand is complex and overburden variation has the effect of changing the detailed shape of the depth structure from that of the imaged time structure. An improved understanding of this velocity field will be important in defining the reservoir rock volume within the closure and the depth of the lowest closing contour which will influence well targeting.

4.3 Proposed Appraisal Plan

The forward minimum appraisal philosophy and recommended plan therefore involves four main components:

Further Data Mining From Existing Wells: The nature of this project and in particular the requirement to publish as much of the analysis as possible has placed some constraints on data access where such data has been deemed of a confidential nature by the holder. Access to specific well data from operators under appropriate confidentiality agreements will help to infill some regional and local data gaps, especially regarding well status and abandonment records.

Regional Dynamic Performance: There may be important information around aquifer characterisation embedded in a collective interpretation of the production performance of nearby Bunter gas fields and in particular the pressure decline characteristics. This will require the assembly of pressure data from these fields and some regional geological interpretation work to more completely understand the development of reservoir quality across the region and the history and mechanics of the gas fill to the Bunter structures over geological time.

3D Seismic Acquisition: Whilst the 3D seismic data from the PGS MegaSurvey is a high quality product, it represents a complex merge of more than one survey over the Bunter Closure 36 area. The joins between the surveys can introduce anomalies between the surveys which makes quantitative work difficult. Furthermore, the PGS MegaSurvey was not specifically designed to image the Bunter Sandstone and its overburden in detail. A new 3D acquisition across the broader storage complex would enable the following to be achieved:

- High resolution detailed imaging of the overburden interval to characterise small discontinuous faults and layers to support confidence around the high quality containment properties of the structure.
- New 3D acquisition could also be processed to reveal more quantitative information regarding the porosity and reservoir quality of the storage site away from existing well information to enable wells to be placed optimally. Whilst the quantitative potential may be limited, a new survey may improve confidence around reservoir quality characterisation and long term performance.
- Finally, a new modern 3D seismic would provide a key high resolution reference survey against which to compare any future post injection surveys and perform fluid tracking analysis. This 4D seismic approach is limited by the lowest resolution survey over the area and a new survey would enhance the value of the MMV programme.

Appraisal Drilling: A new appraisal well is also proposed to provide further information on the seismic velocity field and also key reservoir, formation fluid and caprock samples to assist subsurface characterisation. The detailed location and trajectory of this well require further work, but a potential location is shown in Figure 4-2. The initial outline objectives of the well will include:

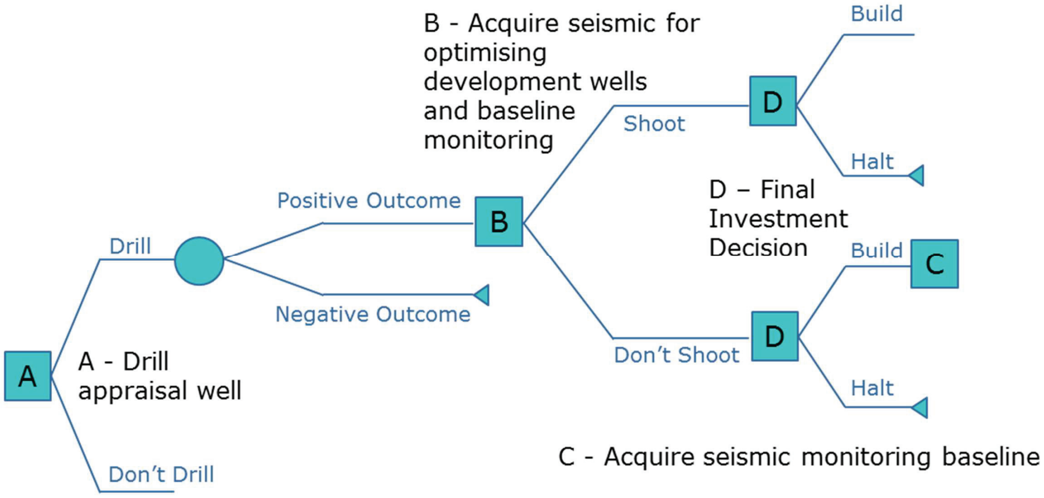
1. Simple vertical well located within Bunter Closure 36, but away from the crest of the structure to the North East where the velocity field is less well defined. The well should TD in the upper part of the underlying Bunter Shale.
2. The well should be cored through the lower 50ft of the halite caprock and the Rot Shale and also throughout the full Bunter Sandstone interval to provide reservoir quality information and rock samples for further analysis.
3. Conventional wireline logging targeted at lithology, reservoir quality, mineralogy and geomechanics (Gamma Ray, Resistivity, Neutron, Density and Sonic).
4. Specialize wireline logging will include image logging across the caprock and reservoir interval will support search for small scale fracturing and also the interpretation of future development wells whilst minimising future coring, Dipole sonic and potentially NMR to measure permeability.
5. Pressure profiling through the reservoir will be required to try to identify any small levels of pressure depletion associated with production at Caister or other nearby Bunter gas fields since this would confirm regional connectivity.
6. Mini-fracture testing to calibrate the geomechanical models further and vertical interference testing to check the significance of any shale baffles.
7. Formation water salinity samples will be taken through the Bunter Sandstone interval to confirm the value and variability of salinity because of its link to potential pore space occlusion through halite cementation. Specifically, these samples will be subject to specific isotopic analysis to assist in the understanding of the evolution of these waters and the porosity occluding halite cement risk.
8. Finally - a significant water production and/or injection test will be completed to confirm initial injectivity and minimum connected volume.

It may be possible to combine many of these objectives and have this appraisal well ready to keep as a potential injection well, but further cost definition and uncertainty assessment would be required to make this decision. As ever, the drilling rig rate of the day is expected to strongly influence this choice.

Timing

Ideally, it would be desirable to acquire the 3D seismic ahead of locating an appraisal well. In this situation, the current 3D is considered high enough quality to successfully locate the appraisal well. It is accepted however that any final investment decision would benefit from the additional confidence of the new 3D seismic. This allows the appraisal drilling and seismic acquisition to be decoupled such that they can be conducted in parallel. There are some concerns that leading with new seismic acquisition will likely defer any final investment decision by up to 18 months.

The decision sequence is illustrated in Figure 4-1.



Note

- Decision A precedes B because seismic is not deemed necessary to locate the appraisal well. Drilling well after new seismic has been interpreted would add ~ 12 months to the programme
- New seismic is required to optimise location of injection wells and to provide a baseline survey - but may not be essential for selecting the location of the appraisal well

Figure 4-1 - Appraisal plan development decision sequence

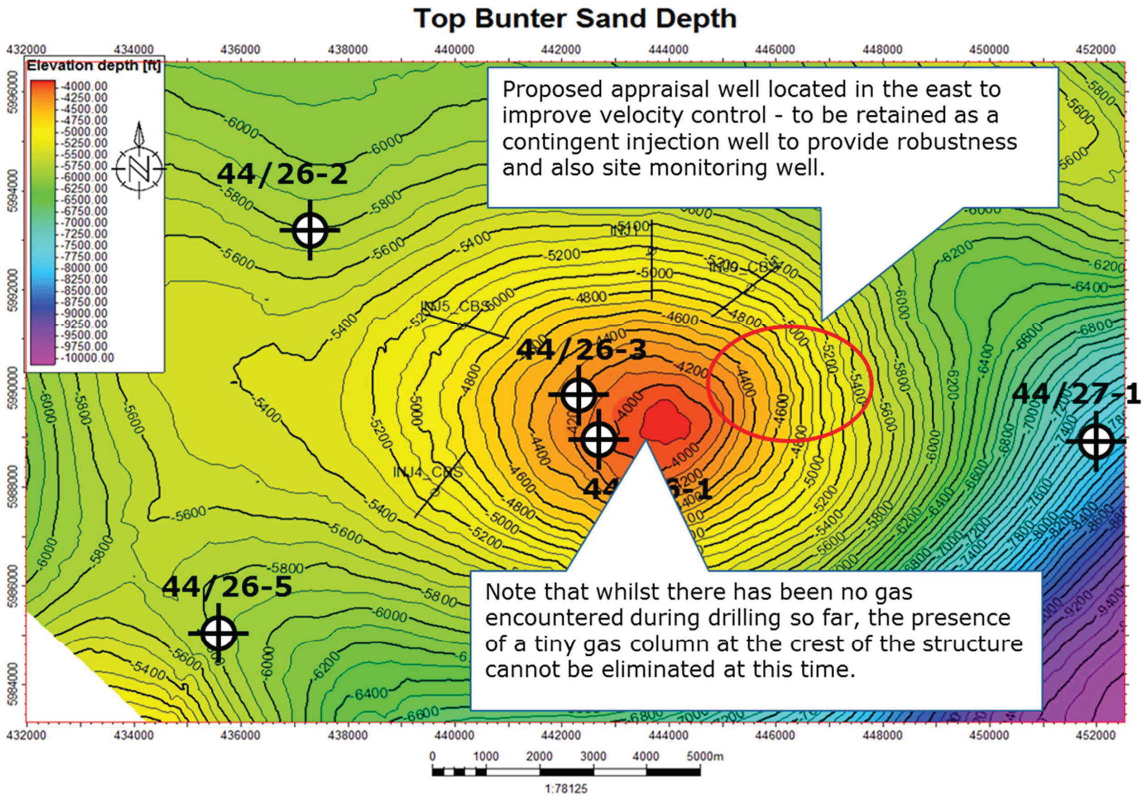


Figure 4-2 - Potential Location of Appraisal Well

5.0 Development Planning

5.1 Description of Development

The Bunter Closure 36 site is located within UKCS block 44/26 and 44/27, approximately 150km East of Barmston (Yorkshire coast) and 75km South East of the White Rose 5/42 location, and is partially overlying the deeper Carboniferous Schooner field.

The current base case for the Bunter Closure 36 CCS development consists of a new 160km 20" pipeline from Barmston to a newly installed Normally Unmanned Installation (NUI) located at the Bunter Closure 36 site. The location of Bunter Closure 36 also makes it an ideal candidate to be an extension (step out) to the White Rose CCS Project. The project is currently in FEED and has not yet been sanctioned. Therefore, a step out from White Rose has also been considered as an option herein.

The pipeline will be surface laid (laid on the seabed) and stabilised and protected by concrete weight coating. The NUI will take the form of a conventional 4-legged steel jacket standing in 75m water depth and supporting a multi-deck minimum facilities topsides. The steel jacket will be piled to the seabed and provide conductor guides which in conjunction with a 12 slot well bay will enable cantilevered jack-up drilling operations for the injection wells.

The installation will be controlled from shore via dual redundant satellite links with system and operational procedures designed to minimise offshore visits.

The installation will be capable of operating in unattended mode for up to 90 days with routine maintenance visits scheduled approximately every six weeks to replenish consumables (fuel, chemicals, etc.), and carry out essential maintenance and inspection activities.

5.2 CO_2 Supply Profile

The assumed CO_2 supply profile for the Reference Case is for a 7Mt/y to be provided from a future shore terminal at Barmston as illustrated in Figure 5-1.

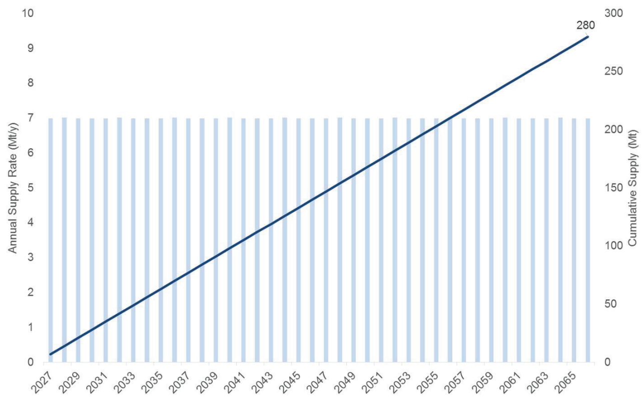


Figure 5-1 - CO_2 Supply Profile

5.3 Well Development Plan

The well placement strategy has been informed by considerations of geology, Bunter Closure 36 structural geometry, reservoir engineering modelling and the economics of development. Reservoir engineering results indicate that four wells are required over field life to inject the target CO_2 volumes. Four wells, located part way down the flank of the structure, towards the north-west, will result in the highest storage capacity being realised while achieving target injection rates. Wells are expected to have a useful life of approximately 20 years and consequently the current plan is to re-drill all wells around this time.

Whilst the wells will penetrate the full Bunter Sandstone interval, they will only be perforated in the zones 3 & 4 in the best quality sands to achieve the desired injection rates. Vertical wells would result in the point of CO_2 injection lying directly below the point of caprock penetration, thereby presenting the highest integrity risk (high concentration of CO_2 at the penetration point and high injection pressures). Deviated wells are therefore preferred, as they will also maximise the sand-face contact. Deviation has not been limited for wireline access in the injector wells, as regular well interventions are not planned, and well tractor technology allows access to highly deviated wells if intervention is required.

The planned “crescent” shaped well pattern is illustrated in Figure 5-2. The rationale for this pattern is provide in the Site Characterisation section 3.

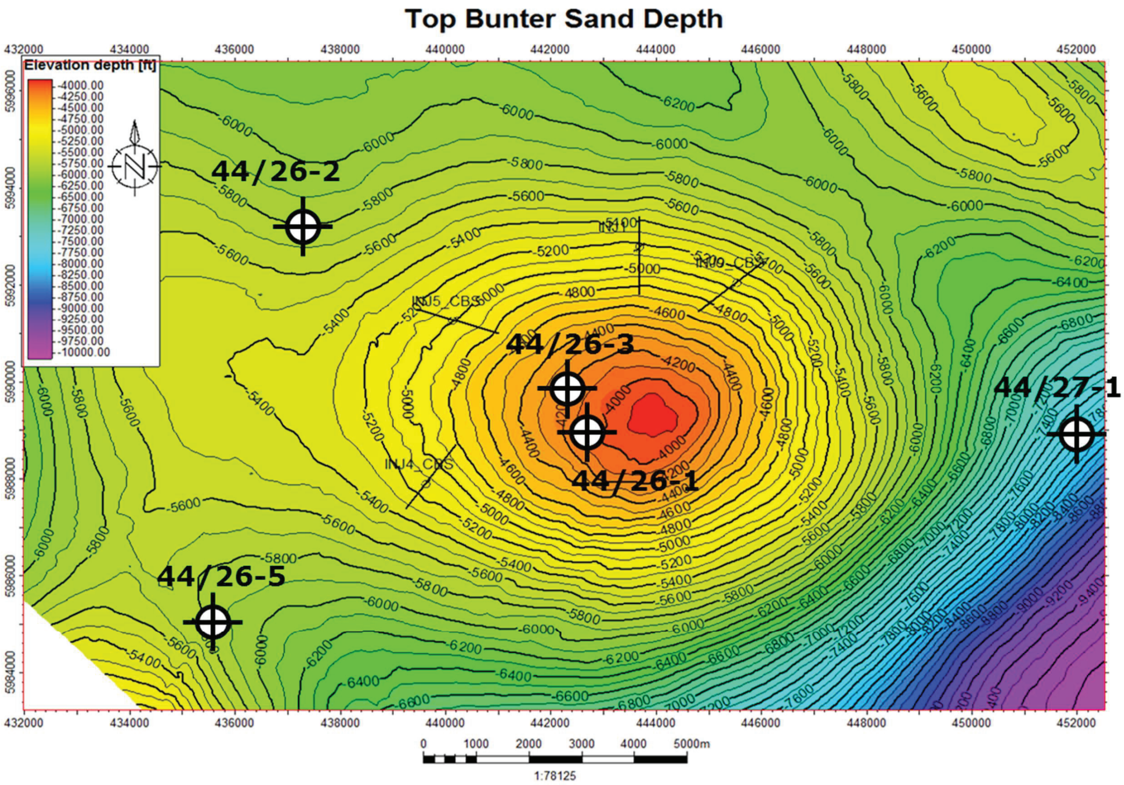


Figure 5-2 - Well Placement Strategy

5.3.1 Well Design

The key design criteria for the injection wells is that they must be capable of injecting 2.5Mt CO_2 in dense phase throughout the project life and require minimal intervention during that time.

The main features of the injection wells are summarised below:

1. Drillable from a NUI platform by standard North Sea jack-up.
2. Deviated (up to 77deg) in the tangent section, dropping to 60deg through the target formation.
3. Casing consisting of 26" conductor, 18-5/8" surface casing, 13-3/8" intermediate casing, 9-5/8" production casing and 7" production liner (cemented and perforated).
4. Completed with 5-1/2" production tubulars.
5. All flow wetted surfaces will be 13%Cr material.
6. Maximum FTHP will be 120 bar.
7. Maximum SITHP will be 80 bar.
8. Maximum WHT will be 16°C.

5.3.1.1 Well Construction

A platform surface location and well locations in the reservoir have been selected for conceptual well design purposes. The platform location has been selected to enable each well to be reached from a single platform. The coordinates of the surface location are:

5,989,400m North, 443,400m East

The following reservoir targets have been identified for the top of the Bunter Sand.

Target Name	TVDSS (m)	UTM North (m)	UTM East (m)
Bunter INJ1	1,359.3	5,991,223.7	444,000.0
Bunter INJ4	1,394.7	5,988,107.6	441,356.9
Bunter INJ5	1,347.1	5,990,901.3	442,178.2
Bunter INJ6	1.325.8	5,989,675.0	441,661.6

Table 5-1 - Well Locations

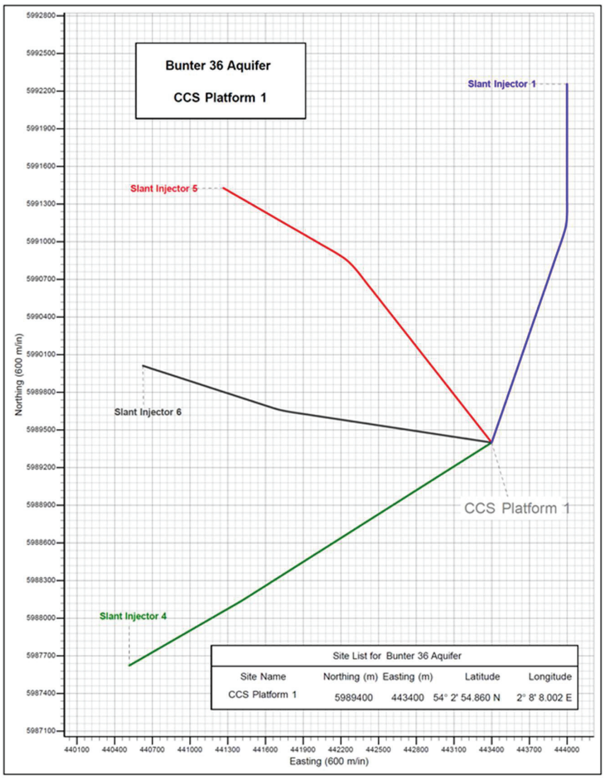


Figure 5-3 - Well Directional Spider Plot

The conceptual directional plans for the CO_2 injectors have been designed on the following basis:

1. The injection wells will be drilled as high angle slant wells.
2. The surface hole sections will be drilled vertically, to minimise the risk associated with shallow swelling clays and a weak Upper Chalk formation.
3. All wells will be kicked off directly below the surface casing shoe, with dog leg severity kept to 3.5° per 30m.
4. A build section will be drilled from the surface shoe to the depth at which inclination is sufficient to reach the identified reservoir target.
5. A turn and drop section will be drilled in the 12 ¼" hole section to reduce inclination to 60° at the top of the Bunter Sand while turning the well path onto the desired azimuth.
6. The reservoir section will be drilled as a tangent section, holding inclination at 60° to TD below the base of the Bunter Sand.

The directional profile for Injector 1 is shown in Figure 5-3 and Figure 5-4.

MD (m)	Inc	Azi	TVD	+N/-S	+E/-W	Dleg	Tface	VSect
0	0	0	0	0	0	0	0	0
450	0	360	450	0	0	0	360	0
1116	78	238	930	207	-237	3.5	238	387
3049	78	238	1340	1218	-1921	0	0	2275
3202	60	240	1395	1292	-2043	3.5	173	2417
4321	60	240	-1955	1777	-2883	0	0	3387

Table 5-2 - Injector 1 Directional Profile

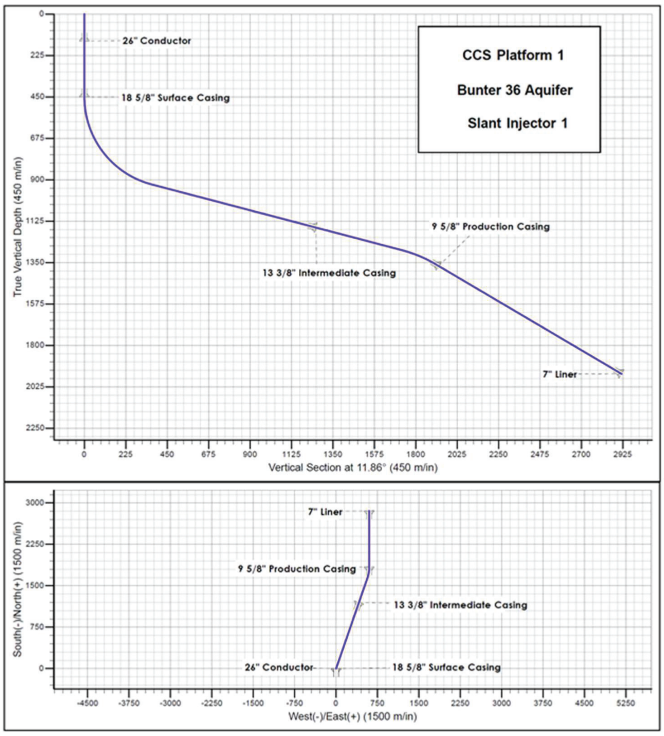


Figure 5-4 - Directional Profile for Injector 1

The lower completion consists of a 7" cemented and perforated liner. No sand control is incorporated following the recommendations of the sanding risk review.

5.3.1.2 Well Completion

Well performance modelling was used to identify the optimal tubing size and assess some of the factors that may influence well injection performance. The results of this work are provided in Section 3. In summary, 5-1/2" tubing can meet the required injection duty for each well without breaching the safe operating envelope of the reservoir.

For pure CO_2, with negligible water content (<300ppmv), carbon steel is suitable for the purposes of this study, it is assumed that the injected gas will be predominantly CO_2 with small concentrations of water, oxygen and nitrogen. Other minor impurities may exist however will not be present in high enough concentrations to cause corrosion/cracking issues. Consequently 13% chrome is assumed for all wetted components.

NBR nitrile elastomer can be used within the temperature range of -30 to 120°C (Appendix 9 and is therefore suitable for CO_2 injection wells. This elastomer gives the lowest operating temperature among the typical downhole elastomers.

The upper completion consists of a 5-1/2" tubing string, anchored at depth by a production packer in the 9⅝" production casing, just above the 7" liner hanger. Components include:

1. 5-1/2" 13Cr tubing (weight to be confirmed with tubing stress analysis work).
2. Tubing Retrievable Sub Surface Safety Valve (TRSSSV).

3. Deep Set Surface-controlled Tubing-Retrievable Isolation Barrier Valve (wireline retrievable, if available).
4. Permanent Downhole Gauge (PDHG) for pressure and temperature above the production packer.
5. Optional DTS (Distributed Temperature Sensing) installation.
6. 9-5/8" Production Packer.

The DTS installation will give a detailed temperature profile along the injection tubulars and can enhance integrity monitoring (leak detection) and give some confidence in injected fluid phase behaviour. The value of this information should be further assessed, if confidence has been gained in other projects (tubing leaks can be monitored through annular pressure measurements at surface, leaks detected by wireline temperature logs and phase behaviour modelled with appropriate software).

Appendix 9 provides a detailed discussion of the well construction and well completion design.

5.3.2 Number of Wells

Four operational wells are required to inject the anticipated 7Mt/y of supplied CO_2. A back-up well is included within the plan to provide a degree of redundancy. This is in the anticipation that the store operator will have a "take or pay" style contract with the CO_2 supplier and therefore likely to face significant penalties if unable to inject the contract amount.

The number of operational wells was identified following extensive reservoir simulation work, and this work is discussed in Section 3 of this report.

5.3.3 Drilling Programme

The Summary well drilling and completion schedule for the life of the project is illustrated in Table 5-3.

	Year											
Well Type	-2	0	2	5	10	15	20	22	25	30	35	40
Appraisal Well	1											
Injection Wells		4	1				4	1				
Workover							1					
Local Sidetrack				1		1			1		1	
Abandonment												11

Table 5-3 – Proposed Drilling Schedule

5.3.3.1 Well Construction Programme

Section	Casing	Comments
Conductor (Driven)	26", 75m below mudline	
Surface (22") **Water Based Mud**	18⅝", 450m Carbon steel Cemented to the mudline	Seal of selling clays above Chalk
Intermediate 1 (17½") **Water Based Mud**	13⅜", 1160m Carbon steel Cemented to 100m inside previous casing shoe	Top of Cromer Knoll & seal off the often problematic Chalk section
Intermediate 2 (12¼") **Oil Based Mud**	9⅝", 1330m Carbon steel above packer 13Cr below packer Cemented to 200m inside previous casing shoe	20m below Top Bunter to allow Rot Halite & Speeton Clay section to be fully isolated from reservoir
Injection (8½") **Oil Based Mud**	7", Total Depth 13Cr Cemented to 200m inside previous casing shoe.	Into Top of Bunter Shale

Table 5-4 - Well Construction Programme

5.4 Injection Forecast

Injection commences in 2027 and is assumed to continue for 40 years, the final year of injection is 2066.

The injection forecast for the Reference Case is for 7Mt/y over the assumed infrastructure life of 40 years which results in a cumulative injection of 280Mt CO_2. This forecast can be maintained by 4 active injection wells with an additional well held in reserve to provide redundancy.

A tabulation of the profile is provided in Table 5-5.

Year	Rate (Mt/y)	Total (Mt)	Year	Rate (Mt/y)	Total (Mt)	Year	Rate (Mt/y)	Total (Mt)	Year	Rate (Mt/y)	Total (Mt)
2027	7	7	2037	7	77	2047	7	147	2057	7	217
2028	7	14	2038	7	84	2048	7	154	2058	7	224
2029	7	21	2039	7	91	2049	7	161	2059	7	231
2030	7	28	2040	7	98	2050	7	168	2060	7	238
2031	7	35	2041	7	105	2051	7	175	2061	7	245
2032	7	42	2042	7	112	2052	7	182	2062	7	252
2033	7	49	2043	7	119	2053	7	189	2063	7	259
2034	7	56	2044	7	126	2054	7	196	2064	7	266
2035	7	63	2045	7	133	2055	7	203	2065	7	273
2036	7	70	2046	7	140	2056	7	210	2066	7	280

Table 5-5 - Injection Profile

5.4.1 Movement of the CO_2 Plume

CO_2 will be injected in the dense phase at between 1350 and 1700m tvdss into the Bunter Closure 36 site. Under the force of injection the CO_2 can be pushed downwards but ultimately the CO_2 will migrate to the highest point in the structure, as it is less dense than saline water.

Immediately after the cessation of injection the CO_2 has moved updip and has reached the crest of Bunter zone 4, as illustrated in Figure 5-5. The CO_2 migrates vertically from the injection site and then migrates laterally in the upper layers below the pressure barrier. The concentration is greatest in the regions relatively close to the injection well locations in Bunter zones 4 and 5

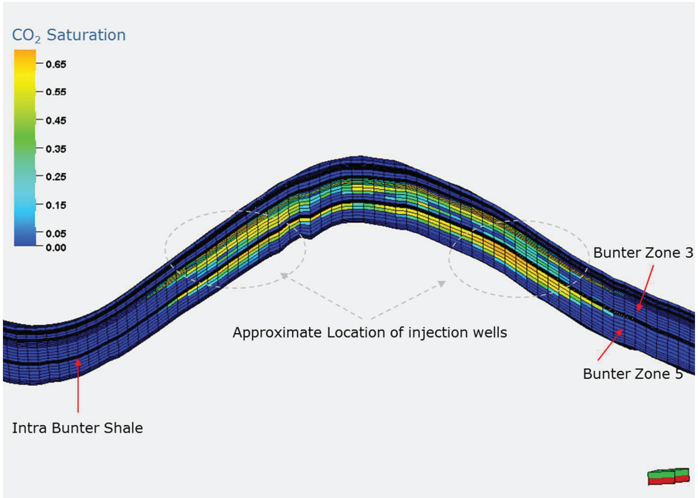


Figure 5-5 - CO_2 Plume when Injection Ceases

At the end of injection the plume is fairly well dispersed around the whole of the anticline, as illustrated in Figure 5-6.

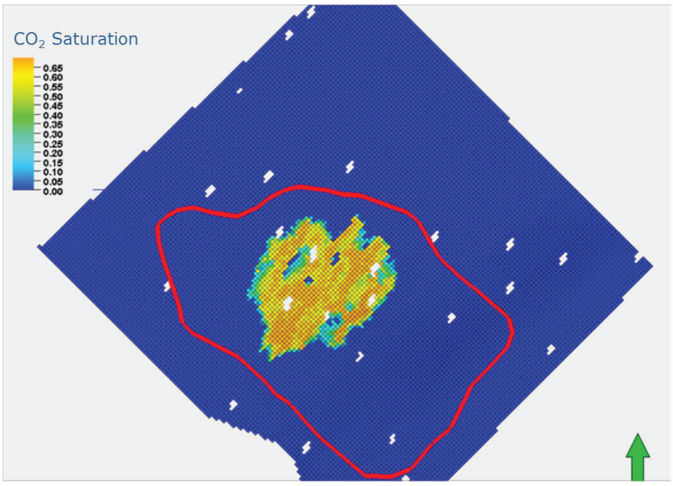


Figure 5-6 - Areal Extent of Plume when Injection Ceases

1000 years after injection has stopped more CO_2 has migrated to the crestal areas and the areal extent is much reduced, as illustrated in Figure 5-7 and Figure 5-8.

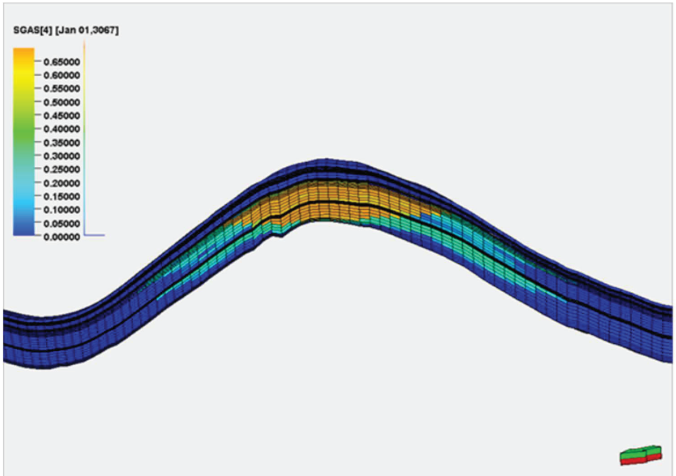


Figure 5-7 - Vertical Extent of Plume after 1000 years

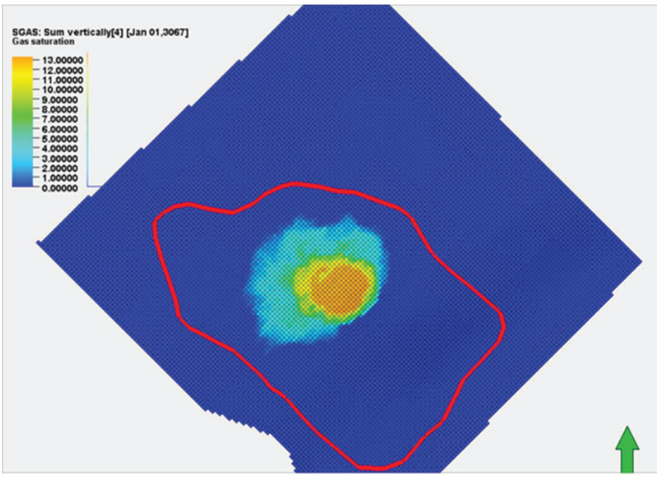


Figure 5-8 - Areal Extent of Plume after 1000 years

5.5 Offshore Infrastructure Development Plan

The optimum platform location for the Bunter Closure 36 NUI has been determined through drilling studies, UTM coordinates are presented in the table below.

Platform	UTM Coordinates	
	Eastings (m)	Northings (m)
Bunter Closure 36 NUI	443400	5989400

Table 5-6 - Platform Location

5.5.1 CO_2 Transportation Facilities

This section provides an overview of the Bunter CO_2 transportation (pipelines) development plan. CO_2 will be transported in the liquid (dense) phase.

5.5.1.1 Pipeline Routing

The location of Bunter Closure 36 makes it an ideal candidate to be an extension (step out) to the White Rose CCS Project (currently in FEED). The White Rose project proposes to transport CO_2 from Barmston to a NUI at 5/42. Cognisant of this and the fact that White Rose is not as yet a sanctioned project there are two options for transporting CO_2 to Bunter Closure 36:

1. Install a new pipeline from Barmston to Bunter Closure 36;
2. Install a new pipeline from White Rose (5/42) to Bunter Closure 36.

The White Rose NUI location coordinates were sourced from the White Rose PON 16 (National Grid Ltd; Carbon Sentinel Ltd; Hartley Anderson Ltd, 2015). Figure **5-9** shows the two routes.

Figure 5-9 - Pipeline Route Options

It can be seen that a new pipeline from Barmston is significantly longer than a step out from White Rose, requiring a pipeline of approximately 160km compared to 80km and resulting in a significant increase in procurement and installation costs for the CO_2 transportation system (pipeline).

Given there is currently no certainty that the White Rose CCS development will be sanctioned, the base case development plan assumed for Bunter Closure 36 is a direct pipeline from Barmston. It is deemed prudent to retain Barmston as the nominated landfall/beachhead given the level of engineering that has been done in support of the White Rose CCS development FEED. Consistent with the plan outlined in the White Rose Environmental Impact Statement (National Grid Carbon Ltd; Carbon Sentinel Ltd; Hartley Anderson Ltd, 2015) the Bunter pipeline will “cross the coast using micro-tunnelling or directional drilling techniques in order to minimise coastal erosion and any interaction with the cliffs. The pipeline will be taken offshore using either a cofferdam constructed on the beach/subtidal area, or using a caisson (which can be constructed entirely sub-tidally).” The pipeline will be trenched in the nearshore out to 30m depth (approximately 15km offshore).

The direct pipeline route from Barmston to Bunter Closure 36 has been selected to minimise the pipeline route length while avoiding existing facilities (Cleeton and Ravenspurn), maintaining appropriate crossing angles and maximizing future expansion potential by ensuring the route passes in the vicinity of nearby potential future storage sites (further discussion on this is included in Section 5.6).

Figure 5-10 – Pipeline Crossings, Direct Route

There are five pipeline crossings along this route, summarised in the table below.

Pipeline	Surface Laid / Trenched	Operator
44" Langeled Pipeline	Surface Laid	Gassco
Cleaton – Whittle Umbilical	Trenched and Buried	BP
34" Shearwater to Bacton	Surface Laid	Shell UK
24" Esmond to Bacton	Surface Laid	Perenco
4" Theddlethorpe to Murdoch	Surface Laid	Conoco Phillips

Table 5-7- Pipeline Crossing for Direct Pipeline

It is worth noting that the Dogger Bank wind farm project is currently ongoing, with the UK government granting planning consent for the first and second phase of the project in 2015 (Figure 5-11). Should this project be sanctioned it may necessitate a re-route to the North adding 5-10km to the overall route length, as shown below (an approximation of the round 3 wind farm zone is shown in yellow).

A full desktop study will also be required to confirm the pipeline route and ensure that all seabed obstructions (wells, platforms, pipelines, umbilicals and cables etc) and seabed features (rocks, sand waves, pockmarks, mud slides etc) are identified and accounted for appropriately.

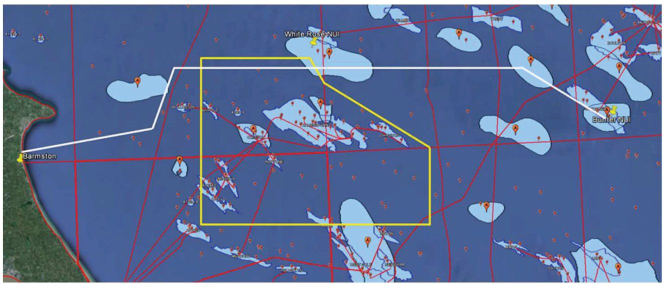


Figure 5-11 - Proximity of Dogger Bank Wind Farm Area

Should the White Rose CCS development project come to fruition it would facilitate the shorter step out to Bunter Closure 36. Figure 5-12 shows the 83km pipeline route between White Rose 5/42 and the Bunter Closure 36 NUI. The pipeline route shown below minimises route length and the number of pipeline crossings while retaining options for future expansion/step out to future storage sites (further discussion on this is included in Section 5.7).

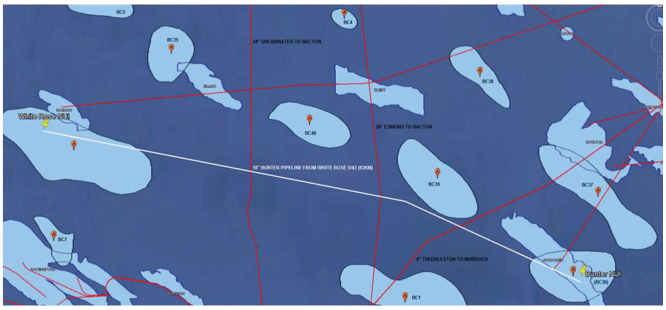


Figure 5-12 - Pipeline Crossings from 5/42

The pipeline crossings along this route are summarised in the table below.

Pipeline	Surface Laid / Trenched	Operator
34" Shearwater to Bacton	Surface Laid	Shell UK
24" Esmond to Bacton	Surface Laid	Perenco
4" Theddlethorpe to Murdoch	Surface Laid	Conoco Phillips

Table 5-8 - Pipeline Crossings from 5/42

5.5.1.2 Preliminary Pipeline Sizing

Dedicated Bunter 36 Pipeline

Preliminary line sizing calculations have been performed to determine the Bunter pipeline outer diameter

A minimum arrival pressure of 85-106 bar (flowing well head pressure, FWHP) has been calculated for the Bunter Closure 36 wells. The required mass flow rate of 7MT/Year has been selected to ensure a sustainable plateau rate over the 40 year design life (280 MT total injected). It has been assumed that the Barmston pump station delivers up to 200 bar in pressure therefore the maximum pressure drop is in the region of 94 bar).

The pipeline route length is 160km, and passes by several other Bunter Closures that may be options for future expansion, there is therefore merit in pre-investing in an increased ullage (larger) pipeline from Barmston with future Tie-In Structures (valved tees) at set locations along the route to facilitate future expansion (discussed further in Section 5.7).

It can be seen from Figure 5-13 and Table 5-6 that a 20" pipeline from Barmston is sufficient, and at a flow rate of 7MTPa results in a pressure drop of approximately 40 bar. This increases to approximately 60 bar at 8.5 MTPa, and 90 bar at a flow rate of 10.5 MTPa (1.5 x 7 MTPa, i.e. a 50% ullage) which will be approaching the limit of a 20" pipeline and beyond which additional pumping will be required. It is worth noting that this calculation assumes the full ullage along the full pipeline route of 160km.

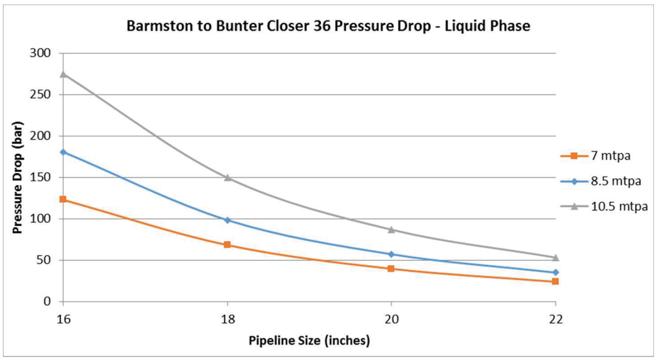


Figure 5-13 - Pipeline Pressure Drops

The Bunter pipeline is sufficiently large (OD > 16”) that is does not require burial or rock-dumping for protection purposes. Instead it is proposed the pipelines be surface laid and protected/stabilised with concrete weight coating, which necessitates installation by S-lay. The near shore section will require burial for stability against wave and current forces.

5/42 Tie Back

Preliminary line sizing calculations have also been performed to determine the outer diameter of a step out pipeline from the White Rose 5/42 platform, and to confirm that there is sufficient ullage in the 24” White Rose pipeline from Barmston.

A minimum arrival pressure of 85-106 bar (FWHP) has been calculated for the Bunter Closure 36 wells. As discussed above, the required mass flow rate of 7MT/Year has been selected to ensure a sustainable plateau rate.

Further details are provided in Appendix 11.

5.5.1.3 Subsea Isolation Valve (SSIV)

For conservatism development costs include for an actuated piggable ball valve SSIV structure being installed on the 20” pipeline adjacent to the Bunter NUI Jacket. The requirement for SSIVs to be installed on CO_2 service pipelines feeding a normally unmanned installation (NUI) is not clear-cut. The Peterhead CCS Project Offshore Environmental statement (Shell, 2014) states that a new SSIV will be put in place to support the proposed project and provide a means of isolation in the event of loss of containment close to the platform. The Offshore Environmental Statement for the White Rose CCS project (National Grid Carbon, et al., 2015) states that the White Rose 4/52 pipeline will not have a subsea isolation valve (SSIV). Comparatively the inventory of the proposed White Rose pipeline is greater than that of Goldeneye. The requirement for an SSIV for the Bunter pipeline should be fully appraised in FEED. The Bunter platform import riser will be fitted with an emergency shutdown valve (ESDV) and the riser located so as to mitigate risk of collision damage by support vessels. Full dispersion modelling will be required in order to position the ESDV and Riser and any temporary refuge facilities specified accordingly in compliance with PFEER regulations. If an SSIV is deemed necessary for the Bunter pipeline then consideration must be given to the pressure rating of the piping, spools and riser to allow for thermal expansion of any potential trapped CO_2 inventory.

5.5.2 Offshore CO_2 Injection Facilities

It is proposed that CO_2 is injected into Bunter Closure 36 from a single Normally Unmanned Installation (NUI Platform) with a 12 slot well-bay that will enable Jack Up drilling and completion of dry injection trees. A NUI platform is considered as both the most economical and technically suited development concept for Bunter Closure 36.

The key input parameters used to size and cost the NUI platform for Bunter Closure 36 are listed below and a master equipment list is provided in:

NUI Jacket:

1. 75m water depth
2. 40 year design life
3. 10,000 year return wave air gap
4. Jacket supported conductor guide frames
5. J-tube and Riser to facilitate future tie back

NUI Topsides:

1. Minimum Facilities Topsides
2. Diesel driven generator package
3. Well and valve controls HPU and MCS package
4. HVAC package
5. Low temperature valving and manifolding pipework package
6. Sampling and Metering package
7. No compression / pumping
8. Consumable tanks sized for 90 days self sustained operations

Requirement	Quantity/Value	Comment
Design Life	40 Years	4 wells + 1 spare injector throughout field life with full replacement after 20 years
Platform Well Slots	12	
Platform Wells	12	
Trees (XT)	10	-
Diesel Generator	3	1 to run full time, 2nd when manned, 3rd as standby
Satellite Communications	2 x 100%	Dual redundant VSAT systems
Risers	2	1 spare for future tie-back/expansion
J-Tube	2	For future tie-back/expansion
Subsea Isolation Valve (SSIV)	1	SSIV at Bunter only
Temporary Refuge	1	4 Man
Lifeboat	1	TEMPSC and Life rafts
Helideck	1	-
Pig Launcher Receiver	Permanent	-
CO_2 Filters	Yes	Bypassable
Crane	1	Electric crane
Vent Stack	1	Low Volume
Leak detection and monitoring	1	
Chemical Injection	MEG	MEG for start-ups/restarts c/w storage, injection pumps and ports. Temporary Water Wash Facilities with Inert Gas for pressurisation
General Utilities	Yes	Open hazardous drains etc.

Table 5-9 - Master Equipment List

A process flow diagram of the Bunter Closure 36 development is presented in Figure 5-14.

CASE 1: BUNTER CLOSURE 36

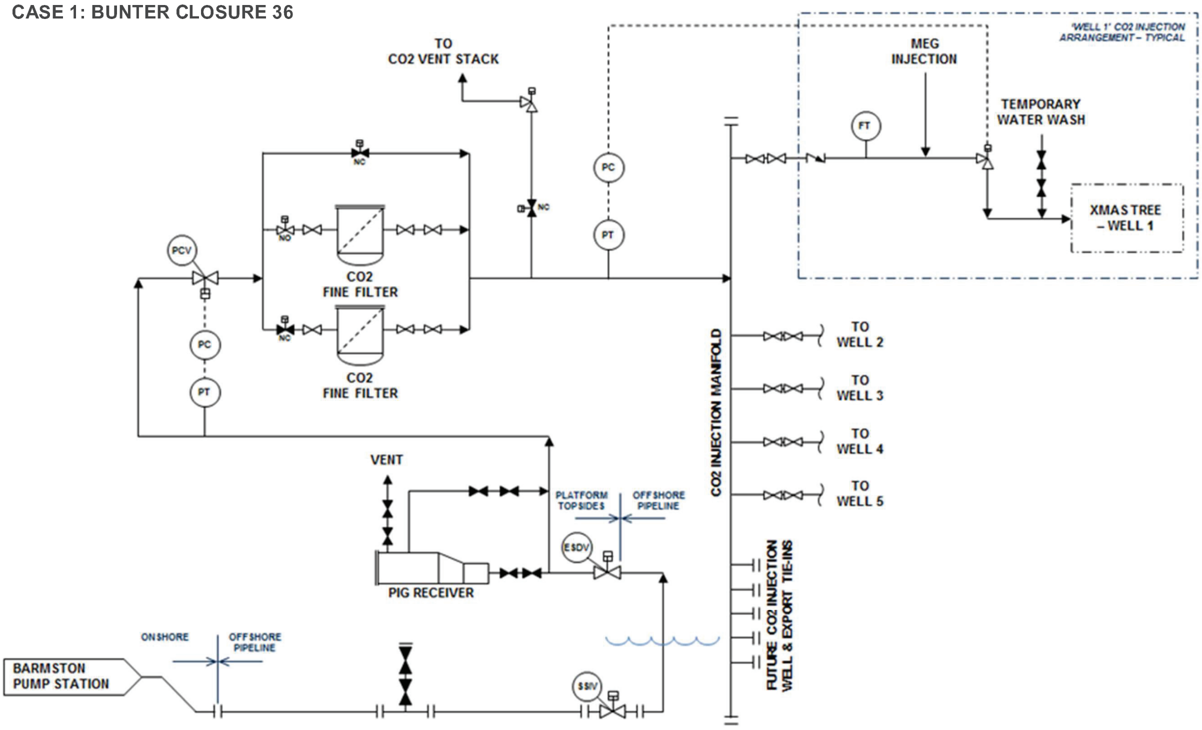


Figure 5-14 - Process Flow Diagram

5.5.2.1 Platform Infrastructure

Jacket Design

A conventional 4-legged Steel Jacket has been assumed. The jacket will be piled to the seabed and will be sufficiently tall to ensure an air gap is maintained between the topsides structure and the 10,000 year return period wave crest height. The Jacket would be protected by sacrificial anodes and marine grade anti-corrosion coat paint.

Jacket Installation

The Jacket will be fabricated onshore, skid loaded onto an installation barge, towed to site, and launched. Mudmats will provide temporary stability once the jacket has been upended and positioned; with driven piles installed and grouted to provide load transfer to the piled foundations.

Topsides Design

The Installation topsides are proposed to be constructed as a single lift topsides module. A multi-level topsides module consisting of a Weather Deck, a Mid-level, a lower Cellar Deck and a cantilevered Helideck has been assumed.;

The Weather deck will be of solid construction to act as a roof for the lower decks, it will provide a laydown area for the crane and house the HVAC package and VSAT domes. A Helideck will be cantilevered out over the Weather Deck.

The Mid-level deck will only partially cover the topsides footprint and will serve to house the Manifolding pipework, and Pig Receiver.

The Cellar Deck will house the Wellhead Xmas Trees, the Power Generation Package, the Hydraulic Power Unit, Process equipment, Chemical and Diesel tanks, Control and Equipment Room and Short Stay accommodation unit.

The Jacket and topsides will be sized and arranged so as to enable Jack-Up set up on two faces, in order to access the 12 well slots.

Platform Power

Platform power will be provided by diesel-fueled generators. Under normal unmanned operations a single generator will power the platform. When manned the electrical load increases (crane operations, HVAC etc) and two generators will provide the power with the third acting as a spare. Diesel storage will be sized to permit 90 days unmanned operation.

Topsides Process

The primary Platform Injection facilities will consist of a topsides Emergency Shutdown Valve (ESDV), a pressure control valve (PSV) which will serve to safeguard the pipeline pressure and maintain the CO_2 in the pipeline in dense phase, Fines Filters that will prevent solid contaminates entering the injection well bores, a vent stack to enable blowdown of the topsides pipework for maintenance, and an injection manifold which will facilitate injection of the CO_2 to the respective wells. Topsides pig receiving facilities will also be provided to enable periodic pipeline integrity monitoring, there is no foreseen requirement for operational pigging. All the topsides process pipework will use low temperature stainless steel materials in the event that a low pressure event occurs (i.e. venting).

Drains

An open hazardous drains system will exist to drain the drip trays from equipment in Environmental Pollutant service i.e. the fuel and chemical tanks, power generation package, and HPU. These drain sources shall be positioned below the weather deck to minimise rainwater runoff from the equipment into the hazardous open drain system. The Hazardous open drains tank shall be emptied during routine maintenance. There is no foreseen requirement for a closed drains system.

Closed Loop Hydraulic system

Topsides and tree valves will be hydraulically actuated and will utilise a water based hydraulic fluid. Dual redundant (2x100%) Hydraulic Power Units (HPUs) will be provided to allow offline maintenance.

Crane

An Electric Crane will enable load transfer between vessel and NUI, and enable load transfer between the working decks of the Installation.

5.5.2.2 Rationale for a Platform-based Development

The following provides a brief overview of why a NUI Platform comprising a steel jacket and topsides has specifically been selected as the reference case for the Bunter Closure 36 development.

The Bunter Closure 36 development requires 10 injection wells over the field life. The proposed trajectories of the slant injector wells is such that they can be drilled from a single drill centre. The water depth at the proposed drilling location of Bunter Closure 36 is 75m. This is sufficiently shallow to enable the wells to be drilled by a Jack Up drill rig cantilevered over a platform with 12 well slots (10 + 2 spare).

From a commercial viewpoint the design, build and installation of a NUI platform will exceed the CAPEX of an entirely subsea development however this will be eroded by the increased CAPEX of drilling subsea wells (approximately 25% more expensive to drill and complete than dry wells) and the provision of power and control/chemical supplies from a suitable nearby host facility or from shore.

Platform based wells will also improve the availability of the injection wells due to more readily achievable and inexpensive maintenance and well intervention. The OPEX for intervening on subsea wells will typically exceed that of dry wells by an order of magnitude. A platform also enables the provision of enhanced process capabilities, including (where required) the provision of the following which are not readily achievable with subsea wells:

1. Pre-injection filtering (filters pipeline corrosion / scaling products), which becomes more critical for a long pipeline and is especially critical when planning matrix (as opposed to fracture) injection.
2. Choke heating.
3. Physical sampling facilities to ensure CO_2 injection quality.
4. Pressure monitoring of all well casing annuli for integrity monitoring.

Providing the following process facilities to subsea wells is possible but will be more costly than for platform based wells:

1. Process monitoring, and well allocation metering for reservoir management.
2. Process chemical injection of MEG, and N2 for transient well conditions and wash water for halite control.
3. Pig receiver.
4. Future connections are easier as the connections are above water thereby avoiding water ingress into existing systems and it's easier to dry any future pipelines.

Due to the requirement of a heavy lift vessel to remove the platform and topsides at the end of field life the ABEX costs associated with decommissioning a NUI platform is likely to exceed that of a subsea development, however the P&A

(plug and abandonment) of subsea wells will be approximately 25% more costly than the P&A of platform wells

5.6 Other Activities in this Area

There are several hydrocarbon fields in the vicinity of Bunter Closure 36, and along the pipeline route. The nearest of these are shown in the figures in Section 5.4.1.1. The pipeline is routed to avoid the Cleeton and Ravenspurn facilities (and associated tie-backs). The closure itself overlies the Schooner gas field, operated by Faroes Petroleum and tied back 28km to the Murdoch platform to the North East via a 16" pipeline. The Dogger Bank wind farm project is currently ongoing, with the UK government granting planning consent for the first and second phase of the project in 2015. Should this project be sanctioned it may necessitate a re-route of the pipeline (further information is included in Section 5.5.1).

Other activities in the area that are pertinent to the Bunter development are fishing and shipping. Fishing and shipping intensity should form part of the future work.

A protection philosophy should be produced for the Bunter development, the results of which should be adopted to ensure all risks are identified and mitigated/minimized. To ensure the risks of any interaction with dropped anchors or fishing gear are minimized it is also recommended that any new infrastructure associated with the Bunter development is entered into fishing and marine charting systems to notify other marine users.

5.7 Options for Expansion

A future tie-in could be facilitated via pre-investment in future Tie-In Structures (valved tees) at set locations.

There is merit in pre-investing for future expansion, particularly if a new pipeline from Barmston is required. A future tie-in could be facilitated via pre-investment in future Tie-In Structures (valved tees) at set locations. Valved tees are recommended as this will allow future connections without the need for purging and flooding the existing pipeline. The structures will consist of a bar tee, dual valve arrangement for isolation and will likely be piled with structural protection for any fishing gear interaction. An alternative to providing tee structures is to perform a hot-tap operation. This is a considerably more expensive operation however it does limit pre-investment and allows for flexibility for selection of the connection location.

There are a number of additional Bunter Closures and depleted gas fields that are located along the pipeline route in the vicinity of Bunter Closure 36 that could be potential step out sites for expansion. The figure below shows the chosen location for the Bunter NUI and the surrounding Bunter Closures.

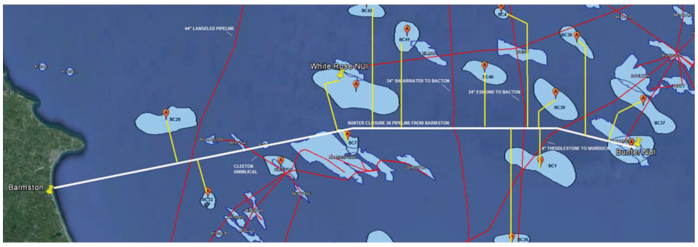


Figure 5-15 - Options for Expanding the Development

The distances, both approximate distance from the Bunter NUI to the centre of closure and the distance to a potential tie-in structure location along the pipeline route (shown in yellow) have been extracted from CO2Stored data and are summarised in the table below.

Bunter Closure	Approximate Distance from Closure 36 (NUI to Center of Closure)	Approximate Distance from Bunter Closure 36 Pipeline (Tee)	WP3 Ranking (Top 20)
1	25km	12km	Not Ranked
4	50km	28km	Not Ranked
5	65km	37km	Not Ranked
7	75km	7km	Not Ranked
26	40km	32km	Not Ranked
29	Not Feasible	12km	Not Ranked
32	Not Feasible	12km	Not Ranked
35 (5/42)	83km	10km	Not Ranked
37	12km	13km	Not Ranked
38	32km	20km	Not Ranked
39	25km	6km	Not Ranked
40	45km	13km	17
41	67km	22km	Not Ranked
42	80km	28km	Not Ranked

Table 5-10 - Options for Expansion

Note that the distances for a White Rose 5/42 (Closure 35) step out are based on the platform location and pipeline route as discussed in Section 1.5.

5.8 Operations

The Bunter Closure 36 Development will inject CO_2 at a constant injection rate of 7Mt/y, via 4 wells plus 1 spare injector throughout field life.

The Bunter Closure 36 platform will be a Normally Unmanned Installation (NUI), and will be capable of operating unattended for approximately 3 months (90 days). The NUI will be controlled from the beach, utilizing dual redundant satellite links.

The NUI will require regular IMR (Inspection, Maintenance and Repair), and it is envisaged that visits will typically be required every six weeks. Routine maintenance activities will include the following:

1. Replenishing fuel;
2. Replenishing chemicals;
3. IMR of diesel generators;
4. IMR of emergency power generation system;
5. IMR of lifeboats;
6. IMR of telecommunications system (satellite comms);
7. IMR of mechanical handling (crane);
8. IMR of HVAC system;
9. IMR of venting system;
10. IMR and certification of metering system for CO_2 injection;
11. IMR of chemical injection system including pumps, tanks and associated equipment;
12. IMR of CO_2 filters;
13. IMR of hazardous open drains (drain tanks, heaters and pumps);
14. IMR of non-hazardous open and closed drains (drain tanks, heaters and pumps);
15. IMR of fire and gas detection systems, fire pumps and firewater systems;
16. IMR of nitrogen system;
17. Painting (fabric maintenance);
18. Cleaning.

The pipeline from Barmston will also require regular IMR. This will include regular (typically bi-annual) surveys (ROV) of the pipeline to confirm integrity. Although inline pigging facilities are available the frequency will be minimal subject to an integrity management risk assessment of the control of the CO_2 quality.

5.9 Decommissioning

The decommissioning philosophy assumed for the Bunter facilities is as follows:

Note that this philosophy is subject to the outcome of the comparative assessment process and subsequent approval by DECC.

- Wells plugged and abandoned.
- Topsides facilities are cleaned, prepared and disconnected.
- Removal of Topsides (reverse installation).
- Steel jacket completely removed and taken ashore for dismantling and recycling.
- Pipeline is cleaned and left in place, part end recovery and ends protected by burial/rock dump.
- Bunter pipeline (surface laid) is assumed to be covered by the UK fisheries offshore oil and gas legacy trust fund.
- Pipeline spools to be recovered.
- Subsea structures to be recovered (SSIV).
- Subsea concrete mattresses and grout bags recovered.

The crossed pipelines are discussed in Section 5.5.1. Note that if any of the crossed pipelines are still in service the decommissioning of the pipeline crossing will likely have to occur as part of the associated crossed pipeline field decommissioning

5.10 Post Closure Plan

The aim of post-injection/closure monitoring is to show that all available evidence indicates that the stored CO_2 will be completely and permanently contained. Once this has been shown the site can be transferred to the UK Competent Authority.

In Bunter Closure 36 this translates into the following performance criteria:

1. The CO_2 has not migrated laterally or vertically from the storage site. (This is not necessarily the original site, if CO_2 has migrated then the site will have been extended and a new volume licensed.)
2. The CO_2 within the structural containment storage site has reached a gravity stable equilibrium. Any CO_2 in an aquifer storage containment site is conforming to dynamic modelling assumptions – i.e. its size and rate of motion match the modelling results.
3. The above are proven by two separate post closure surveys – with a minimum separation of five years.

The post closure period is assumed to last for a minimum of 20 years after the cessation of injection. During this time monitoring will be required, as detailed in Appendix 7.

5.11 Handover to Authority

Immediately following the completion of the post closure period the responsibility for the Bunter Closure 36 CO_2 storage site will be handed over to the UK Competent Authority. It is anticipated that a fee, estimated at ten times the annual cost of post closure monitoring will accompany the handover.

5.12 Development Risk Assessment

The following development risks have been identified:

Survey data: A full pipeline route survey is required. There is a risk that this may identify unknown seabed obstructions or features that will necessitate route deviations.

CO_2 composition/chemistry: This is unknown and therefore there is a risk of it being significantly different than that assumed throughout this study, with unforeseen consequences.

The following opportunities have been identified and should be considered as part of further work:

Value Engineering: A value engineering exercise should be carried out to assess all equipment to ensure all specified equipment is technically justified in its application and not included on the basis of accepted oil and gas practice. Some examples are provided below.

Wells: A significant reduction in OPEX could be achieved by increasing the flow rates through the wells (and thus reducing design life).

CO_2 Screens: A reduction in CAPEX and OPEX could be realized by removing the requirement for CO_2 screens.

Venting: Opportunity to remove the requirement for venting, with all venting performed from the beach.

Pig Receiver: Temporary v Permanent. Should permanent facilities not be required this will result in a reduction in topsides weight and the associated savings in CAPEX/OPEX.

SSIV: Requirement for an SSIV can be challenged during FEED and potentially omitted which would reduce the requirement for increased pressure rating of the riser and associated piping between SSIV and ESDV, to account for thermal expansion of riser inventory during shut in.

SSIV Location: If it is not possible to remove the requirement for an SSIV the location should be optimized with consideration to the impact of the riser volume on temporary refuge specification.

Jacket Weight: A reduction of between 10 and 15% in Jacket weight may be achieved by adopting a "twisted base" or "floating diamond" configuration, albeit at the expense of more complex nodes towards the base of the jacket, which may require castings to achieve desired fatigue lives.

Helideck: A significant reduction in cost may be realised by removing the Helideck and relying on Walk to Work vessels for platform visits. Helidecks have typically been specified for hydrocarbon producing NUI's due to the requirement for personnel to be on the facility to restart production following a shutdown, and the associated cost of deferred production until the restart can be enacted. Removing this requirement by enabling remote restart of CO_2 injection will improve uptime and negate the requirement for a Helideck for platform visits.

Pipeline Route: The pipeline has been routed around the existing infrastructure that make up the Ravenspurn and Cleeton developments. It is likely that these fields will be decommissioned (estimated COP for these fields is 2020) and there may therefore be an opportunity for a reduction in pipeline route length and associated costs.

Pipeline design: Pipeline design to be progressed to confirm wall thickness and remove uncertainties in mechanical design. Pipeline design to be performed to either PD8010 Part 2 or DNV OS F101, and should follow the requirements of DNV RP J202.

Geotechnical data – site surveys result in complex foundations and increased costs. Ensure early development of desktop study and geotechnical testing programme performed/supervised by experienced geotechnical specialists.

Risk of pipeline leak/rupture – ensure pipeline is designed in accordance with DNV RP J202 Design and Operation of CO_2 pipelines, for the full range of design conditions, with an appropriate corrosion and fishing protection measures, integrity management plans and operating procedures.

Monitoring requirements may result in a well offset from the platform resulting in subsea controls tie-back, resulting in an increase in costs.

Legislation – development of UK legislation could result in modifications to facilities requirements (e.g. emissions, safety case requirements, MMV).

Seabed conditions may require expensive seabed intervention to avoid pipeline instability and free-spanning. MetOcean and geophysical surveys are required to confirm seabed conditions.

Barmston has been selected as the location for the land fall following National Grid Carbon's White Rose FEED conclusions. Subsequent supply locations may be identified which may change the landfall and pipeline routing.

6.0 Budget & Schedule

6.1 Schedule of Development

A level 1 schedule (up to first CO_2 injection) has been produced and is included in Figure 6-1. The schedule is built up using the same breakdown structure as the cost estimate to allow for cost scheduling and is based on the following assumptions:

- Project kick off summer 2020.
- Drilling of appraisal well last quarter 2020.
- The seismic survey is independent of the appraisal well.
- 12 months of EPC ITTs, contract and financing negotiation prior to FID.
- Project sanction / FID end of 2022.
- Detailed design commences immediately following sanction.
- Bunter NUI jacket and topsides installed prior to drilling (facilities on critical path).
- The pipeline and facilities are pre-commissioned following completion of construction.
- Drilling and completing of first 4 injector wells commencing 2026.
- The pipeline, facilities and wells are commissioned in a continuous sequence of events.
- First CO_2 injection summer 2027 which coincides with the projected supply profile.

A total project duration from pre-FEED to first injection is projected to be approximately 7 years.

WP5 Bunter Closure 36 Schedule

ID	Project Phase ID	Task Name	Duration	Start	Finish
1	MS0	Start of Project	0 days	Wed 01/07/20	Wed 01/07/20
2	MS1	End of FEED	0 days	Thu 30/12/21	Thu 30/12/21
3	MS2	Final Investment Decision	0 days	Fri 30/12/22	Fri 30/12/22
4	MS3	First Injection	0 days	Sat 08/05/27	Sat 08/05/27
5	**A**	**A. Pre-Final Investment Decision (Pre-FID)**	**1095 days**	**Wed 01/07/20**	**Fri 30/06/23**
6	A1.1	Transportation	548 days	Wed 01/07/20	Thu 30/12/21
7	A1.2	Facilities	548 days	Wed 01/07/20	Thu 30/12/21
8	A1.3	Wells	548 days	Wed 01/07/20	Thu 30/12/21
9	**A1.4**	**Other**	**1095 days**	**Wed 01/07/20**	**Fri 30/06/23**
10	A1.4.1	Appraisal Well	180 days	Tue 29/09/20	Sat 27/03/21
11	A1.4.2	Seismic and Baseline Survey	180 days	Tue 29/09/20	Sat 27/03/21
12	A1.4.3	Engineering and Analysis	273 days	Sun 28/03/21	Sat 25/12/21
13	A1.4.4	Licencing and Permits	1095 days	Wed 01/07/20	Fri 30/06/23
14	MS1	End of FEED	0 days	Thu 30/12/21	Thu 30/12/21
15		EPC Contract and Financing Period	365 days	Fri 31/12/21	Fri 30/12/22
16	MS2	FID	0 days	Fri 30/12/22	Fri 30/12/22
17	**B**	**B. Post-Final Investment Decision (Post-FID)**	**1994.35 day**	**Sat 31/12/22**	**Fri 16/06/28**
18	**B1.1**	**Transportation**	**1589.4 days**	**Sat 31/12/22**	**Sat 08/05/27**
19	B1.1.1	Detailed Design	273 days	Sat 31/12/22	Fri 29/09/23
20	B1.1.2	Procurement	548 days	Fri 31/03/23	Sat 28/09/24
21	B1.1.3	Fabrication	180 days	Fri 29/11/24	Tue 27/05/25
22	B1.1.4	Construction and Pre-Commissioning	90 days	Wed 30/07/25	Mon 27/10/25
23	B1.1.4.1	Pipeline Commissioning	90 days	Sun 07/02/27	Sat 08/05/27
24	**B1.2**	**Facilities**	**1589.4 days**	**Sat 31/12/22**	**Sat 08/05/27**
25	B1.2.1	Detailed Design	365 days	Sat 31/12/22	Sat 30/12/23
26	B1.2.2	Procurement	548 days	Thu 29/06/23	Fri 27/12/24
27	B1.2.3	Fabrication	548 days	Sat 30/03/24	Sun 28/09/25
28	B1.2.4	Construction and Commissioning	180 days	Sun 28/09/25	Thu 26/03/26
29	B1.2.4.1	Platform Commissioning	90 days	Sun 07/02/27	Sat 08/05/27
30	**B1.3**	**Wells**	**1994.35 day**	**Sat 31/12/22**	**Fri 16/06/28**
31	B1.3.1	Detailed Design	548 days	Sat 31/12/22	Sun 30/06/24
32	B1.3.2	Procurement	730 days	Fri 31/03/23	Sat 29/03/25
33	**B1.3.4**	**Construction and Commissioning**	**812.35 days**	**Fri 27/03/26**	**Fri 16/06/28**
34	B1.3.4.1	Well 1-4	317.4 days	Fri 27/03/26	Sun 07/02/27
35	B1.3.4.2	Well 5	82.35 days	Sun 26/03/28	Fri 16/06/28
36	B1.3.4.3	Wells Commississioning / First Injection	90 days	Sun 07/02/27	Sat 08/05/27
37	**B1.4**	**Other**	**1095 days**	**Thu 08/02/24**	**Sun 07/02/27**
38	B1.4.1	Approvals and Consents	1095 days	Thu 08/02/24	Sun 07/02/27
39	**MS3**	**First Injection**	0 days	Sat 08/05/27	Sat 08/05/27

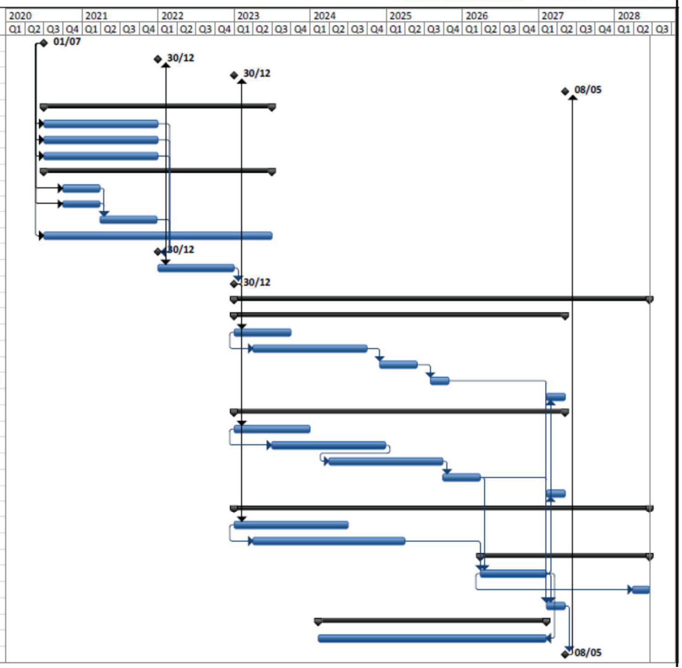


Figure 6-1 - Summary Level Project Schedule

6.2 Budget

The costs associated with the capital (CAPEX), operating (OPEX) and abandonment (ABEX) phase expenditures have been calculated for the engineering, procurement, construction, installation, commissioning, operation and decommissioning of the Bunter Closure 36 facilities. The OPEX has been calculated based on a 40 year design life. A 30% contingency has been included throughout.

Cost estimates are calculated for the base case development:

- Direct pipeline from Barmston including a tie-in structure for future expansion.
- Bunter NUI (jacket and topsides).
- Five wells in Phase 1 with five more in Phase 2.

6.2.1 Cost Estimate Summary

The cost estimate summary for the Bunter Closure 36 development is outlined in Table 6-1. These numbers are current day estimates for the base case development, with a direct pipeline from Barmston. Details are provided in Appendix 10.

In the tables that follow estimates are provided in Real, 2015 terms and Nominal, 2015 PV10 terms.

- Real, 2015. These values represent current-day estimates and exclude the effects of cost escalation, inflation and discounting.
- Nominal, 2015 PV10. These values incorporate the time value of money into the estimates (i.e. including the effects of cost escalation and inflation (2%) that are then discounted back to a common base year of 2015 using an annual discount rate of 10%).

Category	Cost £millions
CAPEX	669
OPEX	751
ABEX	188
Total Cost	1608
Cost CO_2 Injected (£ per Tonne)	5.75

Table 6-1 - Bunter Closure 36 Development Cost Estimate Summary

It should be noted that the cost estimates in Table 6-1 are 2015 estimates for 2015 activity and the present value estimates are provided in Table 6-3.

The cost over time is illustrated in Figure 6-2 (values are not inflated or discounted). It should be noted that these are early cost estimates and it is anticipated that detailed engineering during or after FEED would also include a specific cost reduction challenge to ensure that any cost savings presented by synergies with other offshore activities or development sin technology deployment can be fully realised.

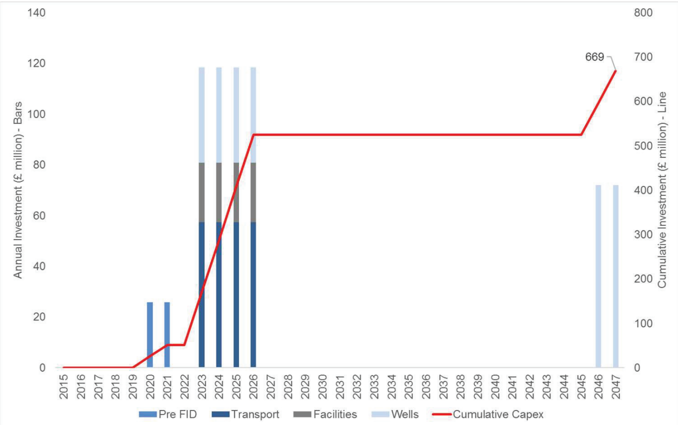


Figure 6-2 - Phasing of Capital Spend

6.2.2 Life Cycle Costs

The total project costs, inflated at 2% p.a. with a discount factor of 10% p.a., are summarised in Table 6-2.

Category	£millions (PV10, 2015 Nominal)		
	Phase I	Phase II	Total
Transportation	117		117
Facilities	48		48
Wells	77	12	89
Opex	90		90
Decommissioning & MMV	3		3
Total	335	12	347

Table 6-2 - Project Cost Estimate

Details of when these costs are incurred based on 2015 spending activity are shown in Figure 6-3.

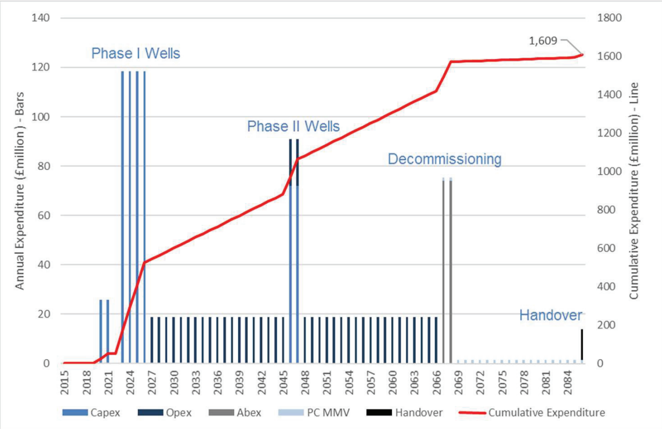


Figure 6-3 - Elements of Cost over the Project Life (Real)

6.2.2.1 Capital Expenditure

The CAPEX estimates for the Bunter Closure 36 development are summarised in the following tables. The costs are split up into transportation, facilities, wells and "other". The cost estimates in these tables are in 2015 real terms.

Phase	Category	Cost (£ MM)
Pre-FID	Pre-FEED	0.3
	FEED	0.5
Post-FID	Detailed Design	1.6
	Procurement	118.0
	Fabrication	20.3
	Construction & Commissioning	89.5
Total CAPEX – Transportation (£MM)		230.2

Table 6-3 - Bunter Closure 36 Development - Transport CAPEX

The CAPEX for the Bunter NUI (jacket + topsides) was generated using the Que$tor cost estimating software, and benchmarked using Costain Norms.

Phase	Category	Cost (£ MM)
Pre-FID	Pre-FEED	2.8
	FEED	5.7
Post-FID	Detailed Design	16.9
	Procurement	26.5
	Fabrication	21.5
	Construction & Commissioning	29.1
Total CAPEX – Facilities (£MM)		102.5

Table 6-4 - Bunter Closure 36 Development - Facilities CAPEX

The both phases of well expenditure are included within the following estimate.

Phase	Category	Cost (£ MM)
Pre-FID	Pre-FEED / FEED PM&E	2.9
Post-FID	Detailed Design	2.9
	Procurement	83.2
	Construction and Commissioning (Drilling)	205.4
Total CAPEX – Wells (£MM)		294.3

Table 6-5 Bunter Closure 36 Development - Wells CAPEX

Phase	Category	Cost (£ MM)
Pre-FID	Seismic and Baseline Survey	5.7
	Appraisal Well	28.4
	Engineering and Analysis	2.9
	Licencing and Permits	2.6
Post-FID	Licencing and Permits	2.6
Total CAPEX – Other Costs (£MM)		42.2

Table 6-6 - Bunter Closure 36 Development - Other CAPEX

6.2.2.2 Operating Expenditure

The 40 year OPEX for the Bunter Closure 36 development has been estimated to be £751 million based on the following:

- Transportation at 1% of pipeline CAPEX per year
- Offshore facilities at 6% of facilities CAPEX per year
- Wells based on requiring 4 major and 1 minor workovers during the project life as summarised in Table 6-7.
- Other, as summarised in Table 6-8.

OPEX Estimate	Total Cost (£MM)
Major workover or Local Sidetrack	25.6
Workover 1	10.4

Table 6-7 - Bunter Closure 36 Development - Wells OPEX

A breakdown of the OPEX associated with "Other" costs is presented below.

OPEX Estimate	Total Cost (£MM)
Measurement, Monitoring and Verification	40.0
Financial Securities	159.0
Ongoing Tariffs and Agreements	0.0
Total	199.1

Table 6-8 - Bunter Closure 36 Development - Other OPEX

6.2.2.3 Abandonment Expenditure

Abandonment costs for the Bunter Closure 36 CO_2 transportation (pipeline) system has been estimated at 10% of transportation CAPEX.

The decommissioning costs for the offshore facilities are summarised in the table below, these costs were also generated using Que$tor.

ABEX / Decommissioning	Total Cost (£MM)
Jacket	40.8
Topsides	17.6
Wells	55.1
Total	113.5

Table 6-9 - Bunter Closure 36 Development - Facilities ABEX

A breakdown of the ABEX associated with "Other" costs is presented below.

Other	Total Cost (£MM)
Post Closure Monitoring	27.6
Handover	12.5
Total	40.1

Table 6-10 - Bunter Closure 36 Development - Other ABEX

6.3 Economics

This section summarises the cost based economic metrics for the proposed development.

6.3.1 Project Component Costs

£million	Real (2015)	Nominal (Money of the Day)	PV_{10} (Nominal, 2015)
Transport	254	302	117
Facilities	104	124	48
Wells	310	472	89
Opex	751	1439	90
Decommissioning & Post Closure Activity	188	564	3
Total	1609	2901	347

Table 6-11 - Development Cost in Real and Nominal Terms.

6.3.2 Transportation and Storage Costs

The contribution of each major element of the development to the overall cost is summarised in Table 6-12.

£million	Real (2015)	Nominal (MOTD)	PV_{10} (Nominal, 2015)
Transportation	349	532	117
Injection	1260	2369	230
Total	1609	2901	347

Table 6-12 - Transportation and Storage Costs

6.3.3 Unit Costs

The life-cycle costs of the development are summarised in Table 6-13, Figure 6-4 and Figure 6-5.

£/T	Real (2015)	Levelised (PV_{10}, Real 2015)	Nominal (MOTD))	Levelised (PV_{10}, Nominal, 2015)
Transportation	1.2	4.5	1.9	5.4
Injection	4.5	7.8	8.5	10.5
Total	5.7	12.3	10.4	15.9

Table 6-13 - Transportation and Storage Costs per Tonne of CO_2

Note: the calculation of levelised cost includes the discounted value of the CO_2 stored (22Mt rather than the undiscounted value of 280Mt).

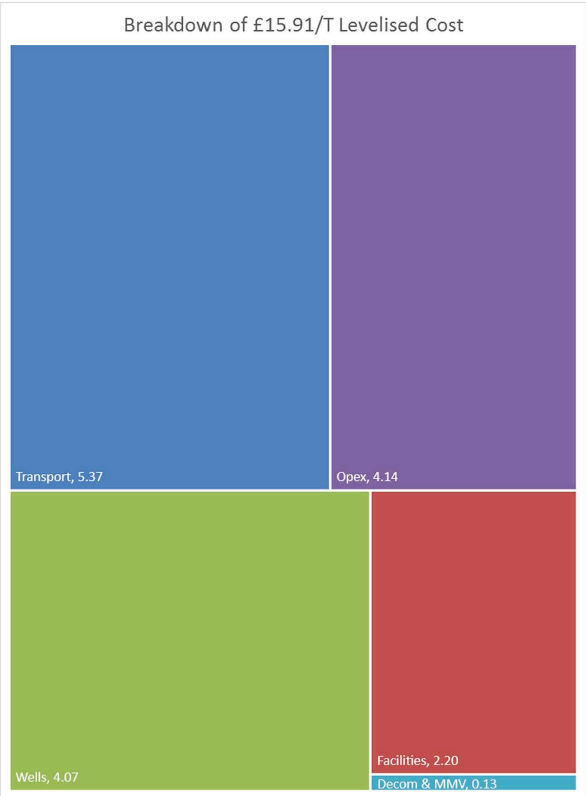


Figure 6-4 - Breakdown of Levelised Costs

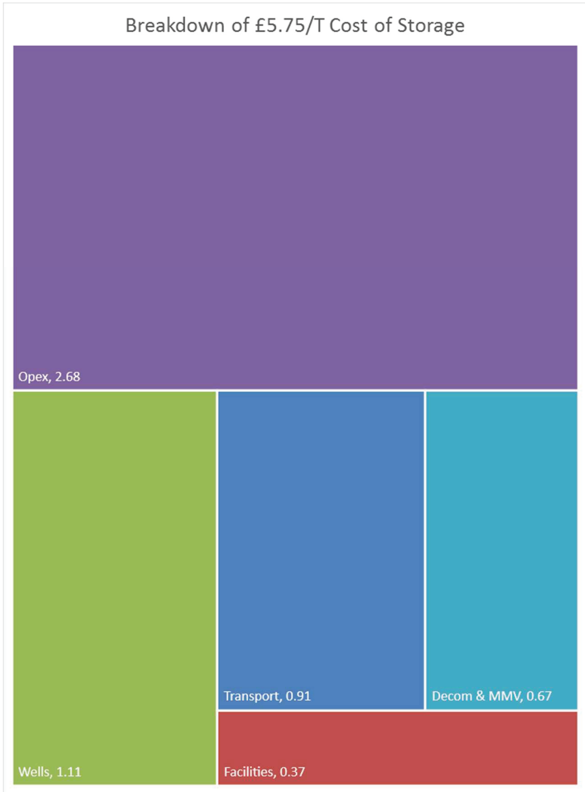


Figure 6-5 - Breakdown of Life-cycle Costs

The charts shown in Figure 6-4 and Figure 6-5 show the components of unit cost on a levelised and real basis and illustrate the relative rank of each component for the two calculations. The levelised cost calculation (DECC, 2013) includes both inflation and discounting and therefore shows the impact of the timing of the timing of expenditure and injection. Thus expenditure far in the future such as MMV and handover (dark blue rectangles) appear smaller than on an undiscounted basis, as shown in Figure 6-5.

The variation between the Levelised and Real cost is due to both the timing of the expenditures as well as the rate at which the expenditure takes place.

£/T	Real (2015)	Levelised (PV_{10}, Real 2015)	Nominal (MOTD)	Levelised ($PV_{10,}$ Nominal, 2015)
Pre-FID	0.18	1.28	0.21	1.42
Transport	1.25	4.32	1.81	5.34
Facilities	1.48	2.74	2.59	3.68
Power	0.00	0.00	0.00	0.00
Wells	2.16	3.96	3.74	5.34
Abex	0.53	0.04	1.50	0.12
PC MMV & Handover	0.14	0.00	0.52	0.01
Total	5.75	12.33	10.36	15.92

Table 6-14 - Unit Costs in Detail

7.0 Conclusions & Recommendations

7.1 Conclusions

Data

- There is good 3D seismic coverage across the whole of the storage complex and the nearby relevant fairway. This is capable of providing a competent basis for a development decision, however a new 3D seismic survey would improve confidence in development well placement and also enable more quantitative information to be extracted as well as serving as a baseline survey for 4D monitoring.
- There is good regional well coverage and reasonable well data available within the storage complex. Core data is sparse on the site itself and logging suites not always optimised for evaluation of the Bunter Sandstone and adjacent formations.

Containment

- There is a high level of confidence that over 280Mt of CO_2 can be contained within the Bunter 36 structure.
- 1000 years after injection has ceased the CO_2 plume is contained within the Bunter 36 structural closure and easily within the defined storage complex.
- The overlying Rot Halite formation forms the primary seal is 60m thick over the structure. Its' mobile nature means that it is resilient to fracturing and almost totally impermeable.
- There are multiple further secondary sealing intervals within the overlying Haisborough group which further secure the integrity of the site.
- Underlying the Bunter Sandstone is approximately 1000ft of Bunter Shale which comprises a series of shales and siltstones.

Site Characterisation

- The site is salt induced dome structure in the Bunter Sandstone that forms a 4-way dip closure with minimal evidence of faulting.
- The most appropriate interpretation is a sand dominated model with minor shales, two shale intervals are considered to be potentially significant baffles.
- The five zone Bunter correlation compares well with that used at the nearby Caister field.
- Average permeability is 200mD, average porosity is 22% and the average Kv/Kh ratio is 0.4.
- The PGS Southern North Sea MegaSurvey seismic volume which extends over the Bunter Closure 36 and the regional fairway has been interpreted. The key horizons have been identified, interpreted and mapped. Seismic data quality is considered adequate for structural interpretation.
- There is no clear evidence of any faulting in the reservoir or primary cap rock of the Bunter Closure 36 storage site that is considered likely to breach the primary seal (Rot Halite and Solling Mudstone).

- The mapped time surfaces have been depth converted using a combination of a V0+k and interval velocity layer cake depth conversion method. A layer cake depth conversion was identified as the most technically robust approach, due to velocity variations in the overburden units.
- A limited depth sensitivity study highlights that the Bunter Closure 36 spill point could shift from the South West corner to the North East and be at a shallower depth.
- No gas column has been observed in Bunter Closure 36, but a small gas column cannot be ruled out at this stage.

Capacity

- Capacity estimates range between 49 - 566 Mt and is strongly dependent on injection rate.
- Uncertainty in depth conversion causes gross rock volume to be the largest contributor to uncertainty in storage capacity.
- Well placement has a major impact on capacity:
- Deeper wells tend to allow for higher injection rates and storage of a greater mass of CO_2..
- Open well patterns minimise interference between wells, allowing reservoir pressure to increase more slowly and therefore store a greater mass of CO_2..
- A greater mass of CO_2 can be stored in the gently dipping western side of the structure than the steeply dipping eastern side. This is because the larger connected volume there allows pressure to be dissipated more readily allowing in a greater mass of CO_2 to be stored.
- The optimum injection strategy has 4 deviated injection wells with bottom-hole locations 2000 - 4000m apart, a depth of 1400m tvdss, located on the western side of the structure and injecting at a combined rate of 7Mt/y.
- Relative permeability assumptions have a significant impact on how readily injection pressure is dissipated throughout the store and consequently how much CO_2 can be injected before the fracture pressure constraint is reached. Capacity changed by up to 15% depending on which relative permeability assumptions were used.

Appraisal

- The appraisal programme addresses the four key uncertainties: depth conversion, impact of the aquifer, confirmation of site specific reservoir quality and quality of merged seismic data set.
- The existing 3-D seismic data is considered to be of sufficient quality for further more detailed study including selecting the location of an appraisal well.
- The primary objective of the appraisal well is to provide further information on the seismic velocity field and also key reservoir, formation fluid and caprock samples to assist subsurface characterisation.

Development

- Final Investment Decision needs to be in 2022 in order to achieve the first injection date of 2027.
- The planning work indicates that approximately 7 years are required to fully appraise and develop the store.

- A £254 million (in present value terms discounted at 10% to 2015) capital investment is required to design, build, install and commission the pipeline, platform and initial tranche of 5 wells. Provision has been made for an additional investment of £144 million (real terms) (£12 million in present value terms discounted at 10% to 2015) in 2047 to replace all wells after an assumed well life of 20 years.
- The shallow water and anticipated higher cost of the alternative subsea system make a platform development the most logical choice at this stage.
- Factoring of Opex and Abex from the capital estimates is appropriate for this stage of project concept development.
- The deviated wells are relatively straightforward to drill and complete from a single drill centre. The outline drilling programme is designed to minimise drilling hazards. Those typically encountered in the Southern North Sea are: tight hole in the Chalk, mobile halite and swelling shales.
- The completion equipment will be CO_2 resistant, using chrome materials. 5.5" diameter tubing is optimum for providing the required well performance.
- Using a store-wide fracture pressure constraint to terminate injection is a more robust approach to store management than applying this limit only at the bottom-hole well locations.
- CO_2 delivered via a new 160km 20" pipeline from Barmston to Bunter Closure 36 to a new Normally Unmanned Installation (NUI) with a design life of 40 years.
- An alternative pipeline route could be available from White Rose 5/42 platform, if available.
- There is some pre-investment in the facilities to allow for additional ullage, future tie-ins and the two-phase development campaign.
- Facilities have been selected to minimise offshore manning requirements, thereby reducing OPEX.
- Cost estimates have been generated accounting for capital, operating and decommissioning expenditure.

Operations

- The fracture pressure at Top Bunter (1170m) is estimated to be 197 bar based on geomechanical analysis and the maximum allowable pressure has been constrained to 90% of this (177 bar).
- During steady state operations the impact of temperature on the well completion and reservoir are considered to be insignificant. Management of transient temperature changes may be operationally challenging and is a subject for further work.

Workflow

- The Peer Review session with ETI Advisors and external experts was helpful and contributed to an improved assessment of the site.

7.2 Recommendations

Appraisal Programme

- Identify a preferred well location and data acquisition programme that has the best chance of resolving the key subsurface uncertainties.
- Improve the characterisation of the regional/local aquifer by procuring and analysing pressure and production data from the nearby fields.
- Complete a more regional assessment of the Bunter Sandstone to improve understanding of reservoir quality and its evolution, specifically this should include the structural evolution and history of halokinesis and the development of the formation water composition. It should also include an exploration of the connectivity (both past and present) between the Bunter Sand and deeper intervals such as the Zechstein and the Carboniferous such that the salt and gas charging mechanisms can be better understood. This work should include the very recent history since the Bunter Sandstone may have been subject to recent erosion and freshwater charge.
- Acquire a new 3-D seismic survey focussed at the Bunter level to aid placement of development wells, remove any concerns associated with splicing artefacts in the current merged 3D, and provide the baseline survey from which 4D seismic can be compared as part of the MMV programme.
- Plan to acquire the seismic survey after the appraisal well has been drilled but probably before the final investment decision is taken.
- Gain more detailed access to the Schooner data set so that well status and abandonment status can be fully understood. Work to ensure that the Operator is familiar with the potential for CO_2 storage in the area and seek collaboration to leverage cost reductions from potential synergies that this might present.

Design

- Further detailed injection performance modelling should focus on operational intermittency.
- Consider running the simulation model with a finer vertical layering to better understand the impact of modelling technique on well placement.

Operational Planning

- Identify and quantify opportunities for cost and risk reduction across the whole development, for instance designing and drilling the appraisal well in such a way that it could become one of the operational injection wells.
- Identify synergies with other offshore operations.

Development Planning

- Consider the commercial aspects required for the development of Bunter Closure 36 in the light of past petroleum use to ensure that all existing rights are honoured whilst enabling the development to proceed.
- Incorporate the regulatory licensing and permitting requirements into the development plan.

- Work with the petroleum operator of Schooner and the regulator to ensure that the Schooner wells are abandoned using all best practice to secure the CO_2 integrity of the site.

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10.0 Glossary

Defined Term	Definition
Aeolian	Pertaining to material transported and deposited (aeolian deposit) by the wind. Includes clastic materials such as dune sands, sand sheets, loess deposits, and clay
Alluvial Plain	General term for the accumulation of fluvial sediments (including floodplains, fan and braided stream deposits) that form low gradient and low relief areas, often on the flanks of mountains.
Basin	A low lying area, of tectonic origin, in which sediments have accumulated.
Bottom Hole Pressure (BHP)	This the pressure at the midpoint of the open perforations in a well connected to a reservoir system
Clastic	Pertaining to rock or sediment composed mainly of fragments derived from pre-existing rocks or minerals and moved from their place of origin. Often used to denote sandstones and siltstones.
Closure	A configuration of a storage formation and overlying cap rock formation which enables the buoyant trapping of CO_2 in the storage formation.
CO_2 Plume	The dispersing volume of CO_2 in a geological storage formation
Containment Failure Mechanism	The geological or engineering feature or event which could cause CO_2 to leave the primary store and/or storage complex
Containment Failure Modes	Pathways for CO_2 to move out of the primary store and/or storage complex which are contrary to the storage development plan
Containment Risk Scenario	A specific scenario comprising a Containment Failure Mechanism and Containment Failure Mode which might result in the movement of CO_2 out of the primary store and/or storage complex
Evaporite	Sediments chemically precipitated due to evaporation of water. Common evaporates can be dominated by halite (salt), anhydrite and gypsum. Evaporites may be marine formed by the evaporation within an oceanic basin, or non-marine typically formed in arid environments.

Defined Term	Definition
Fault	Fracture discontinuity in a volume of rock, across which there has been significant displacement as a result of rock movement
Fluvial	Pertaining to or produced by streams or rivers
Formation	A formation is a geological rock unit that is distinctive enough in appearance and properties to distinguish it from surrounding rock units. It must also be thick enough and extensive enough to capture in a map or model. Formations are given names that include the geographic name of a permanent feature near the location where the rocks are well exposed. If the formation consists of a single or dominant rock type, such as shale or sandstone, then the rock type is included in the name.
Geological Formation	Lithostratigraphical subdivision within which distinct rock layers can be found and mapped [CCS Directive]
Halokinesis	The study of salt tectonics, which includes the mobilization and flow of subsurface salt, and the subsequent emplacement and resulting structure of salt bodies
Hydraulic Unit	A Hydraulic Unit is a hydraulically connected pore space where pressure communication can be measured by technical means and which is bordered by flow barriers, such as faults, salt domes, lithological boundaries, or by the wedging out or outcropping of the formation (EU CCS Directive);
Leak	The movement of CO_2 from the Storage Complex
Outline Storage Development Plan (OSDP)	The Outline Storage Development Plan defines the scope of the application process for a storage permit, including identification of required documents. These documents, include a Characterization Report (CR), an Injection and Operating Plan (IOP) (including a tentative site closure plan), a Storage Performance Forecast (SPF), an Impact Hypothesis (IH), a Contingency Plan (CP), and a Monitoring, Measurement and Verification, (MMV) plan.
Playa Lake	A shallow, intermittent lake in a arid or semiarid region, covering or occupying a playa in the wet season but drying up in summer; an ephemeral lake that upon evaporation leaves or forms a playa.
Primary Migration	The movement of CO_2 within the injection system and primary reservoir according to and in line with the Storage Development Plan
Risk	Concept that denotes the product of the probability (likelihood) of a hazard and the subsequent consequence (impact) of the associated event [CO2QUALSTORE]

Defined Term	Definition
Sabkha	A flat area of sedimentation and erosion formed under semiarid or arid conditions commonly along coastal areas but can also be deposited in interior areas (basin floors slightly above playa lake beds).
Secondary Migration	The movement of CO_2 within subsurface or wells environment beyond the scope of the Storage Development Plan
Silver Pit Basin	Located in the northern part of the Southern North Sea. Over much of the basin up to 400 m of Silverpit Formation interbedded shales and evaporites are present. The absence of the Leman Sandstone reservoir over much of the basin has meant that gas fields predominate in the Carboniferous rather than in the Permian, as is the case in the Sole Pit Basin to the South.
Site Closure	The definitive cessation of CO_2 injection into a Storage Site
Storage Complex	The Storage Complex is a storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations (EU CCS Directive).
Storage Site	Storage Site is a defined volume within a geological formation that is or could be used for the geological storage of CO_2. The Storage Site includes its associated surface and injection facilities (EU CCS Directive);
Storage Unit	A Storage Unit is a mappable subsurface body of reservoir rock that is at depths greater than 800 m below sea level, has similar geological characteristics and which has the potential to retain CO_2 (UKSAP)
Stratigraphic Column	A diagram that shows the vertical sequence of rock units present beneath a given location with the oldest at the bottom and youngest at the top.
Stratigraphy	The study of sedimentary rock units, including their geographic extent, age, classification, characteristics and formation.
Tectonic	Relating to the structure of the Earth's crust, the forces or conditions causing movements of the crust and the resulting features.
Tubing Head Pressure (THP)	The pressure at the top of the injection tubing in a well downstream of any choke valve

11.0 Appendices

The following appendices have been provided separately:

11.1 Appendix 1 – Risk Matrix

11.2 Appendix 2 – Leakage Workshop Report

11.3 Appendix 3 – Database

11.4 Appendix 4 – Blank - Not in use

11.5 Appendix 5 – Peer Review Reports

11.6 Appendix 6 – Geological Information

11.7 Appendix 7 – MMV Technologies

11.8 Appendix 8 - Geomechanics

11.9 Appendix 9 – Basis of Well Design

11.10 Appendix 10 – Cost Estimate

11.11 Appendix 11 - Methodologies

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D10: WP5A – Bunter Storage Development Plan

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Contents

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Disclaimer:

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11 Appendices

11.1 Appendix 1 – Risk Matrix

Provided separately in Excel

11.2 Appendix 2 – Leakage Workshop

11.2.1 Objectives

The objectives for this workshop were to discuss and capture the leakage scenario definitions for Bunter Closure 36 & their risk (likelihood & impact).

11.2.2 Methodology

The Leakage Scenario Definition Workshop (WP5A.T23) covered all aspects of natural and engineering integrity. The project team of subsurface experts came together to brainstorm an inventory of potential leak paths (both geological and engineered) for the Bunter Closure (BC) 36 site. These potential leak paths were then assessed for their likelihood and impact, based on all the available evidence.

The scope of the workshop was for the BC36 site only, from the subsurface to the wellhead and did not include offshore facilities or pipeline transportation.

The roles in the room included:

- Facilitator, timekeeper, note-taker
- Geophysics expert
- Geology expert
- Reservoir Engineering expert
- Wells expert
- 2 x CO_2 Storage experts

The workshop focussed one at a time on each of the following 10 containment failure modes (pathways for CO_2 to move out of the primary store and/or storage complex which are contrary to the storage development plan):

1. Flow through Primary Caprock
2. Lateral Exit from Primary Store
3. Lateral Exit from Secondary Store
4. Flow through Secondary Caprock
5. CO_2 entry into a post operational or legacy well
6. CO_2 flow upwards in wellbore zone within Storage Complex
7. CO_2 exit from welbore zone outside Primary Store
8. CO_2 flow upwards in wellbore zone beyond Storage Complex boundary
9. CO_2 flow through Store floor and beyond storage complex boundary
10. CO_2 flow downwards in wellbore zone beyond Storage Complex boundary

These are summarised in the following diagram:

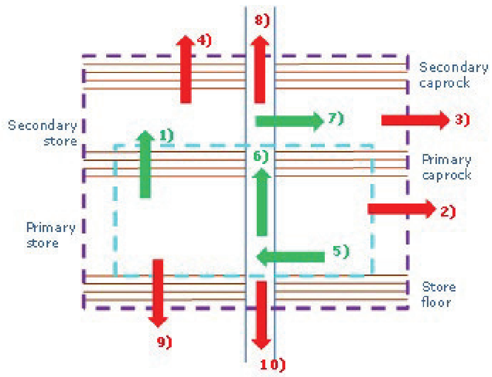

Figure 11-1 Containment failure modes

For each failure mode, a number of containment failure mechanisms were discussed. A containment failure mechanism is a geological or engineering feature, event or process which could cause CO_2 to move out of the primary store and/or storage complex (contrary to the storage development plan). An example is: fault reactivation in primary caprock.

The likelihood and impact of each containment failure mechanism was discussed, based on the CO_2QUALSTORE framework.

The failure mechanisms were then cross-checked with the Quintessa CO_2 FEP (feature, event, process) database to ensure all possibilities were considered.

Pathways that could potentially lead to CO_2 moving out with the Storage Complex were mapped out from combinations of failure modes. For each pathway, the likelihood was taken as the lowest from likelihood of any of the failure modes that made it up and the impact was take as the highest. The pathways were then grouped into more general leakage scenarios.

11.2.3 Results

Leakage scenario	Likelihood	Impact
Vertical movement of CO_2 from Primary store to overburden through caprock	1	3
Vertical movement of CO_2 from Primary store to overburden via existing wells	1	3
Vertical movement of CO_2 from Primary store to overburden via injection wells	1	3
Vertical movement of CO_2 from Primary store to overburden via caprock & wells	1	3
Vertical movement of CO_2 from Primary store to upper well/ seabed via existing	3	5
Vertical movement of CO_2 from Primary store to upper well/ seabed via injection wells	2	5
Vertical movement of CO_2 from Primary store to upper well/ seabed via caprock & wells	1	5
Lateral movement of CO_2 from Primary store out with storage complex w/in Bunter	2	3
Vertical movement of CO_2 from Primary store down to Zechstein or lower via existing wells	3	3
Vertical movement of CO_2 from Primary store down to Zechstein or lower via store floor	1	3

Table 11-1- Leakage Scenarios

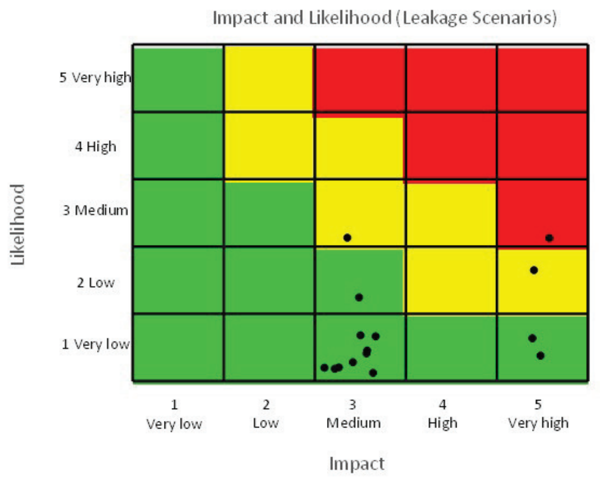

Figure 11-2 Risk matrix of leakage scenarios

The scenarios with the highest risk relate to existing (P&A and development) and injection wells.

Score	1	2	3	4	5
Name	Very Low	Low	Medium	High	Very High
Impact on storage integrity	None	Unexpected migration of CO_2 inside the defined storage complex	Unexpected migration of CO_2 outside the defined storage complex	Leakage to seabed or water column over small area (<100m2)	Leakage seabed water column over large area (>100m2)
Impact on local environment	Minor environmental damage	Local environmental damage of short duration	Time for restitution of ecological resource <2 years	Time for restitution of ecological resource 2-5 years	Time for restitution of ecological resource such as marine Biosystems, ground water >5 years
Impact on reputation	Slight or no impact	Limited impact	Considerable impact	National impact	International impact
Consequence for Permit to operate	None	Small fine	Large fine	Temporary withdrawal of permit	Permanent loss of permit

Table 11-2 - Impact Categories

Score	1	2	3	4	5
Name	Very Low	Low	Medium	High	Very High
Description	Improbable, negligible	Remotely probably, hardly likely	Occasional, likely	Probable, very likely	Frequent, to be expected
Event (E)	Very unlikely to occur during the next 5000 years	Very unlikely to occur during injection operations	Likely to occur during injection operations	May occur several times during injection operations	Will occur several times during injection operations
Frequency	About 1 per 5000 years	About 1 per 500 years	About 1 per 50 years	About 1 per 5 years	About 1 per year or more
Feature (F)/ Process (P)	Disregarded	Not expected	50/50 chance	Expected	Sure

Table 11-3 - Likelihood Categories

11.3 Appendix 3 – Database

11.3.1 Bunter Closure 36: SEG-Y data summary

The seismic 3D survey used for the evaluation of Bunter Closure 36 came from PGS UK SNS Mega Survey:

- Survey: MC3D_SNS_MEGA (UK Sector)
- Final Merged Migration (22 Tiles)

These data were supply as SEG-Y on a USB hard drive and have the following survey datum and map projections:

Survey Datum	Name:	ED50
Ellipsoid:	INTERNATIONAL 1924	
Semi Major Axis	6378388	
1/Flattening	297	
Map Projection	Projection	UTM 31N
Central Meridian	3 EAST	
Scale Factor on Central Meridian	0.9996	
Latitude of Origin	0.00N	
False Northing	0	
False Easting	500000	

Table 11-4 SEG-Y survey datum and map projections

The following tiles of SEG-Y data were used for the Bunter closure 36 evaluation

File Name	Format	Tile	Media	IL Range	XL Range
MC3D_SNS_MEGA_I07P	SEG-Y	I07	27395001	30001 - 35000	32001 - 36000
MC3D_SNS_MEGA_J06P	SEG-Y	J06	27395001	25001 - 30000	36001 - 40000
MC3D_SNS_MEGA_J07P	SEG-Y	J07	27395001	30001 - 35000	36001 - 40000
MC3D_SNS_MEGA_K06	SEG-Y	K06	27395001	25001 - 30000	40001 - 43877
MC3D_SNS_MEGA_K07	SEG-Y	K07	27395001	30001 - 35000	40001 - 44000

Table 11-5 SEG-Y tiles for Bunter Closure 36 evaluation

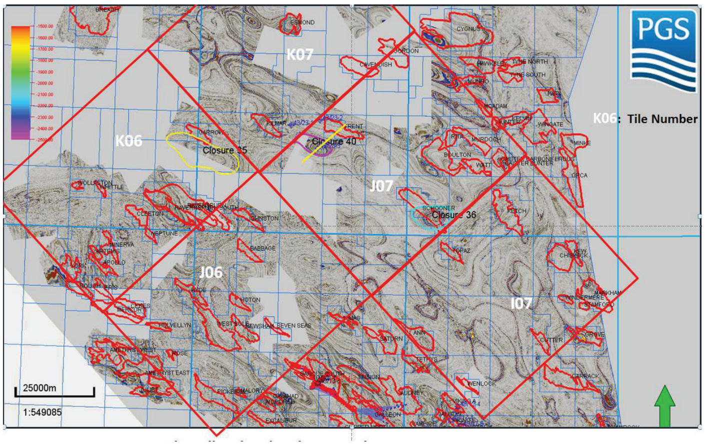

Figure 11-3 PGS SNS Mega survey time slice showing the SEG-Y data extent and tiles

11.3.2 Bunter Closure 36: Well log data summary

The table below shows a summary of the well log data for Bunter Closure 36, downloaded from CDA.

Field	Well	Completion Date	Interpreted logs	Well used in site model	Well used in fairway model
Schooner	44/26-1	16/05/1968	Y	Y	Y
	44/26-2	24/01/1987	Y	Y	Y
	44/26-3	20/08/1987	N	N	N
	44/26-4	11/02/1988	Y	Y	Y
	44/26a-A7	22/03/1999	N	Y	Y
	44/26a_A9	23/05/2003	N	N	N
Caister	44/23-3	11/08/1992	Y	N	Y
	44/23a-A3	11/09/1993	Y	N	Y
	44/23-5	12/12/1992	Y	N	Y
	42/25-1	05/10/1990	Y	N	Y
	43/23-3	11/06/1994	Y	N	Y
	43/25-1	17/07/1984	Y	N	Y
	44/27-1	17/02/1987	Y	Y	Y
	44/26c-5	05/03/1994	Y	Y	Y
	44/26c-6	08/05/1994	N	N	N
	49/01-3	08/11/1987	N	Y	Y
	49/21-2	03/07/1970	N	N	N
Schooner	44/26a-A8	20/07/2000	Y	N	N
	44/26a-A2	01/10/1996	N	N	N
	44/26a-A1	01/10/1996	N	N	N
Caister	44/23-1	20/06/1968	N	N	N
	44/23a-7z	22/12/1997	N	N	N
	43/30-1	25/03/1969	N	N	N
	43/28a-3	06/04/1996	N	N	N
	43/23-2	15/02/1993	N	N	N
	43/23-1	25/09/1991	N	N	N
	43/21b-5z	27/03/2009	N	N	N
	43/21-3	18/08/1994	N	N	N

Table 11-6 Well log data summary

11.3.3 Bunter Closure 36: Core data summary

The table below show a summary of the core data available over the Bunter Closure 36 site.

Well	Cored interval (MD ft)	Cpor	CKH	CKV	Core Log	Core Description	Core Photos
44/26-1	4257 - 4320	Y	Y	N	N	Y	N
44/23-3	4470 - 4530	Y	Y	N	Y	Y	N
	4548 - 4629	Y	Y	N	N	N	N
	4633 - 4751	Y	Y	N	N	N	N
44/23-5	4626 - 4719	Y	Y	Y	N	Y	Y
	4720 - 4804	Y	Y	Y	N	N	N
42/25-1	3665 - 3678	Y	Y	N	N	N	N
	3716 - 3756	Y	Y	N	N	N	N
	3757 - 3763	Y	Y	N	N	N	N

Table 11-7 Core data summary

11.3.4 Data from Operators

Well data (including some abandonment records) from Operators in the Bunter Closure 36 area were provided under Non-disclosure Agreements, but did not include any pressure or production data.

11.4 Appendix 4 – [HOLD – not in use]

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11.5 Appendix 5 Peer Review Reports

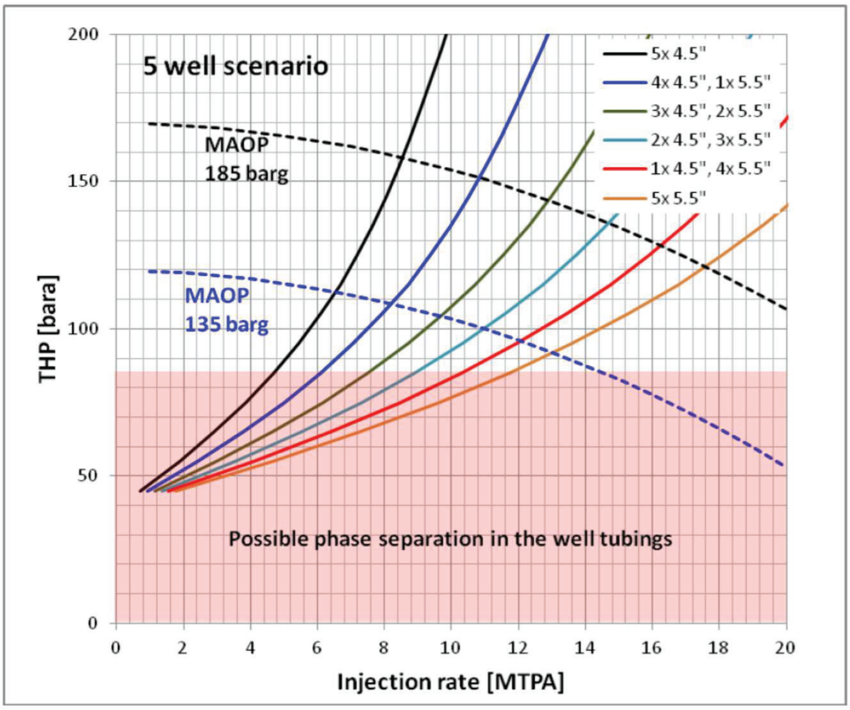
BUNTER CLOSURE 36 DEVELOPMENT PLAN PEER REVIEW - FACILITIES AND WELLS COMMENTS

R Nixon - Reviewer

1. **TRANSPORTATION**
   a. **Capacity Constraint**

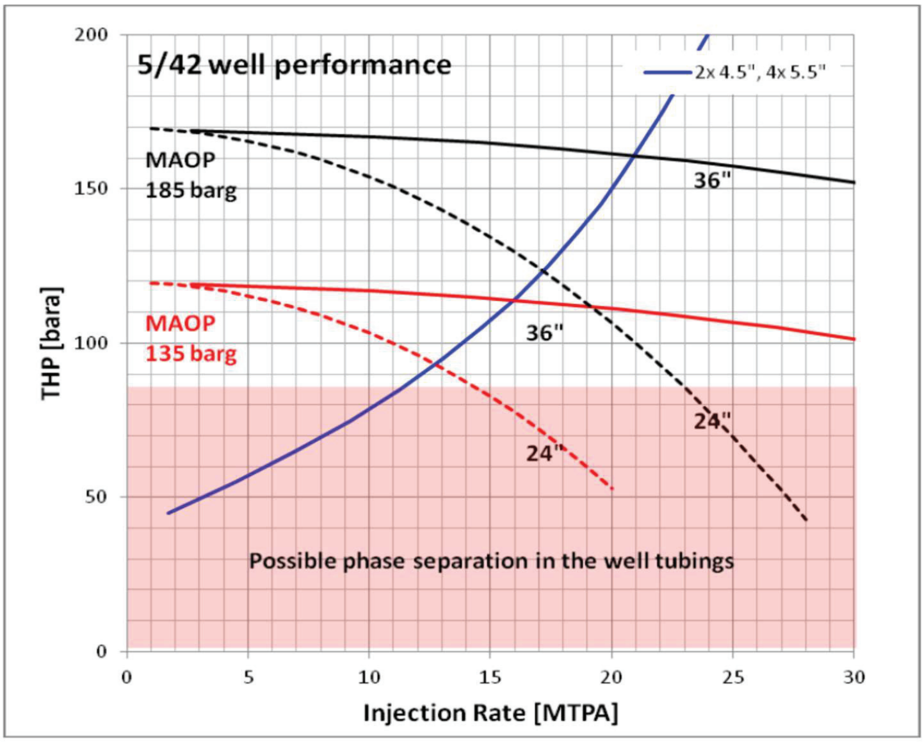
The 5/42 24” pipeline was designed to supply up to 17 MTPA of CO_2 to the 5/42 reservoir assuming a design pressure of 200 bar and maximum allowable operating pressure of 185 barg. The 17 MTPA capacity was a reservoir maximum injection rate into 5/42 using 5 x 5.5” injection wells rather than a pure pipeline constraint. At this rate the required tubing head pressure at the 5/42 wellheads is around 120 barg. If the tubing head pressure drops below 120 barg the injection capacity of 5/42 would decline, so for example, if the tubing head pressure at 5/42 drops to the minimum acceptable tubing head pressure of 84 barg the system capacity would decline to only 12 MTPA.

The minimum tubing head pressure of 84 barg was set to prevent two phase flow occurring in the well tubing. For pure CO_2, the bubble point is 56 bara at 16°C (maximum summer sea temperature). National Grid however designed the system for impurities in the CO_2. The impurities in the fluid increase bubble point pressure, hence phase separation occurs at a higher pressure. The hydraulic design of 5/42 system was based on a CO_2 concentration of 96% vol which had a bubble point of 70.6 bara at 16 °C. The 84 bag was specified to provide a suitable operating margin.



The 5/42 platform was designed for future expansion in mind and includes spare risers, J tubes, and control/power system capacity. The jacket structure was also designed with sufficient structural capacity to allow installation of future hang off modules. This included a water production hang off module, to facilitate equipment for ESP lifted water wells on 5/42, and a CO_2 Booster Pump module to allow future onward transportation of CO_2.

Future expansion hydraulic capacity was considered from 5/42 however this was constrained unless a booster pump module was installed on the platform or a 36" pipeline provided from Barmston to 5/42. A 24" pipeline was selected by the project. The hydraulic performance of the 5/42 24" and 36" pipeline options is shown below.



The specified flowrate to Bunter Closure 36 is 7 MTPA over 85 km and the required minimum injection pressure at the wellheads is between 85 barg and 106 barg. With an 18" line from 5/42 to the Bunter Closure 36 a pressure drop of 35 barg is expected. This results in a required pressure at 5/42 of up 141 barg (106+35) if a booster pump module is not installed on 5/42. It can be seen from the above hydraulic curve that the capacity of the 24" pipeline to 5/42 would be around 14 MTPA of which 7 MTPA is taken by the flow to Bunter Closure 36. The residual capacity remaining for 5/42 would therefore only be 7 MTPA.

Comment: The onward transportation of 7 MTPA of CO2 to Bunter 36 through an 85km 18" pipeline would reduce the overall capacity of the 5/42 pipeline from 17 MTPA to 14 MTPA and the capacity remaining for 5/42 injection to 7 MTPA. The booster pump module would be required on the 5/42 platform with associated cost if the 17 MTPA capacity to 5/42 is to be retained coincident with injection to Bunter 36.

b. Subsea Development Option

During the peer reviews for 5/42 there was a strong challenge as to why we did not propose a subsea option which was around £50M lower Capex than the platform option and associated Opex around £2M per year less. The existing example of CO_2 subsea injection at Snohvit in Norway was given as strong case for a subsea development. The argument for a platform at 5/42 was successfully based on the following:

- 5/42 was to be the first CCS project in the UK sector of the North Sea and therefore high profile. Reducing risk was seen as a key project requirement.
- The water depth was shallow (around 45m) so wellhead jacket structures were relatively low cost.
- Dry trees improved monitoring capability of the wells and reservoir, and provided easier and lower cost access for workovers.
- The platform provided a hub for future expansion through the provision of a CO_2 booster pump hang off module.
- There was uncertainty as to whether ESPs would be required for water production. ESPs required an offshore platform for the power supply and associated variable speed drives and transformers.
- The platform provided a suitable offshore location for the pipeline vent. A vent onshore at Barmston was close to a caravan park and nearby village. Based on transient modelling the pipeline venting would take around 2 weeks and result in unacceptable high noise levels and disruption onshore.
- The 90 km umbilical length to a subsea development was feasible but approaching the upper limit for conventional hydraulic umbilicals.
- The water depth was too shallow for a buoy power/umbilical solution.
- Water wash was potentially required in 5/42 reservoir to prevent salt deposition in near wellbore reservoir. The water wash design was based around standard drilling water wash modules being lifted onto a suitable laydown area on the platform, as and when water wash was required. There were additional operational complexities of combining dry CO_2 and water which would make a subsea wash water system impractical.
- Problems had at occurred at Snohvit with CO_2 injectivity.

Comment: If the above justifications are reviewed for the Bunter 36 Closure most would no longer apply given a satisfactory operating period at the 5/42 injection site. If aquifer water samples from Bunter 36 showed salinity to be below saturation, and therefore no requirement for water wash, there would be a strong case to consider a subsea development at Bunter 36. It is recommended that a subsea option is retained and highlighted in the report as a potential opportunity to significantly reduce Capex and Opex for the Bunter 36 project.

c. Pipeline routing

The routing options all look reasonable. 5/42 pipeline routing philosophy followed existing pipeline corridors where possible. The routing into the injection site at 5/42 changed significant following the pipeline route survey. Extensive and very large sandwaves were found in the area off to the flanks of the 5/42 reservoir. This resulted in a change in the pipeline approach and some additional cost.

Comment: The northern pipeline route although slightly longer results in closer access to other CO_2 injection sites which may be justified. Pipeline crossing were generally not an issue for the 5/42 development although early engagement with pipeline operators is recommended The pipeline crossing materials cost at £100,000 per crossing looks a little low at least for the larger pipelines. For 5/42 a cost per installed crossing of £1M was used based on a historical costs provided by JP Kenny.

d. Design and Costs

The Capex cost for the 18" pipeline to Bunter 36 were within 10% of the costs development for 5/42 18" pipeline option considered during the feasibility phase.

The following comparison of pipeline vessel rates:

£ per day	5/42 Project	Bunter 36 Closure
Survey Vessel	83,000	100,000
Trenching Vessel	140,000	Not required
Pipeline Lay vessel (S- lay)	600,000	350,000
Diving Support Vessel	182,000	150,000

The following is a comparison of pipeline material costs:

	5/42 Project	Bunter 36 Closure
Coatings (Concrete Weight)	£34 / m	£ 20 / m
Material 18" Line pipe	£254/m (Wall thickness 19.1 mm)	£272/m (Wall thickness 21.3)

A comparison of pipeline Capex is shown below:

£ per day	5/42 Project (90km pipeline)	Bunter 36 Closure (87 km pipeline)
Materials /Procurement	26,994,160	39,000,000
Fabrication	5,280,000	6,710,628
Installation	27,187,402	25,926,839
Project Services / Design	8,760,003	1,210,000
Total (exc contingency)	68,221,565	72,847,464
Total (inc contingency)	78,804,969 (15%)	93,900,381 (28.9%)

Comment: There was a significant difference in the S lay vessel cost. For 5/42 a cost of £600,000 a day was assumed whereas for Bunter 36 this was £350,000. This difference is possibly explained by the downturn in recent oil and gas activity. There was also a large difference in lay rate. For 5/42 a lay rate of 6 km a day and 2 km a day within 15km of shore was specified. These rates were provided by JP Kenny during the conceptual study. For Bunter 36 a lay rate of 2.4 km a day was assumed. There could be potential cost savings for Bunter 36 if the lower day rate and higher lay rate of 6 km a day are acceptable. The wall thickness for the Bunter 36 closure is 2mm greater than 5/42 which accounts for some of the higher materials cost. It is questionable whether a corrosion allowance of 3mm is required for the trunkline as the CO_2 must remain dry under all operating circumstances. National Grid removed any corrosion allowance from trunkline designs.

2. FACILITIES

a. Design and Costs

The wellhead platform design PFD appears almost identical to the 5/42 platform design. The cost of the 5/42 wellhead platform (18" option which excludes the Booster pump hang off module structure allowance) was £96M (including contingency). The estimate for the Bunter 36 Closure wellhead platform post FID was £94M (including contingency) which was estimated using Questor.

A comparison of the costs is shown below:

£ per day	5/42 Project	Bunter 36 Closure
Materials /Procurement	29,362,000	26,469,381
Fabrication	30,561,000	21,542,917
Installation /Commissioning	14,422,000	29,149,325
Project Management /Engineering	12,718,000	16,900,000
Indirect costs	9,216,000	Included above
Total (inc. contingency)	**96,279,000**	**94,061,622**

Comment: The site survey for 5/42 identified areas of hard ground on the sea floor. This appeared to run along the crest of the Bunter 5/42 reservoir. Conventional piling was not feasible and a drill and grout technique was required to install the jacket which added considerably to the installation costs. If the Bunter 36 site displays a similar characteristic to 5/42 then these additional costs could also be incurred.

b. Commissioning - Low Temperature

Careful consideration should be given to the initial start-up of Bunter 36 pipeline. Assuming 5/42 is in operation prior to Bunter 36 it is unlikely that the main trunkline between Barmston and 5/42 would be depressurised to connect Bunter 36 trunkline to the platform. This creates a HP/LP interface between 5/42 and Bunter 36 trunklines. During commissioning either heating of the 5/42 CO_2 or backpressuring of the new Bunter 36 trunkline would be required to avoid very low and unacceptable temperatures (-70 deg C) occurring in the Bunter 36 trunkline.

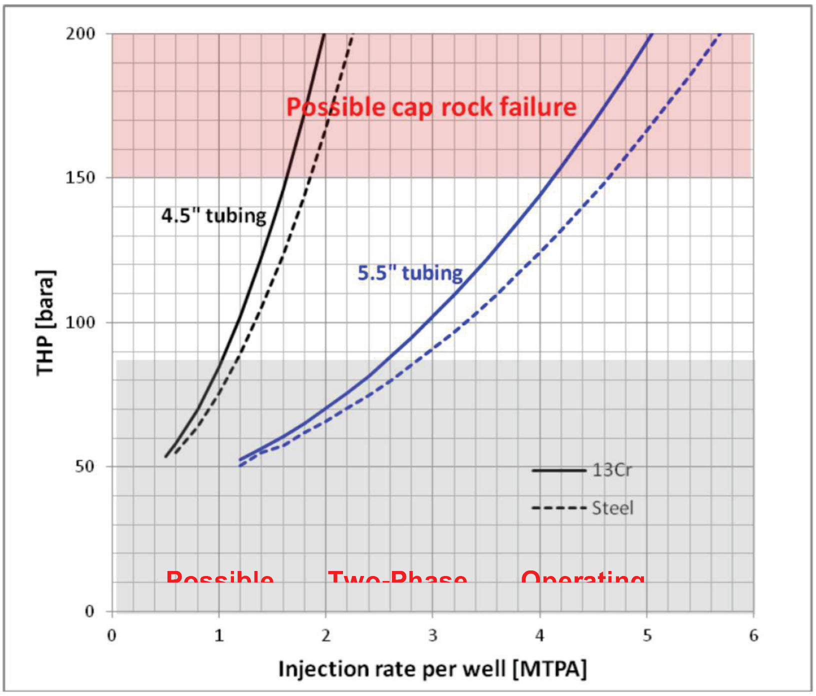
Comment: Dense phase CO_2 can result in a number of commissioning issues around low temperature, pipeline drying and pipeline cleanliness which would not typically be an issue with hydrocarbon pipelines. Commissioning should be considered in some detail during conceptual design.

3. **WELLS**

a. **Capacity**

The well capacity for 5/42 wells is shown below against tubing head pressure. The injection capacity of a well varied from between a minimum of 2.5 MTPA (to avoid 2-phase flow in the tubing) and 4 MTPA (to avoid potential cap rock failure) for a 5.5 "tubing. This appears to match with the Bunter 36 closure well capacities stated in the presentation.

During 5/42 conceptual design no modelling software could reliably model vertical two phase CO_2 hydraulics. Although it was perceived two-phase flow in the wellbore would not be an issue in terms of vibration, fatigue and stability it could not be reliably proved. For this reason both National Grid and Shell Goldeneye proposed using a frictional tubing imposed back pressure. Either a 4.5" or 5.5" tubing was used to create a range of acceptable operating windows for injection. Neither company felt downhole flow control was reliable enough to be used given the variability in flowrates imposed by power stations and the low cost/margin long term disposal nature of the operations.



Comment: It is recommended that the well capacities for Bunter 36 closure are aligned with the National Grid composition specification which allows for impurities in the CO_2 and higher summer ambient sea temperatures in shallow water (up to 16 deg C). The National Grid minimum allowable tubing head pressure is 84 barg compared to around 40 barg for the Bunter 36 design. It is also noted that both Shell Goldeneye project and National Grid 5/42 discounted downhole valve backpressure control on the grounds of reliability.

b. **Water Production Wells**

5/42 required water production to maximise storage potential and avoid uncontrolled water discharge from the outcrop. One of the key risks was the environmental acceptability of discharging highly saline warm water at the seabed. Modelling of water discharge salinity concentrations with distance and the design of the well outfall remained key high risks on the risk register for 5/42.

Comment: Although water production is unlikely to be required for Bunter 36 closure, if this decision is revisited during future reservoir modelling the impact of the saline water discharge should be considered, and a sample of the aquifer water obtained early in the design.

c. CO_2 Injection Well Water Wash

During injection well water wash operations CO_2 column in the well tubing would be displaced by water. The higher density of water results in a large drop in the tubing head pressure which would approach ambient pressure once the entire column of CO_2 had been displaced. On completion of water wash the CO_2 injection would drop to very low temperature across the choke as a result of the low back pressure. Water wash operations therefore should consider displacement of some of the water column either with nitrogen or heated gaseous CO_2 to increase the tubing head pressure prior to re-introduction of the CO_2 injection.

Comment: Although water wash operations are common in hydrocarbon wells they have not been completed in CO_2 injection wells. The operational risks of corrosion, hydrates and low temperatures rations should be considered carefully during conceptual design.

d. Well Materials – Oxygen specification

During normal injection operations the well tubing is exposed only to dry CO_2 and therefore will not be subject to corrosion. Two key corrosion risk areas were however identified during 5/42 well design:

- During water wash operations the tubing will be exposed to water and CO_2 which will be highly corrosion. Careful dosing of the water with corrosion inhibitors and de-oxygenation chemicals will be required to protect the well tubing.
- The bottom of the well tubing will be exposed to CO_2 and saline aquifer water, particularly following a shutdown of injection. This combined with residual oxygen from the power station capture process can result in a highly corrosive environment even for CRA materials. Materials such as Hastelloy are required to protect the tubing unless oxygen levels are specified to be below 50 ppb (parts per billion). Options considered include plastic lined tubing and a non-return valve arrangement to ensure water cannot flow back up the tubing

Comment: Well material design for CO_2 injection into saline aquifers can be challenging and should be considered at an early stage. Additional costs for downhole valves and CRA/lined materials in the bottom section of the tubing should be considered.

4. SCHEDULE

The Schedule for Bunter Closure 36 is similar in overall duration to 5/42 post-FID at around 4.5 years. The pre-FID duration is assumed to be 18 months presumably to allow for both conceptual and FEED studies. The FEED for 5/42 was completed in less than 1 year. Detail design for both projects was assumed to be around 1 year which is reasonable. Procurement durations of around 18 months are also similar to those assumed for 5/42.

Comment: Given the learnings and similarity to 5/42 design it would be expected the FEED for Bunter 36 could be completed in around 9 months. Also typically a simple hydrocarbon wellhead platform and trunkline could be completed in around 3 to 3.5 years so the existing schedule is fairly generous. However, given the previous history of CO_2 projects it is probably reasonable to allow an additional 12 months as is presently presented.

Report by G.E. Pickup on Strategic UK CCS Storage Appraisal Project

December 2015

Introduction

Pale Blue Dot and Axis have performed a thorough study of the Bunter 36 site. This includes a review of geological, petrophysical and seismic data, building of a new geological model and dynamic simulation of CO_2 injection. Many practical details have been considered, such as the number of wells required for injection, the nature of the wells and the completions, and the pipeline facilities required to transport the CO_2. Finally, a costing for this project has been developed. This report focuses mainly on the modelling.

At the meeting on 30th November, the team showed that they had researched previous work in this area, and had an in-depth knowledge of all the issues. They were able to answer the questions and comments made by the reviewers. Overall, I have confidence that the team will make a good job of assessing the five selected storage sites to the level required in the current project.

Geophysics and Geological Modelling

Seismic data from the PGS UK Megamerge 3D was used along with the CDA well data for the region, in order to build-up a comprehensive picture of the geological structure and petrophysics in the region. I was interested to note that when the depth conversion of the seismic data was carried out using a layer cake model, the location of the spill point changed from the NE (as in the model for the ETI UKSAP Exemplar Study) to the SW of Dome 36. Obviously this indicates that careful depth-conversion is required when assessing likely CO_2 migration routes at any CO_2 storage site.

The geological interpretation and modelling seems fairly standard. I queried the accuracy of the upscaling, because I was concerned that some low permeability shales and cemented zones might be lost. However, it was pointed out that slide 17 of the pre-read Static Model slides only shows horizontal permeability, and that there were still some low permeabilities in the vertical permeability of the upscaled model. Some loss of fine-scale detail is inevitable with upscaling, but simulations would take too long with fine-scale models.

An issue regarding the quality of the Bunter sandstone was raised by one of the participants. There is apparently evidence in 5/42 that the sandstone off-flank could be of poorer quality due to halite precipitation. I am not an expert in this area, but it seems to be something which should be noted as a possible problem, if the Bunter Dome 36 is to be considered for CO_2 storage in the future. I do not think much more work is required on this for the time being.

Dynamic Simulation

Simulations were performed using Eclipse 100. (This is a black oil simulator, but can be modified to take account of CO_2 storage.) The sensitivities included investigating the number and location of wells, the size of the aquifer and the CO_2-brine relative permeability curves. It is well-known that these are issues which affect the CO_2 storage capacity. A similar study of Bunter Dome 36 was carried out several years ago for the ETI UK SAP (Williams et al, IJGGC, 2013). Although that study used a different geological model, had different well placements and slightly different well controls, the predicted range of storage capacities was similar, and the conclusions from that study, and similar studies carried out at HWU are the same, for example:

- If CO_2 is injected at too high a rate the pressure will build up at the wells, so they rate will have to be cut back, or the wells shut in.
- There is pressure interference between wells, so they cannot be placed too close together.
- The aquifer size (total connected pore space) has a very large effect on the storage capacity estimates.

There was a discussion on relative permeability. Laboratory data on CO_2-brine relative permeabilities is scarce (compared to oil-water ones), and results from different laboratories are highly variable. Three sets were used in this study, and it was shown that, although the end-point relative permeability for CO_2 was very variable, the shape of the water relative permeability was also variable and affected the results. (Perhaps this can be explained by Buckley-Leverett fractional flow theory.)

A tornado plot for the sensitivity results was shown in the presentation, but this was not in the pre-read slides. It would be a good idea to show this in the final report.

I think this was a good simulation study for this stage in the assessment of a storage site. For a more detailed investigation (i.e. if a storage project was to go ahead at this site), I think an investigation of the effect of grid resolution and pressure build-up near the wells should be undertaken.

Wells

An investigation into the best type of wells to use (deviated) and the completions and the operating conditions was carried out. It was concluded that temperature variations (e.g. Joule-Thomson cooling) was not a serious issue (at least not in the long term). The possibility of halite deposition near the well was considered, and so facilities for injection of water will be required. (One of the reviewers suggested that that water in the well could cause some problems.) We were informed that, since the pre-meeting slides had been sent out, Axis has performed a geomechanical study, which included investigating the effect of a fault in Dome 36.

Development Plan and Budget

Several options for a CO_2 pipeline were considered and it was decided that the best option was a pipeline from the 5/42 White Rose site. The pipeline would be routed to minimise the number of crossings with other pipelines. The plans for a normally unmanned platform were discussed, and also the budget for such a project was outlined (total cost ~ £1.2 B).

Appraisal Plan

There is an issue over whether a seismic survey is required to make the decision for placing an appraisal well, or whether the location for an appraisal well could be chosen based on current knowledge, and a seismic survey could be taken later. In addition, there is the question as to whether the appraisal well should be just for appraisal, or whether it could later be used as an observation well, or indeed an injection well. This issue is not yet resolved.

Containment

There is always the question of why Dome 36 does not contain natural gas. (Is it because the caprock is fractured so gas has escaped?) The team demonstrated that they had studied the migration gas into nearby fields. This seems to occur where the Zechstein Salt is thin and fractured. However, this is not the case near Dome 36 (although there is a thin layer of Zechstein to the south-east of Dome 36, and it's effect needs to be explained).

Regarding the issue of whether there are any fractures at the crest of Dome 36, it was pointed out that the nearby Hunter Field has a fracture, but still contains gas.

Monitoring methods have been chosen based on the screening techniques developed by NETL and IEAGHG, and include side-scan sonar, 4D seismic surveys and well logging.

Conclusions

Although more checks and simulations could be performed on Dome 36, I think the amount of work performed at this stage is adequate for the estimation of CO_2 storage capacity at this site.

I recommend that some of the issues raised at the meeting should be addressed in the final report for the project.

My only concern is that PBD and Axis have a lot to do in a short time, in order to complete the reviews of other four storage sites by March 2016.

Review, commentary, feedback ETI-DECC CCS Storage Appraisal

Pale Blue Dot, Banchory, 8 December 2015

Professor Stuart Haszeldine, University of Edinburgh

Outline of event

At the invitation of Pale Blue Dot, a second expert peer assist event was held on 30 November, from 10-16H. This received a pre-read of results from the work undertaken after the previous 6August review. That took the form of many tens of ppt slides, compiled with maps, graphs and commentary. It is notable on the project Plan, that there is no extra review scheduled until the final report.

It may be worth a short external check before report writing starts in mid-Feb.

A series of shortened summary presentations were given during the meeting by specialists from Pale Blue Dot, and by subcontractors Axis, with ample time for structured discussion, questioning and feedback. The main focus of the meeting was structure Bunter 36.

Helpful and useful technical exchanges were made between PBD and the advisory group, together with the implications for CO2 storage. This short report summarises my own opinions and recommendations, some of which may contradict, or may support, those of other participants.

Present were Alan James, Steve Murphy, Shelagh Baines (by phone) (Pale Blu Dot), Sharon McCollough, Ken Johnson, David Hardy, Doug Maxwell (Axis), Jon Gluyas (Durham, phone), Steve Furnival (by email comments), Richard Nixon (Ingen – Amec), Angus Reid (Costain), Steve Cawley (BP), Gillian Pickup, Stuart Haszeldine (External experts), Andrew Green (ETI), Brian Allison (DECC)

Comments on work programme

The aim of the work programme, tasked by DECC, and enacted by ETI, is to develop desk study appraisal methods and use those to progress the certainty of storage in about 1,500,000,000 t of CO2 available on the UKCS for 2030.

After pre-screening of all UK sites, five representative UK sites have been selected. The purpose of this meeting was to assess the approach, the technologies, and the progress made on the first of these sites, Bunter Closure 36, which is located in UK offshore Block 44/26.

Overall the project is progressing extremely well, and this snapshot appraisal of Bunter 36 provides a significant addition to existing information. That gives additional confidence that there is abundant

CO_2 storage in this structure, and that the pipeline and offshore engineering can be developed in a cost-effective way.

Sites overview

All sites in www.CO2stored were appraised to move to 5 mature sites. The process used screening criteria, part of which were IEAGHG guidelines. A side effect of those is that it could appear that the UK has a greatly reduced capacity for CO_2 storage. That is not the purpose of the screening, and so there is scope for accidental, or deliberate, mis-representation of UK capacity if some graphs are publicly released.

I recommend that the messaging and graphics for downsized capacities are carefully considered by project sponsors or external reviewers, to ensure that the selection process is communicated, not the storage capacity, before any public release.

Additionally, and not discussed yet, is the problem about how these results are archived and how these are to be incorporated into www.CO2stored.com

Bunter site 36 geology

Reflection seismic surveys have been re-analysed, and 3D interpretation made. Bunter boreholes are located on maps. But additional boreholes into the underlying Schooner field are not shown. Because boreholes are the largest of the small risks analysed for CO_2 leakage, it would be helpful to have at least one display map of all 9 extra boreholes into and around the 36 structure.

Structure shape and depth were achieved by different depth conversion of seismic reflection. This changed depths and spill points locations. Internal reservoir geometry with mudrock baffles is imperfectly known. Simplification and upscaling appeared to lose detail. This is quick and adequate for the present purpose, but needs to be clearly stated when reporting.

An appraisal well is needed for calibration.

Based on seismic and limited boreholes, and un-studied core, it is hard to be definitive about the porosity areal and vertical distribution in Bunter 36. Comparisons with emerging information from FEED on 5/42 suggest that the two nearby structures have very different reservoir quality. In particular the 5/42 has a "phase reversal" of seismic interpreted, and that high porosity marker does not extend to Bunter36. It is beyond the scope of this quick-look study to elicit these causes – and hence prediction of porosity across a structure and the intervening aquifers. *Reservoir quality is an imperfectly-estimated risk.*

The top seal was discussed. The reservoir structure is a dome with 7 degree dip on each side. It is likely that the rock is very fractured. Overlying is an evaporitic marl and a “salt” layer. These are essential physical seals and should be resilient against leakage in a general sense. No direct evidence exists.

The implications of fractures for top seal retention of CO2 need to be modeled .

Methane gas charge into Bunter 36 has not occurred, based on present day structure maps. Again beyond the scope, these need backstripped to understand the palaeo-topography and connections. And then combined into a regional scale basin model. *Small cores are available, these need to be examined in a subsequent project.*

The salinity of present formation water is unclear, and may be based on extrapolated measurements from nearly fields. *This needs to be clarified, so that initial injection, and especially salt precipitation can be better simulated.*

Dynamic modeling of CO2 injection

This has been modeled using ECLIPSE 100, with a normal approach of reservoir rock property distributions. Four different relative permeability values have been triailled- this is a sensitive parameter. But choosing a single value or approach is not clear.

Different well patterns and injection rates have been scoped by modeling multiple sensitivities and scenarios. Well positioning is clearly important – off to northwest all on one side being best. It is clearly a major determinant of the total capacity. The rate of injection is also important, to avoid breaching a pressure top seal. Brine production as a pressure control is not yet fully investigated. Interaction of pressure with 5/42 has been scoped, and there will clearly be a connection and degradation of mutual storage capacity. A brief tornado diagram of effects on capacity was shown. Reservoir size, surrounding underburden and side seal by halite cement are very important controls.

The different effects on capacity need to be explained and graphically illustrated

Costings and well design, and abandonment

Boreholes and pipes were presented as standard types of equipment components. Costings were based on UK prevailing rates today. Injection of CO2 from converted low cost manifold and lightweight jacket. There seems to be potential here to reduce costs progressively with serial build, and modular components. Lead-ahead time on booking offshore kit is two years.

Graphical communication of equipment costing options would be hepful

Appraisal drilling

The Bunter 36 can clearly accept CO2, but a new well is needed to gain data on reservoir in in situ properties – including extensive core, fuid samples, and in-situ stress directions. There are multiple options, not yet well worked through.

A clear graphical recommendation of "how to proceed" with costs and timescales would be a useful summary of the whole site study.

Conclusion

PBD and Axis have achieved a very large quantity of accurate work in a short time. This is an excellent level of detail for this stage, and is adequate for SUKSAP purposes. It may be that 4 additional sites can not be undertaken at the same level of detail. Following the style and workflow detail developed for Bunter 36 will be very fine for comparisons, and for validating UK capacity.

The management structure and style seems very fit-for-purpose, and an excellent technical team is in place to make this deliver.

END

11.6 Appendix 6 – Geological Information

11.6.1 Maps

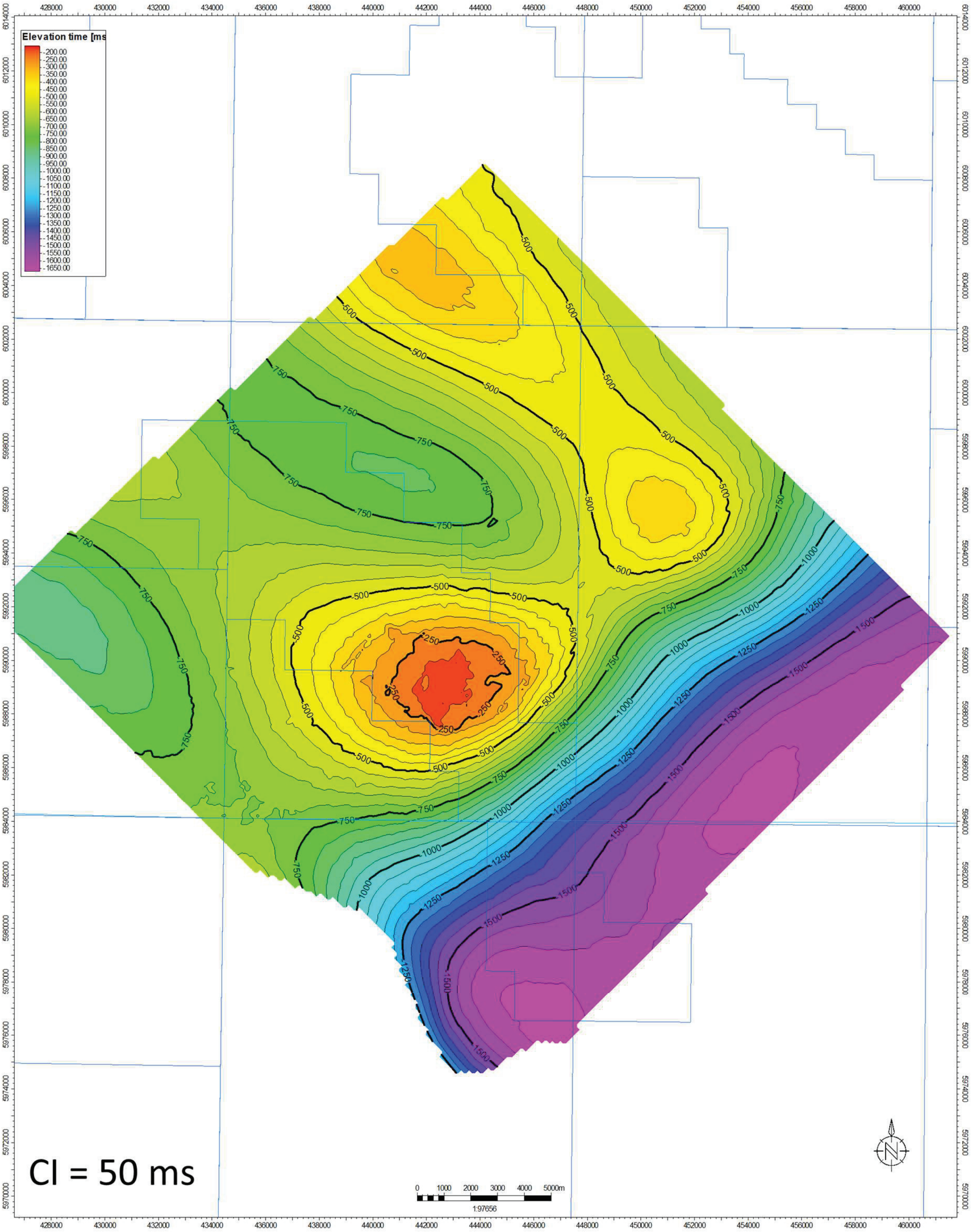


Figure 11-4 Top Chalk TWT map

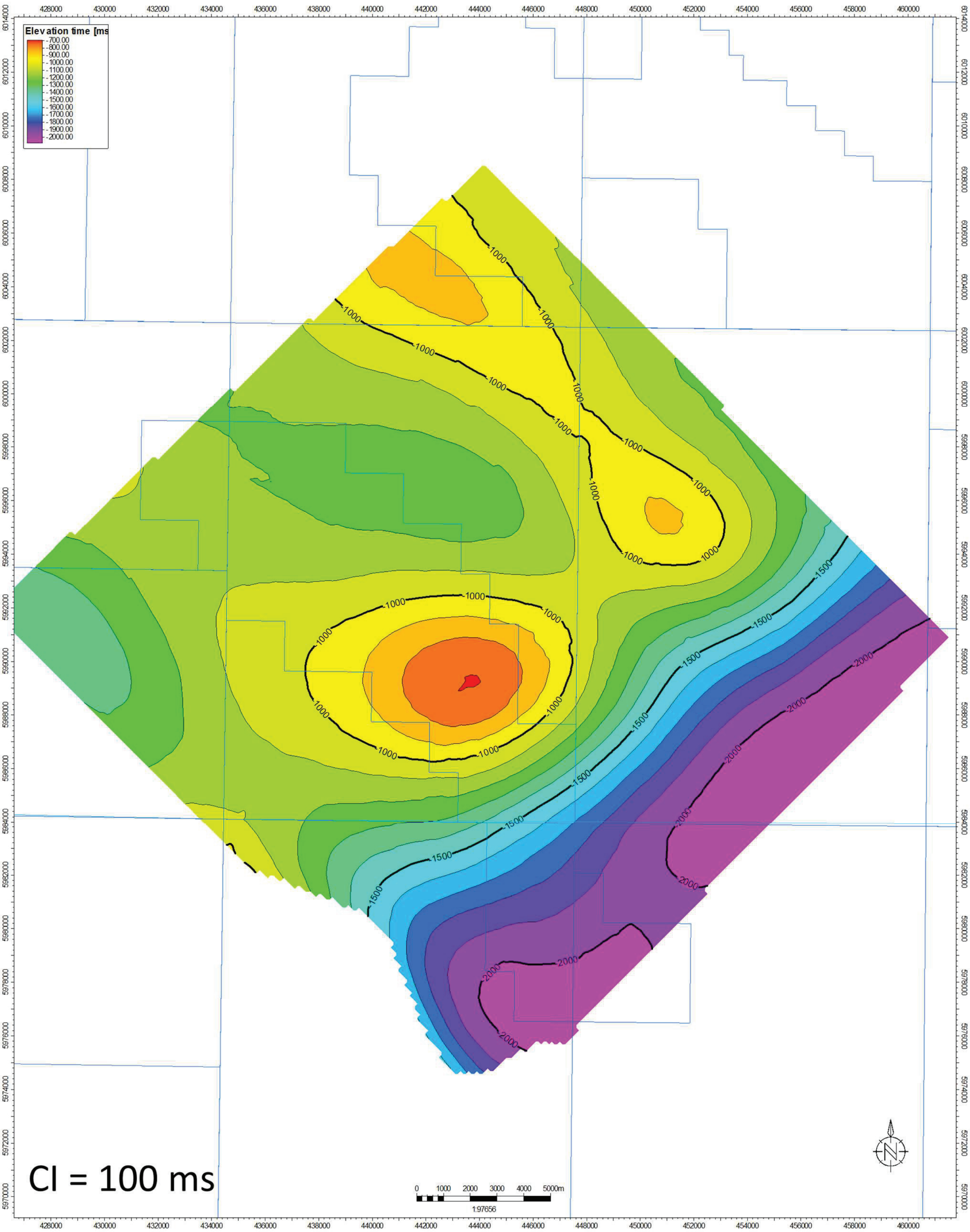


Figure 11-5 Base Cretaceous TWT map

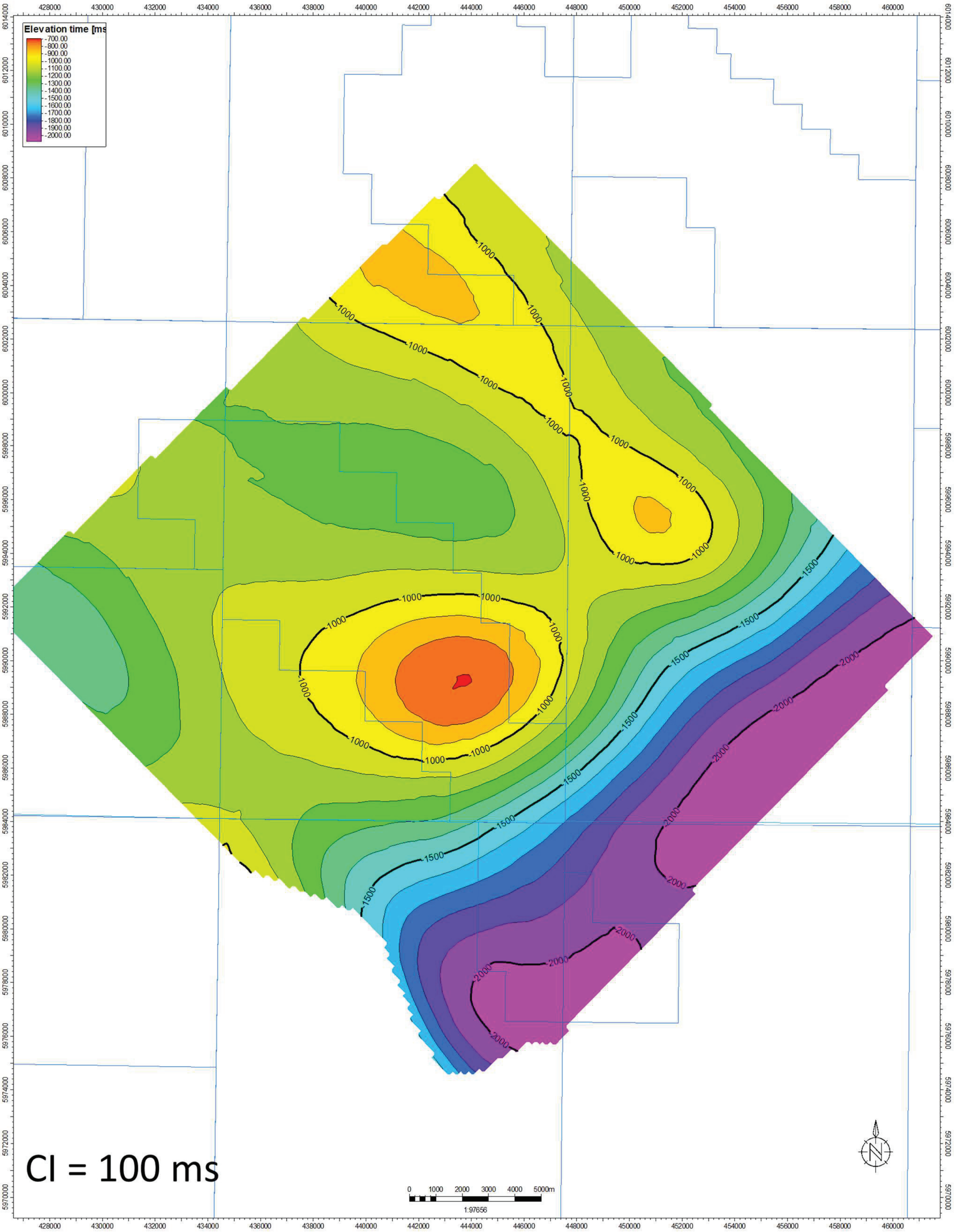


Figure 11-6 Top Triassic TWT map

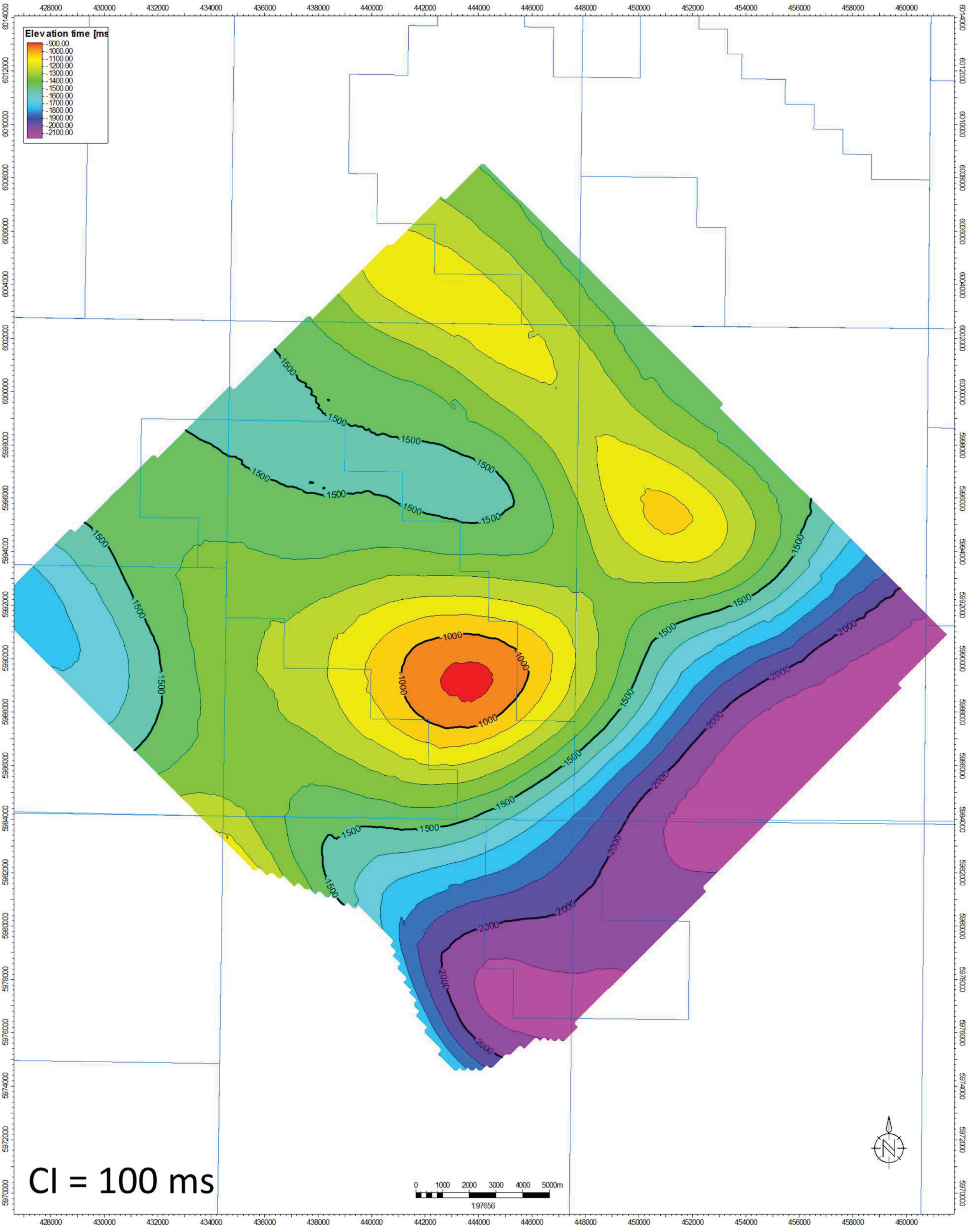


Figure 11-7 Top Bunter Sandstone TWT map

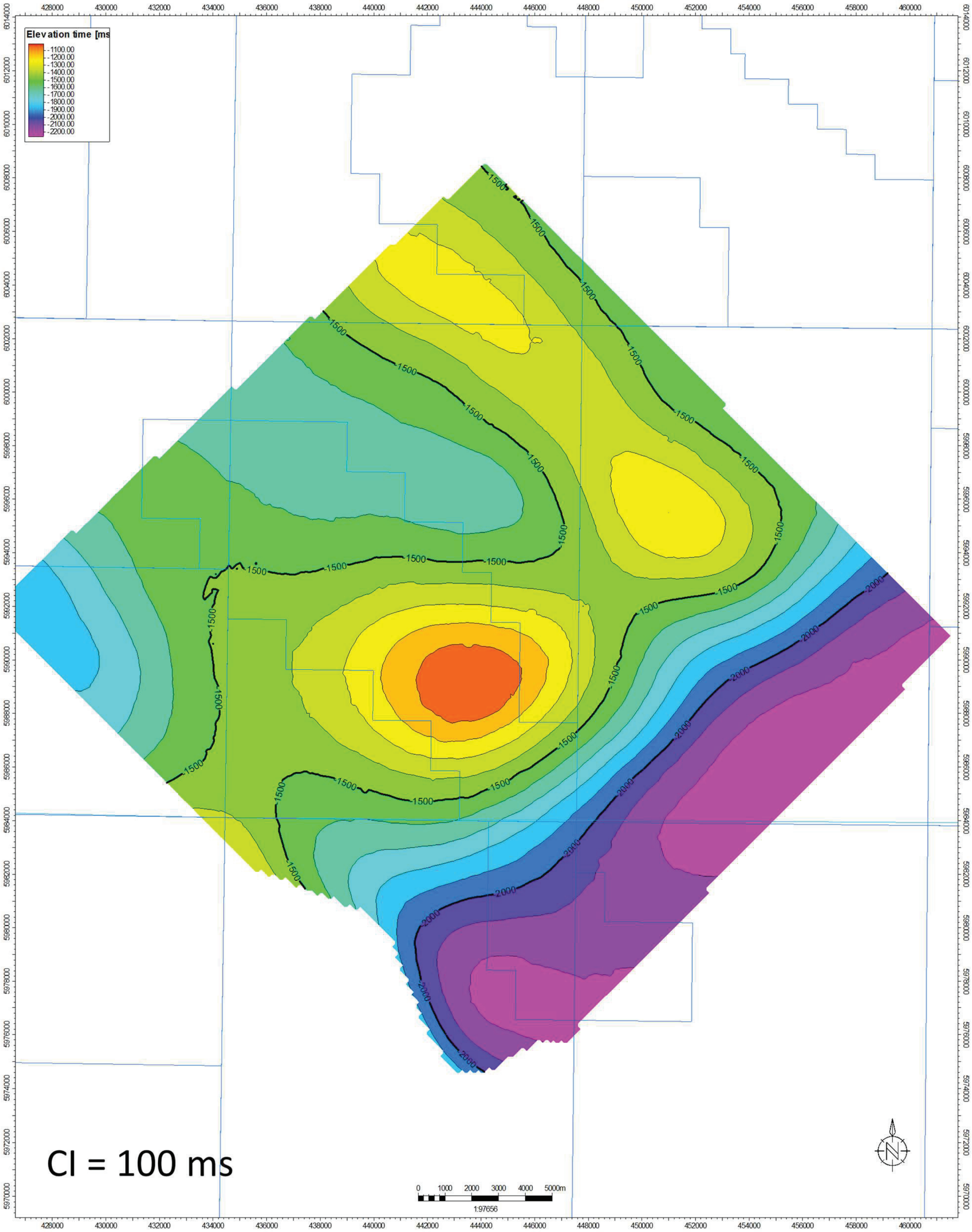


Figure 11-8 Top Bunter Shale TWT map

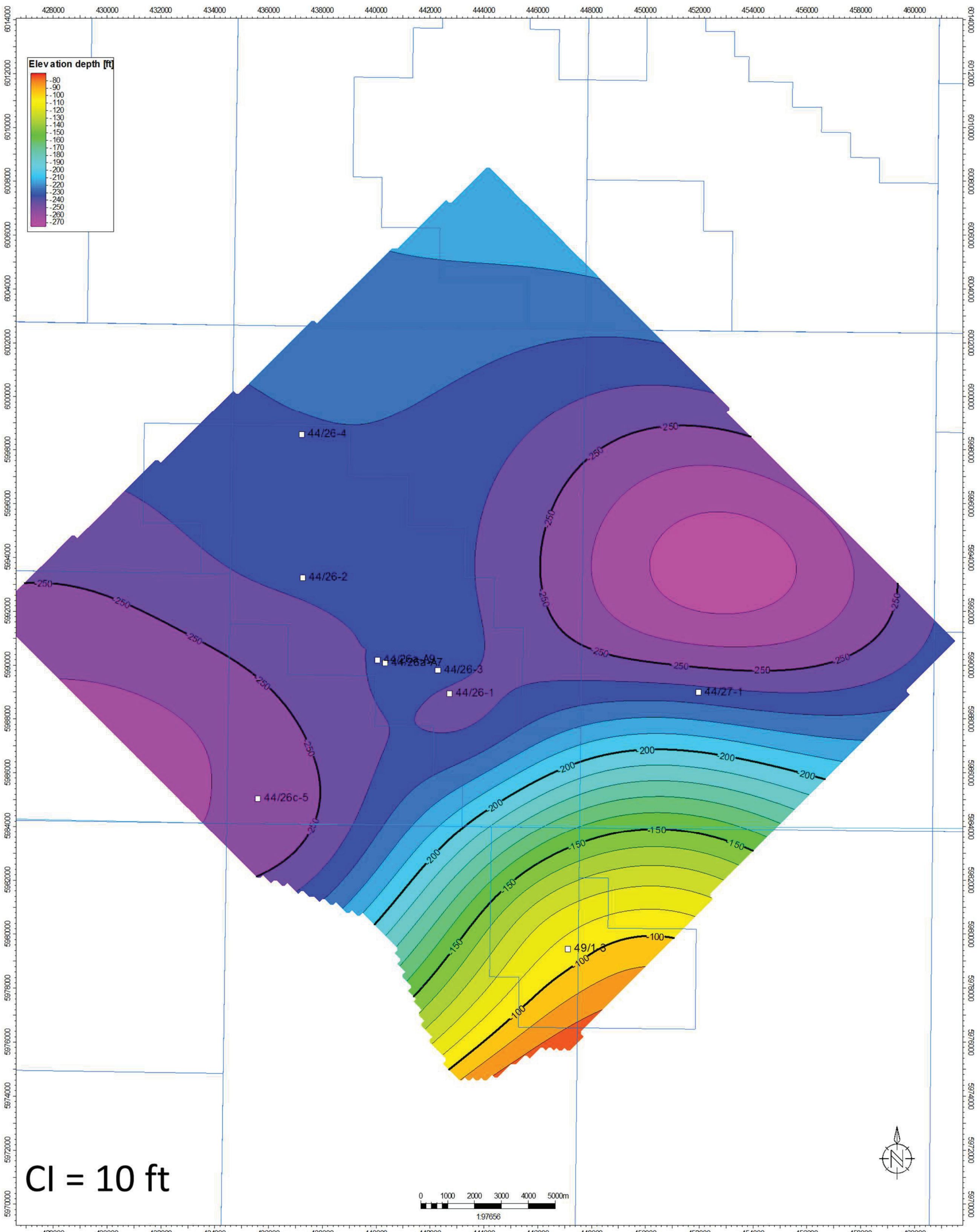


Figure 11-9 Sea bed depth map

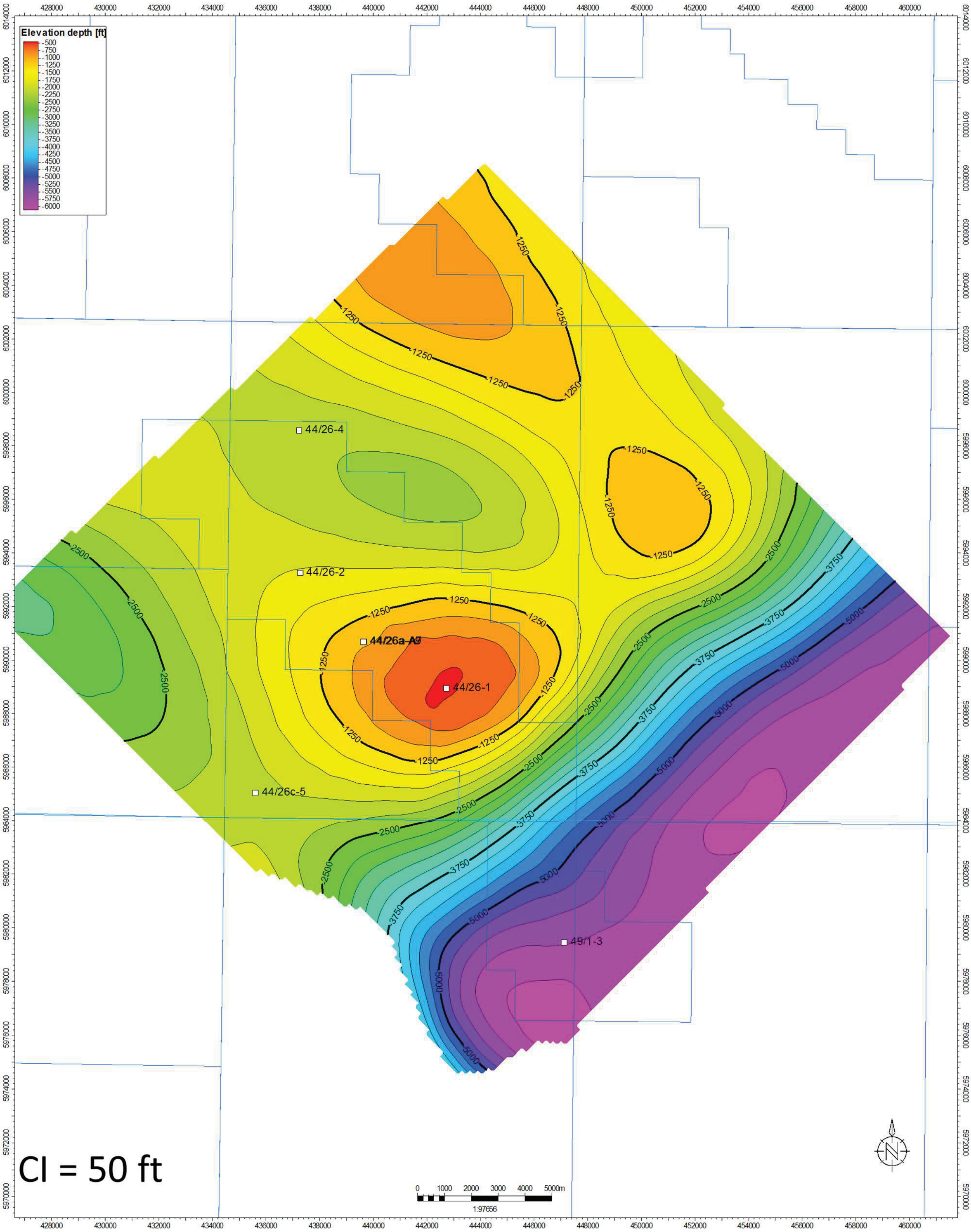


Figure 11-10 Top Chalk depth map

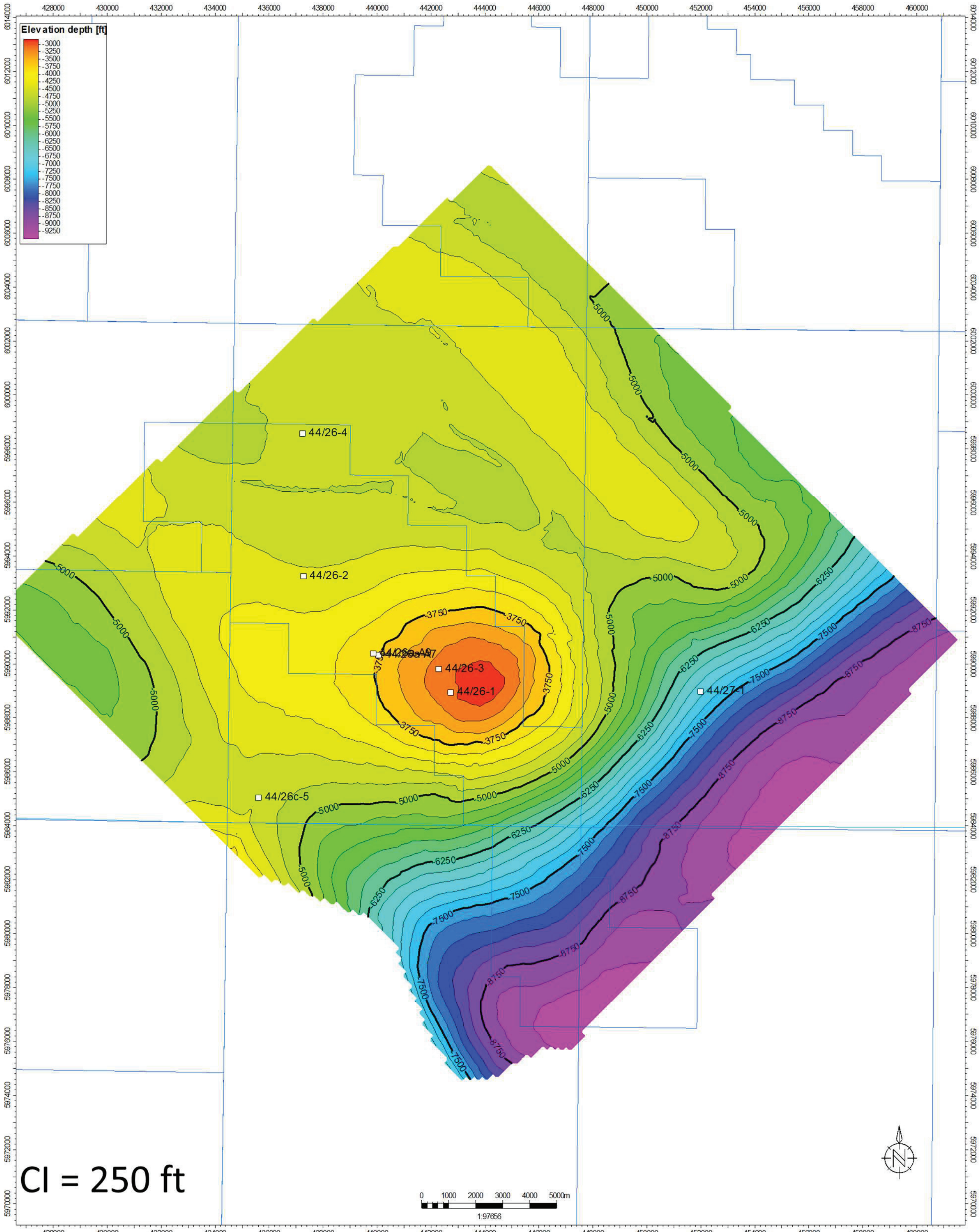


Figure 11-11 Base Cretaceous depth map

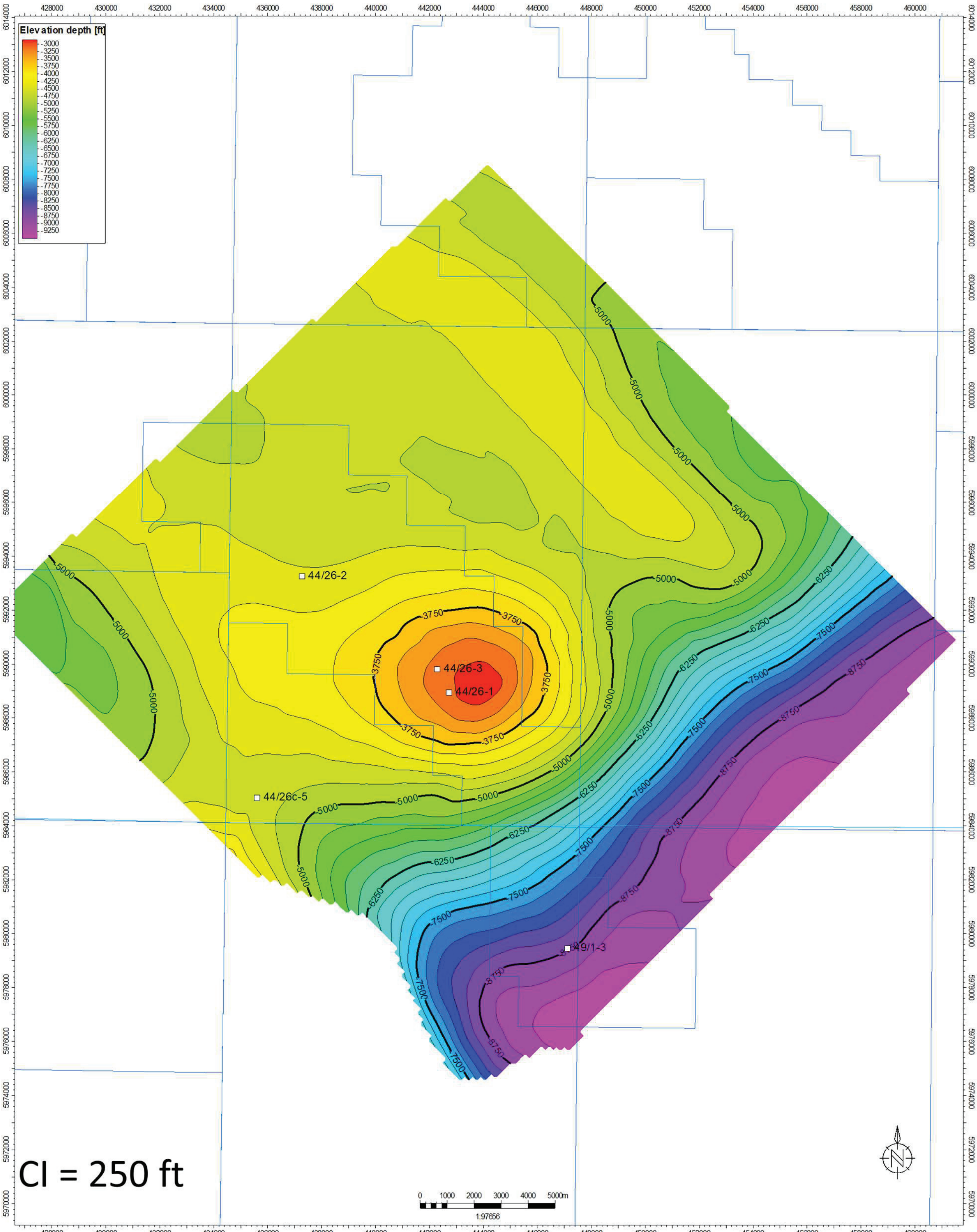


Figure 11-12 Top Triassic depth map

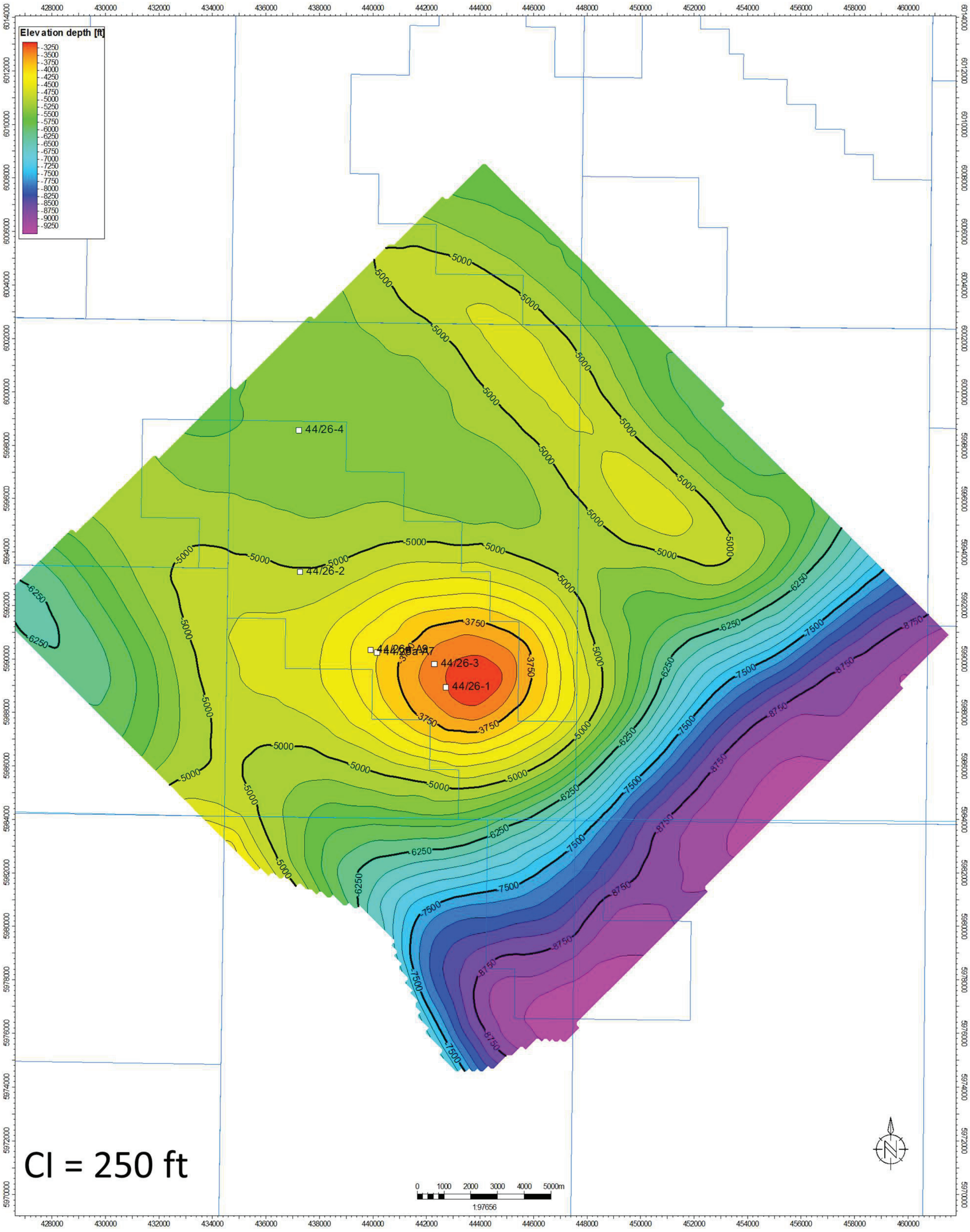


Figure 11-13 Top Muschelkalk depth map

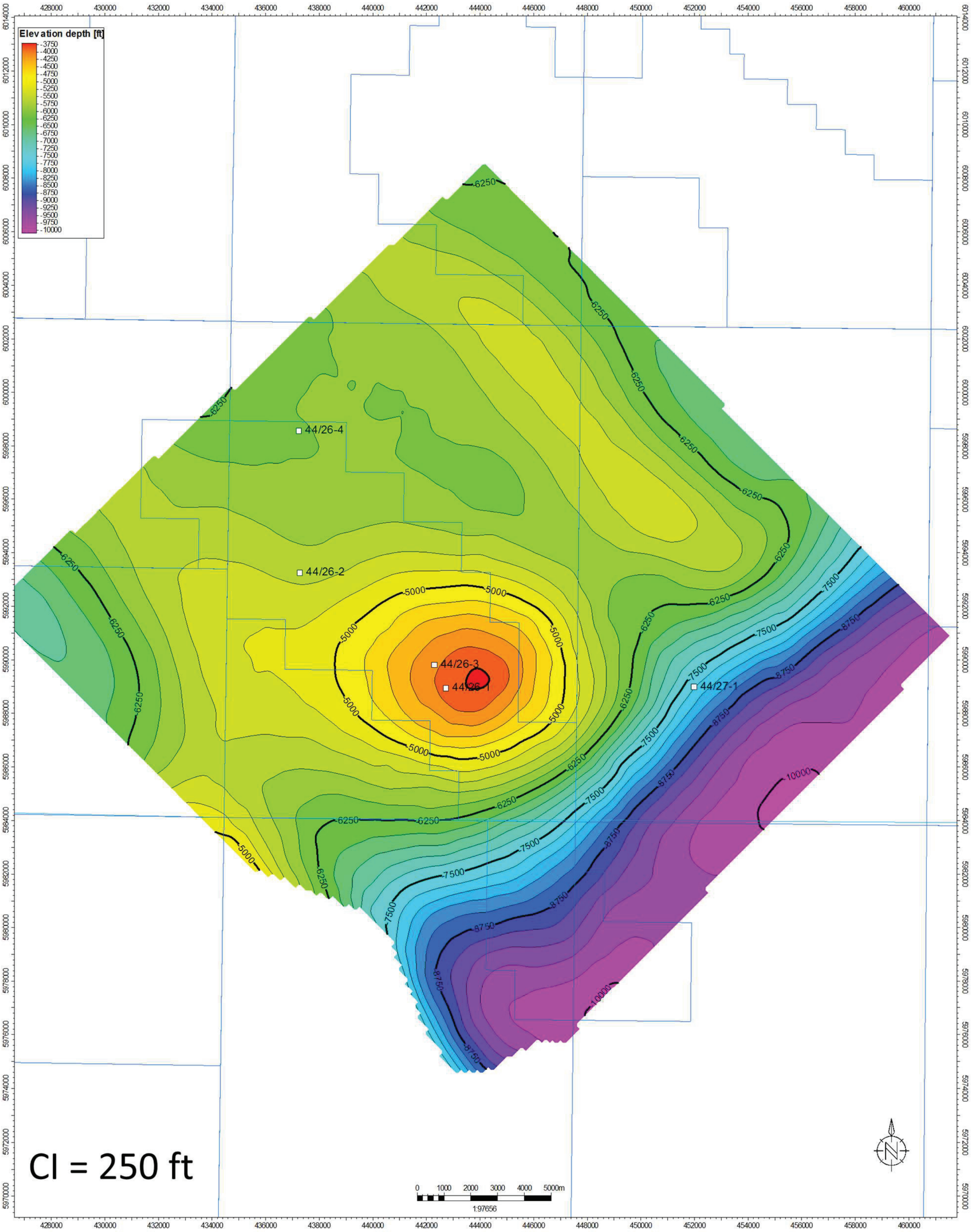


Figure 11-14 Top Rot Halite depth map

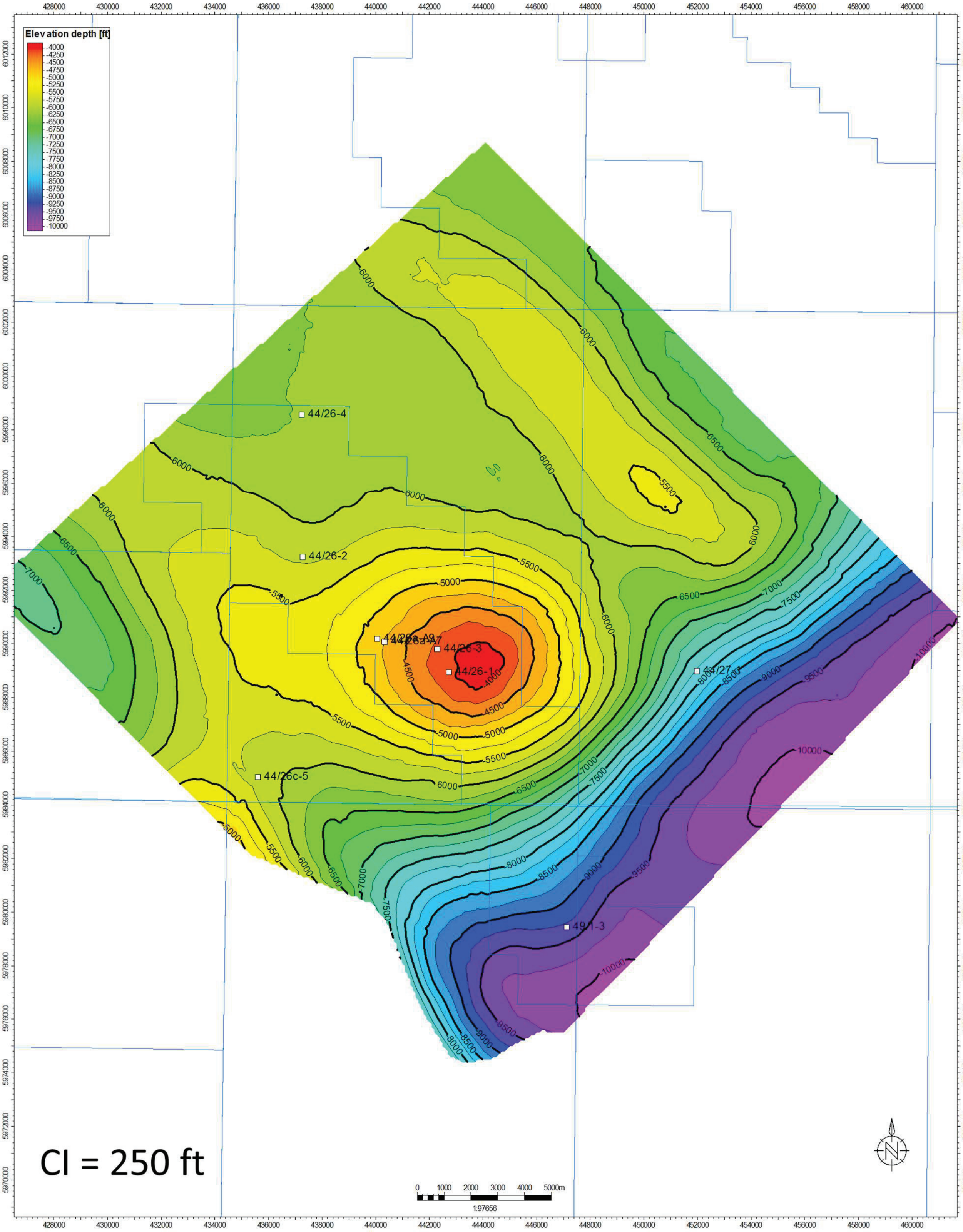


Figure 11-15 Top Bunter Sandstone depth map

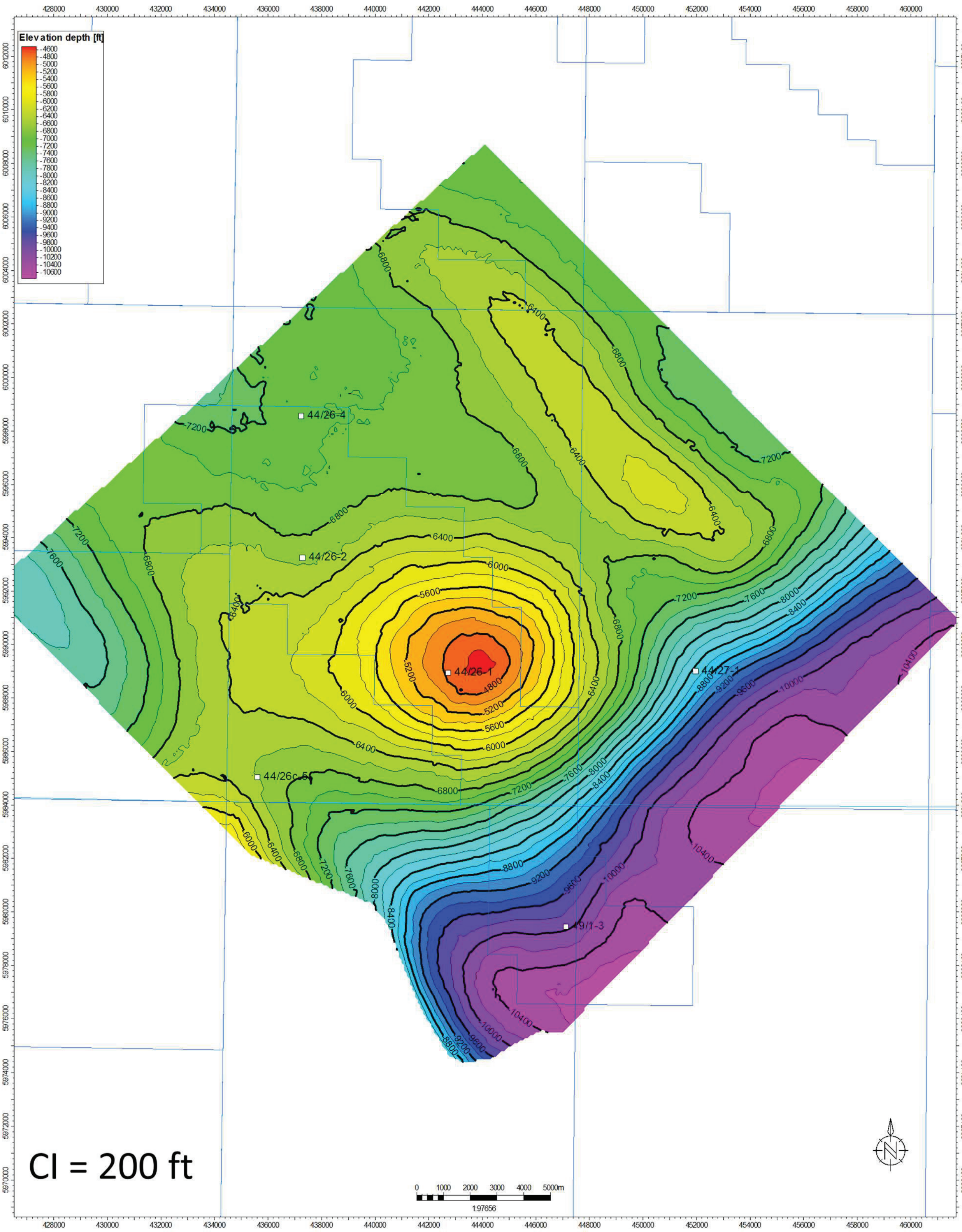


Figure 11-16 Top Bunter Shale depth map

11.6.2 CPI logs

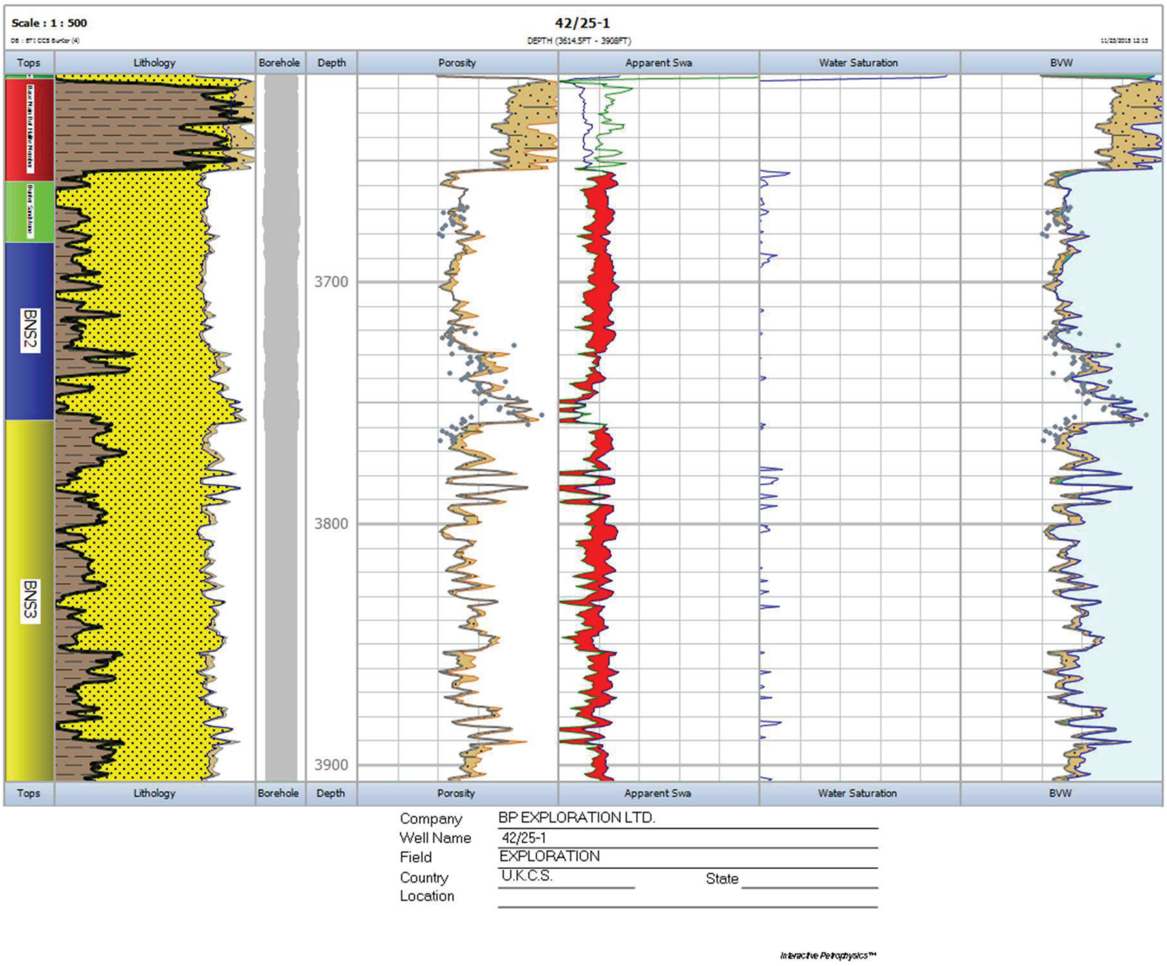


Figure 11-17 Well 42/25-1 Interpretation

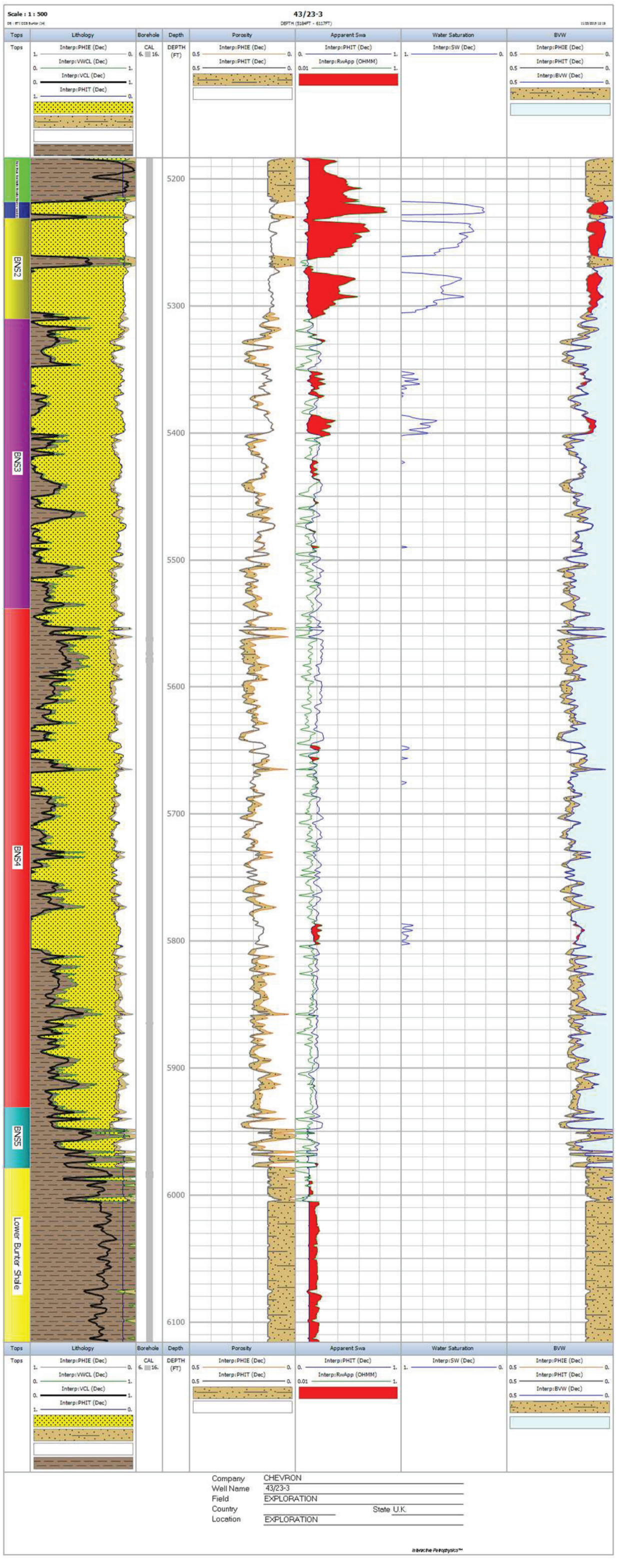


Figure 11-18 Well 43/23-3 interpretation

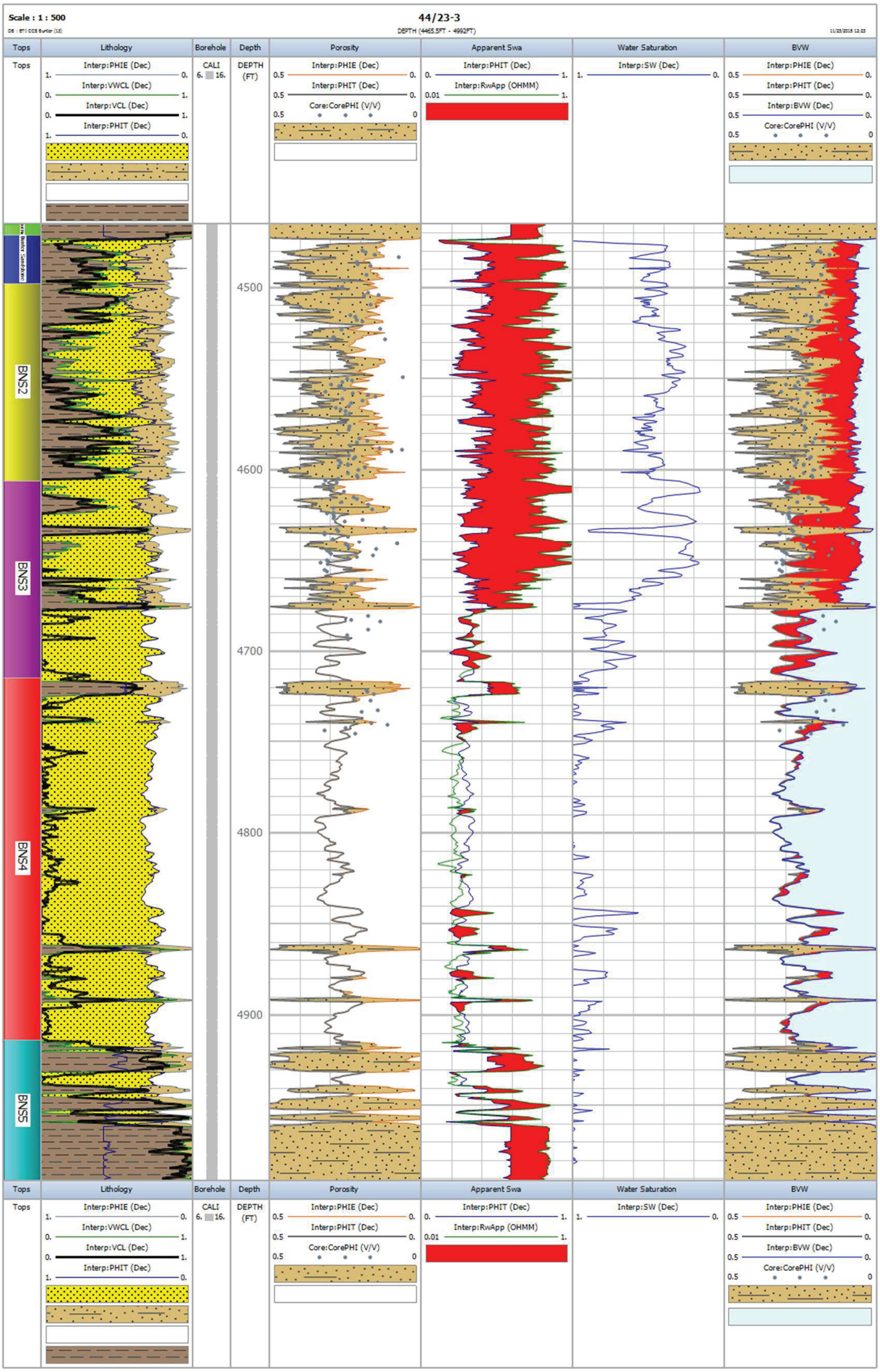


Figure 11-19 Well 44/23-3 interpretation

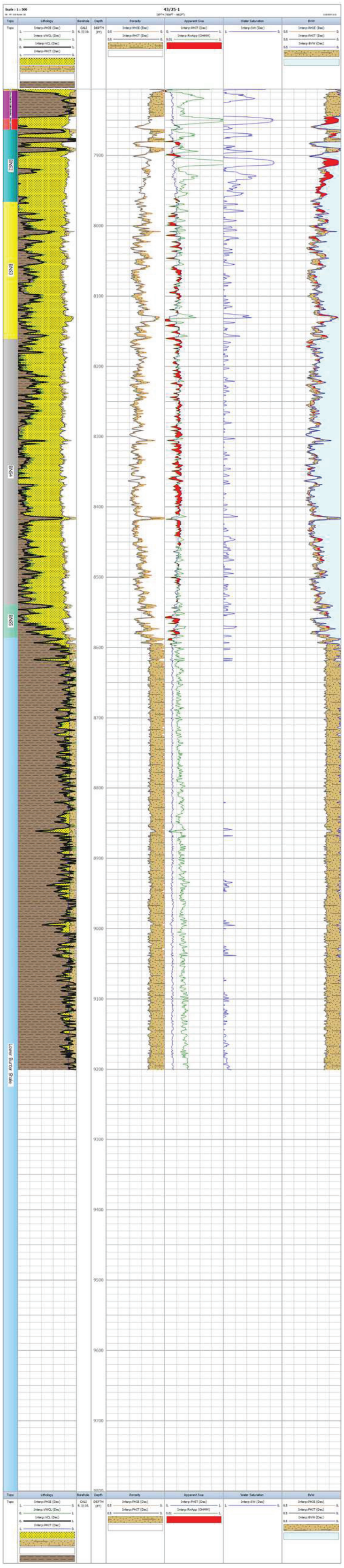


Figure 11-20 Well 43/25-1 interpretation

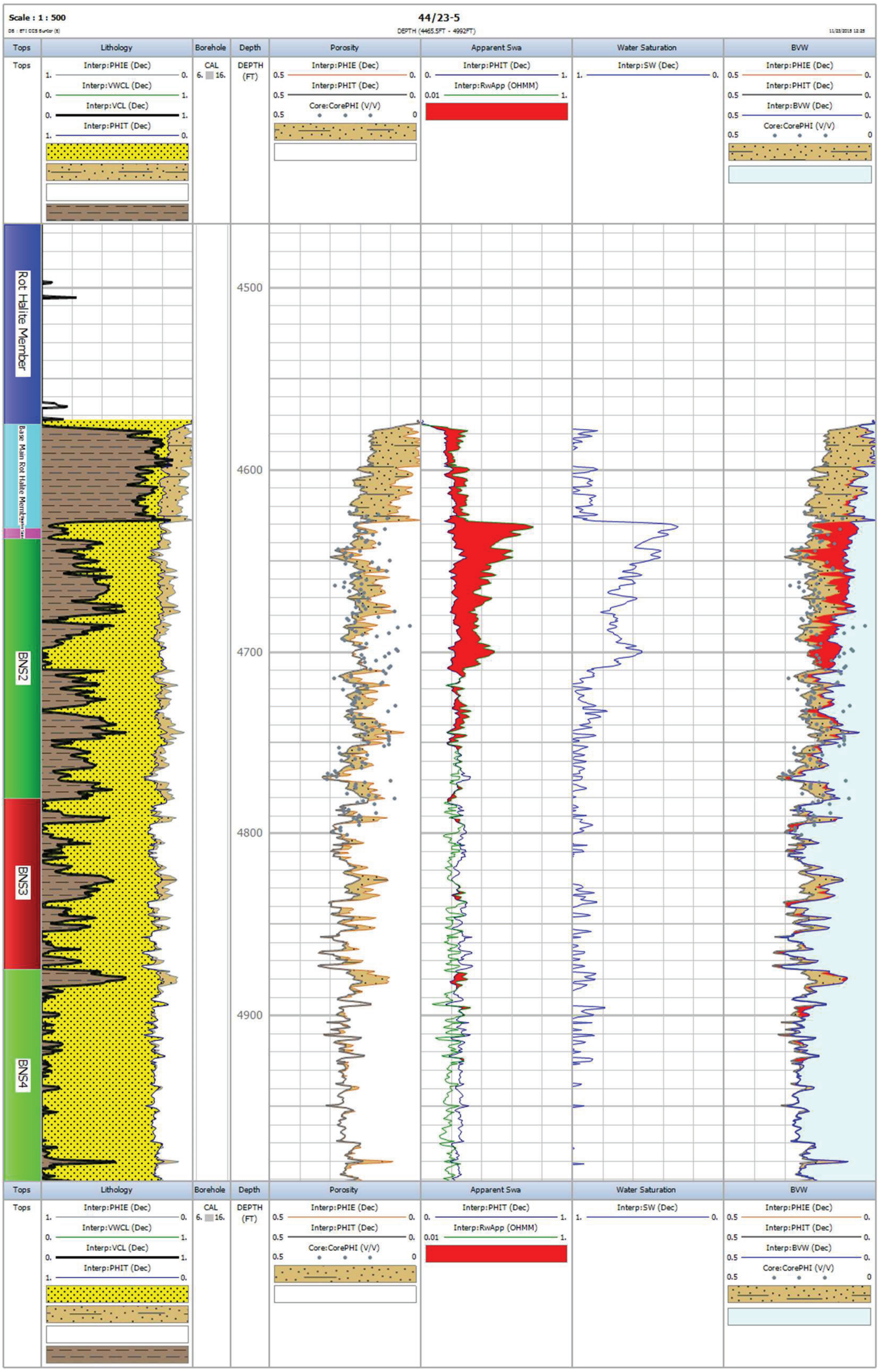


Figure 11-21 Well 44/23-5 interpretation

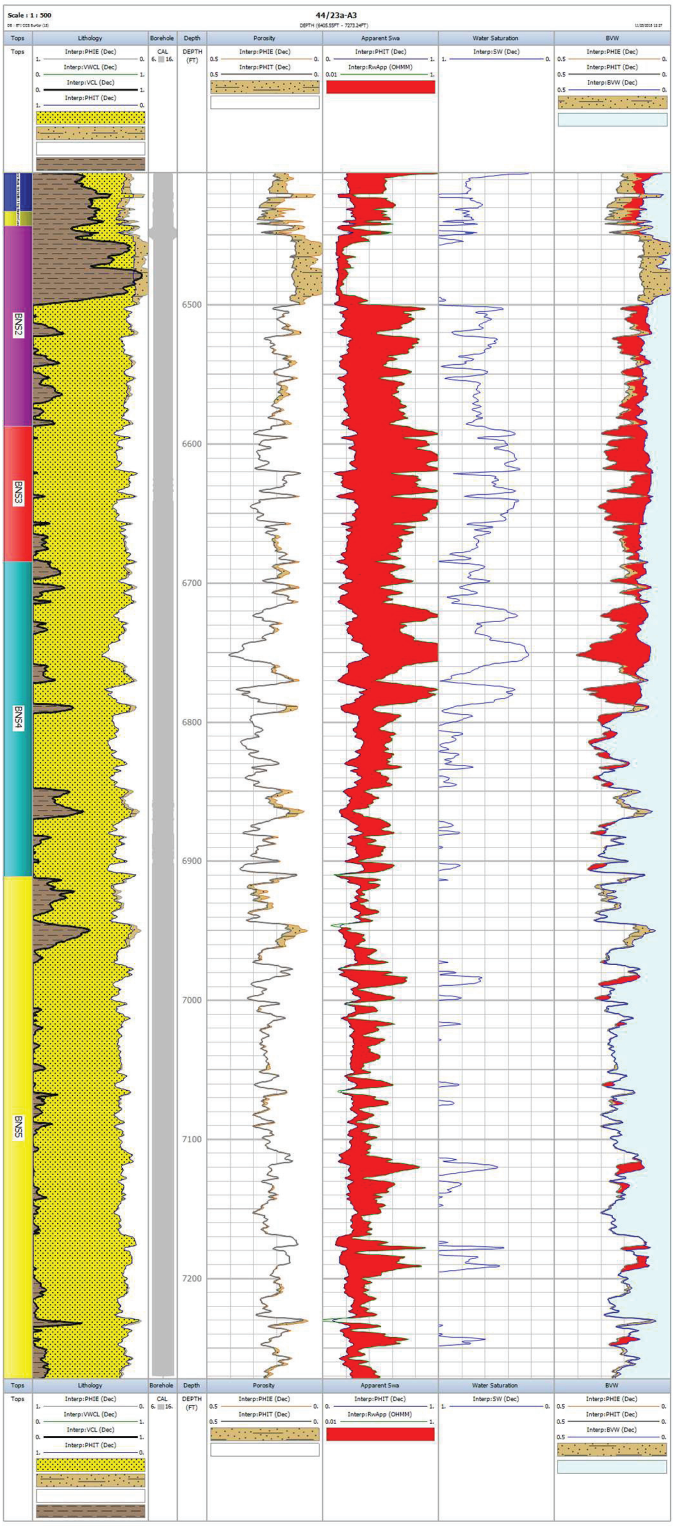


Figure 11-22 Well 44/23a-A3 interpretation

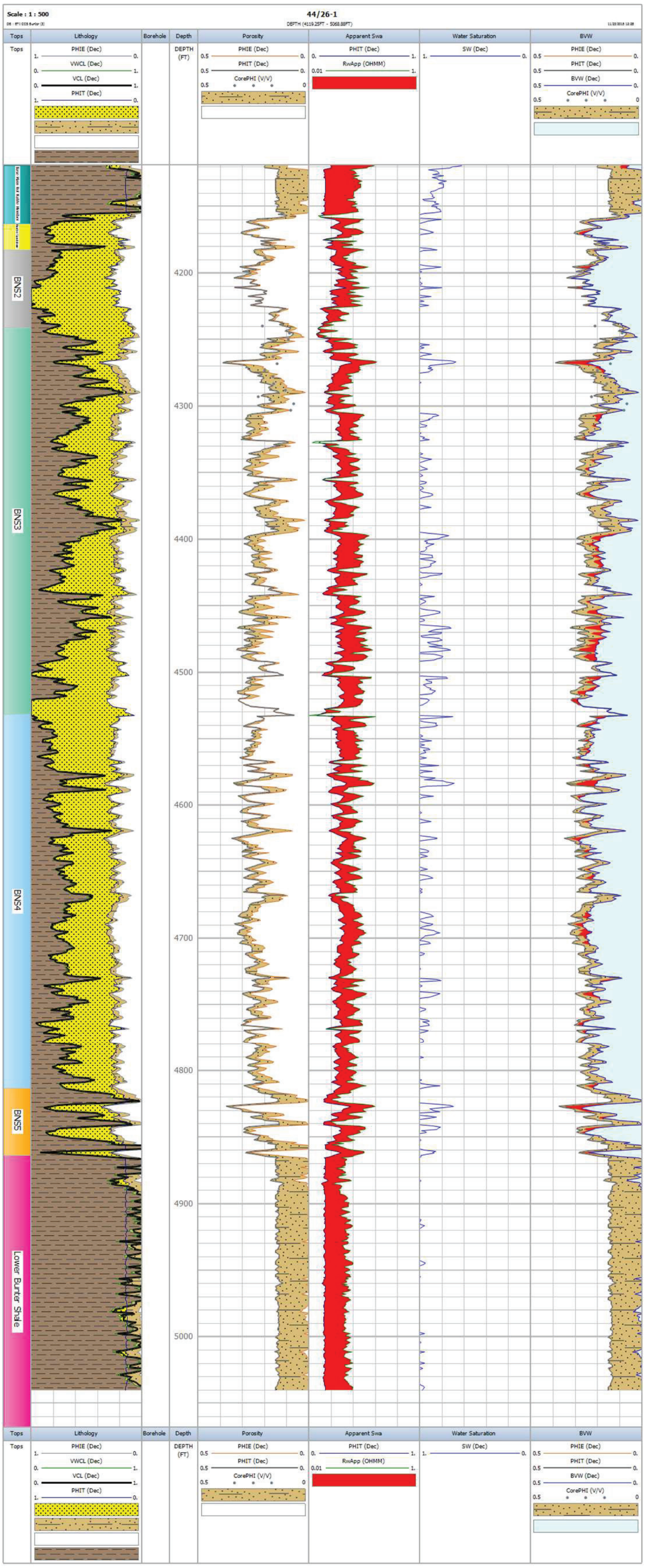


Figure 11-23 Well 44/26-1 interpretation

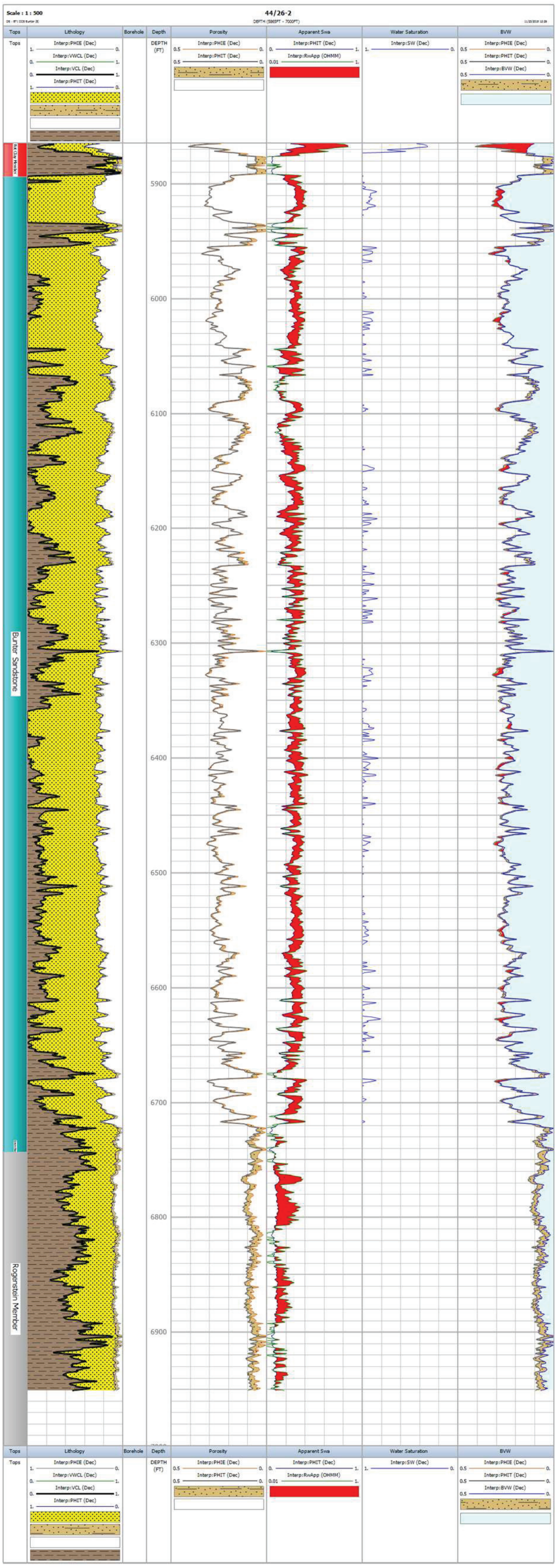


Figure 11-24 Well 44/26-2 interpretation

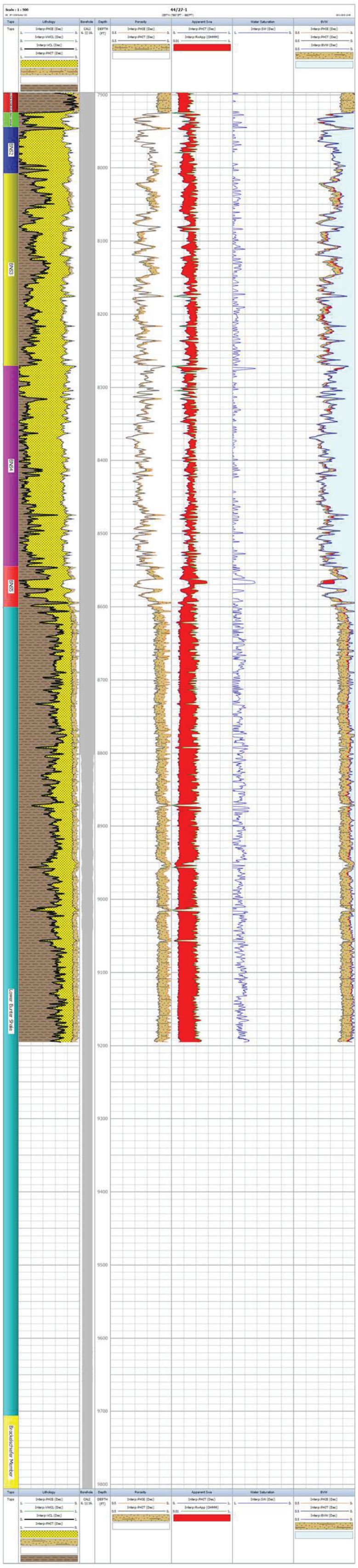


Figure 11-25 Well 44/27-1 interpretation

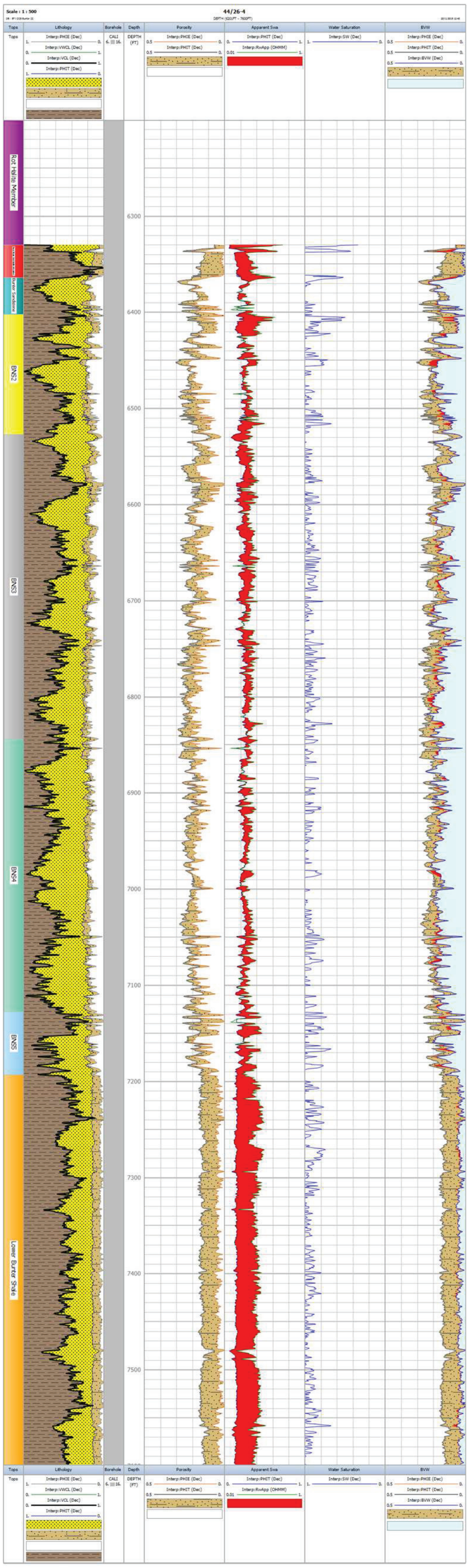


Figure 11-26 Well 44/26-4 interpretation

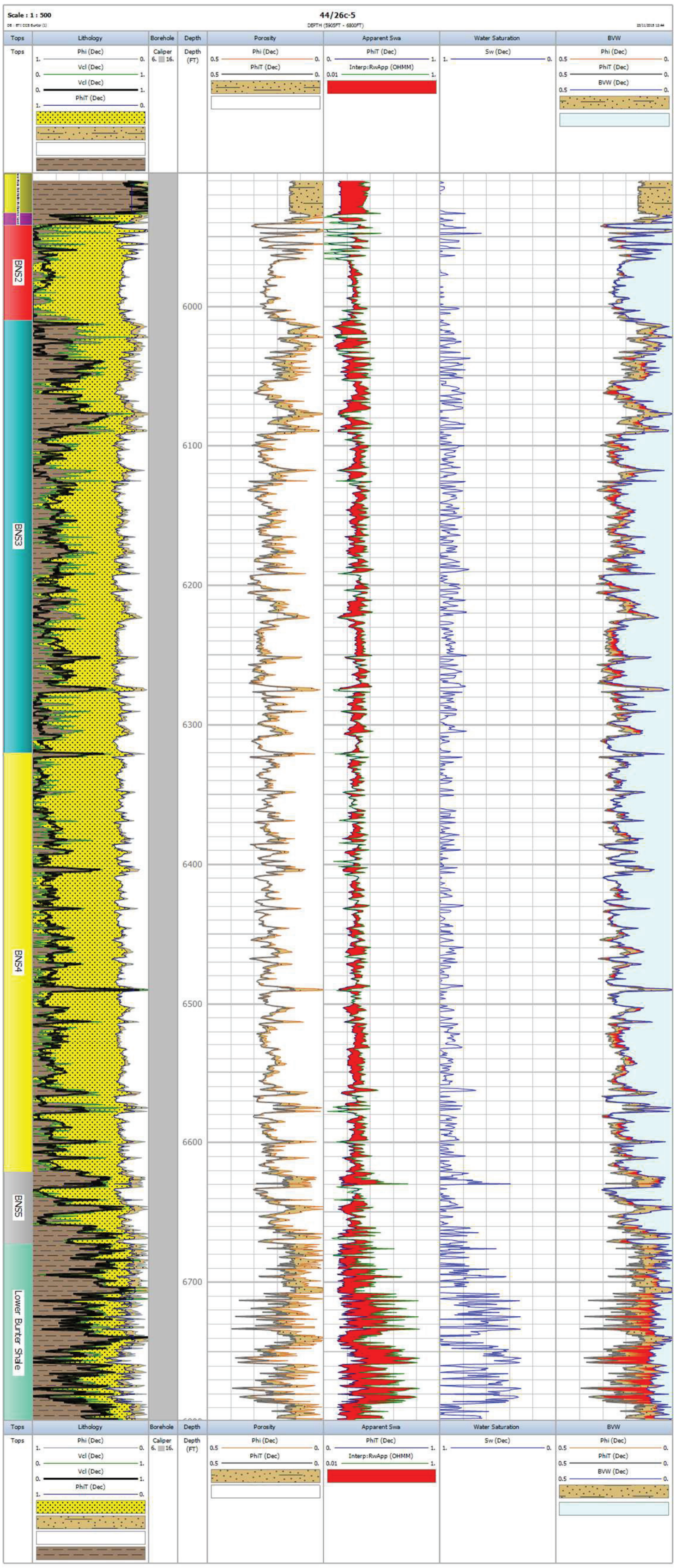


Figure 11-27 Well 44/26c-5 interpretation

11.7 Appendix 7 MMV Technologies

11.7.1 Monitoring Technologies

Many technologies which can be used for offshore CO2 storage monitoring are well established in the oil and gas industry.

Monitoring of offshore CO2 storage reservoirs has been carried out for many years at Sleipner and Snohvit in Norway and at the K12-B pilot project in the Netherlands. Onshore, Ketzin in Germany has a significant focus on developing MMV research and best practice.

A comprehensive list of existing technologies has been pulled together from NETL, 2012 (MMV Ref 4) and IEAGHG, 2015 (MMV Ref 5).

NETL, 2012 (MMV Ref 4) references a "field readiness stage" for each technology, based on its maturity:

Commercial

Early demonstration

Development

IEAGHG, 2015 (MMV Ref 5) included an estimate of the cost of some offshore technology.

To help map each monitoring technology's relevance and applicability to a generic Storage site in the North Sea site, a Boston Square plot was used. This is a useful tool, which has been used on previous CO2 storage projects such as In Salah (operational) and Longannet (FEED study).

Along the x-axis of the plot is the relative cost (low to high) and along the y-axis is the relative value of information (VOI) benefit (high to low) and so each monitoring technology is plotted according to these parameters. The Boston Square can then be divided into four quadrants, which help to refine the choice of monitoring technologies:

"Just do it" - technologies with low cost and high VOI - these should be included as standard in the monitoring plan

"Park" - technologies with high cost and low VOI- these should be excluded from the plan

"Consider" - technologies with low cost but also a low VOI - these should not be ruled out due to their low cost

"Focussed application" - technologies with a high cost but a high VOI- these may be deployed less frequently, over a specific area or included in the corrective measures plan

Note that this Boston Square is for this stage in the project and would likely be modified following additional work to refine costs and benefits of the technologies for this site.

The Boston Square for a generic North Sea storage site is shown in Figure 11-28 and Table 11-8 provides additional information about each technology and the rationale for technologies in each quadrant.

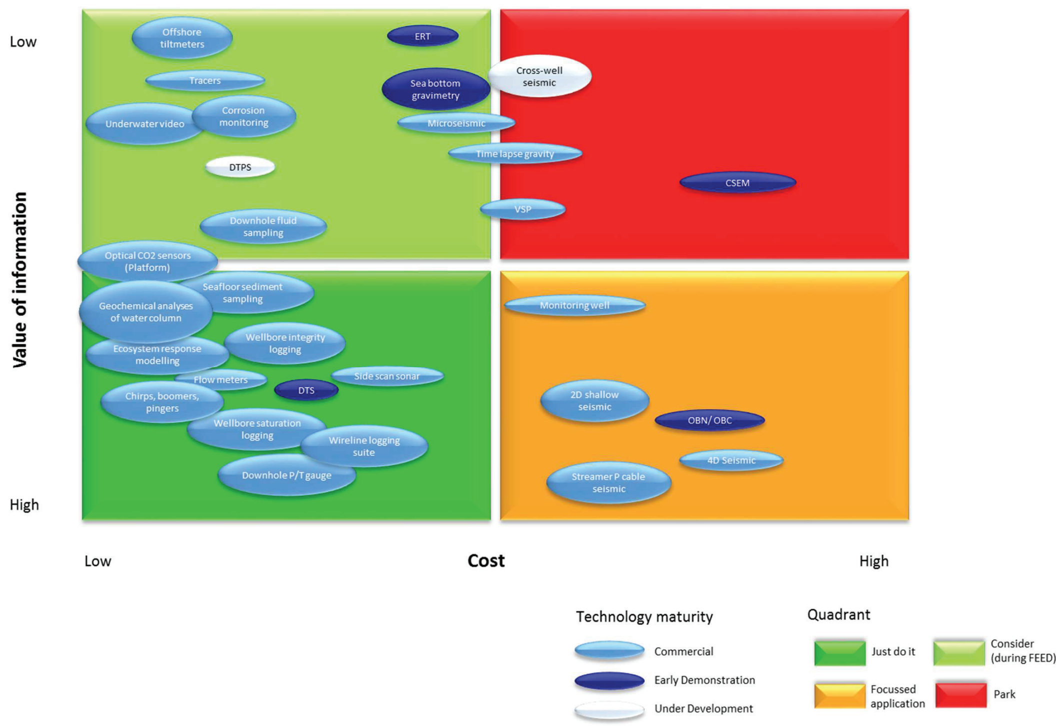


Figure 11-28 Boston square plot of monitoring technologies applicable offshore

11.7.2 Technologies for monitoring offshore

The table below contains technologies suitable for monitoring offshore.

Monitoring Domain	Type	Field Readiness	Technology	Applicability to Offshore	Description	Boston Square Box	Comments/ rationale
Subsurface	Wireline Logging Tool	Commercial	Density logging	Platform and subsea	Standard wireline tool that provides information about a formation's bulk density along borehole length. Bulk density relates to the rock matrix and pore fluid so can be used to infer pore fluid and characterise reservoir models. Uses gamma rays (radioactive source) and detector that detects their scatter, which is related to the formation's electron density.	Just do it	Used for formation characterisation in reservoir models
Subsurface	Wireline Logging Tool	Commercial	Sonic logging	Platform and subsea	Standard wireline tool in the oil and gas industry. Measures velocity of both compressional and shear waves in the subsurface and transit times of acoustic wave. Could detect changes in pore fluid from CO_2 due to velocity contrasts between CO_2 and brine.	Just do it	Used for formation characterisation in reservoir models
Subsurface	Wireline Logging Tool	Commercial	Dual-induction logging	Platform and subsea	Resistivity logging - detects resistivity contrast between CO_2 (resistive) and water (conductive).	Just do it	Used for formation characterisation in reservoir models
Subsurface	Wireline Logging Tool	Commercial	Wellbore integrity logging	Platform and subsea	Well integrity logging focusses on determining the integrity of the wellbore (and its cement, casing etc.) and is important for safe injection operations and reduces leakage risk. i.e. Cement bond logging (CBL) and formation bond logging (VDL)	Just do it	Well integrity logging is considered essential for determining injection well integrity during operations.
Subsurface	Wireline Logging Tool	Commercial	Pulsed neutron tool (PNT)	Platform and subsea	A standard wireline tool using pulsed neutron techniques to measure CO_2 saturation. Sensitive to changes in reservoir fluids and can distinguish between brine, oil and CO_2. PNT will not detect CO_2 dissolved in brine.	Just do it	Used for formation characterisation in reservoir models

Monitoring Domain	Type	Field Readiness	Technology	Applicability to Offshore	Description	Boston Square Box	Comments/ rationale
Subsurface	Permanent Downhole Tool	Early Demonstration Stage	Distributed temperature sensor (DTS)	Platform and subsea	Permanent down-hole optical fibre tools which can detect temperature at ~1m intervals along the wellbore. Can measure in real time and may be able to detect CO2 migration from reservoir with associated temperature drop or any fluid temperature fluctuations which could indicate a poorly sealed wellbore.	Just do it	Considered essential to ensure integrity of injection operations. Also used to update reservoir models.
Subsurface	Permanent Downhole Tool	Development Stage	Distributed thermal pertubation sensor (DTPS)	Platform and subsea	DTPS measures the thermal conductivity of the formation and can estimate CO2 saturation within the zone of injection (decrease in bulk thermal conductivity indicates an increase in CO2 saturation). Equipment includes an electrical heater with DTS.	Consider	The technology is at development stage so monitor its maturation and consider inclusion in FEED.
Subsurface	Permanent Downhole Tool	Commercial	Corrosion monitoring	Platform and subsea	CO2 with brine can be corrosive and so corrosion monitoring can be used to prevent potential failures within the injection system. Two techniques: (i) expose a removable piece of casing to the corrosive fluid for a set amount of time, remove it and analyse it (ii) install a corrosion loop with the injection system which can be removed and examined for signs of corrosion	Consider	Wellbores will designed to minimise corrosion and injection CO2 will be dehydrated to minimise corrosion. Therefore uncertainty over benefit. To consider further in FEED.
Subsurface	Permanent Downhole Tool	Commercial	Downhole & wellhead Pressure/ Temperature gauges	Platform and subsea	Located in the storage reservoir and can give continuous reservoir pressure and temperature throughout field life. The injected CO2 will be at a lower temperature than reservoir temperature so can differentiate between CO2 and brine. Pressure and Temperature data can be used as input to reservoir models. Pressure can be used to confirm mechanical integrity of wellbore. Can be used at monitoring wells to aid in detection of CO2 arrival (CO2 may be at lower temperature and higher pressure than fluids in the formation). Deployment required under the EU Storage Directive	Just do it	Required under the EU Storage Directive and considered essential to ensure integrity of injection operations and to update reservoir models.

Monitoring Domain	Type	Field Readiness	Technology	Applicability to Offshore	Description	Boston Square Box	Comments/ rationale
Subsurface	Permanent Downhole Tool	Commercial	Flow meters	Platform and subsea	Directly measure rate and volume of injected CO2. Different types: differential pressure meters, velocity meters, mass meters. Used for reporting of injected volumes of CO2.	Just do it	Essential for reporting on injected volumes of CO2.
Subsurface	Permanent Downhole Tool		Subsurface Fluid Sampling and Tracer Analysis	Platform and subsea	Collection of liquid or gas samples via wells (from either reservoir or overlying formation) for geochemical analysis of changes in reservoir due to CO2 or identify any tracers. Data can be used to constrain reservoir simulation modelling (e.g. fluid chemistry, CO2 saturation etc). Challenges with additional reservoir fluids of hydrocarbon and brine and preserving samples at reservoir temperature and pressure.	Consider	Moderate cost and can be conducted during wireline runs. To be more fully considered during FEED
Subsurface	Seismic Method	Early Demonstration	Microseismic/ passive seismic	Platform and subsea	Microseismic/ passive seismic monitoring includes installation of geophones down the wellbore when the wells are drilled and may provide real-time information on hydraulic and geomechanical processes taking place within the reservoir. This may give useful insight into reservoir and caprock integrity during the injection process. Challenges with reliability of sensors.	Consider	Moderately high cost and uncertainty over reliability of sensors and of information benefit (since caprocks in five storage sites are excellent). To be more fully considered during FEED.
Subsurface	Seismic Method	Commercial	4D/time-lapse 3D seismic	Platform and subsea	Reflection 3D seismic uses the acoustic properties of geological formations and pore fluid to image the subsurface in a 3D volume. 4D seismic involves repeating the 3D survey over time to detect any changes. Each CO2 storage site is unique and site-specific modelling is required to understand if reflection seismic will detect CO2 at that specific site	Focussed application	High cost, but it may provide extremely useful insight into plume extent for certain sites in the North Sea. Can also be used in corrective measures plan if loss of containment to overburden is suspected.
Subsurface	Seismic Method	Commercial	2D seismic		A seismic survey with closely spaced geophones along a 2D seismic line to give greater resolution at shallower depths.	Focussed application	This may be usefully deployed in a corrective measures plan seeking

Monitoring Domain	Type	Field Readiness	Technology	Applicability to Offshore	Description	Boston Square Box	Comments/ rationale
							to detect CO_2 in the shallow overburden.
Subsurface	Seismic Method		Streamer - P Cable seismic	Platform and subsea	High resolution 3D seismic system for shallow sections (<1000m) so could be used for imaging the overburden	Focussed application	This may be usefully deployed in a corrective measures plan seeking to detect CO_2 in the shallow overburden.
Subsurface	Seismic Method	Development	Ocean bottom nodes (OBN) and cables (OBC)	Platform and subsea	Multicomponent (p and s-wave recording) geophones placed on the seabed and can provide full azimuth coverage. Can provide data near platforms (unlike towed streamers which have an exclusion radius)	Focussed application	Multicomponent seismic may provide greater cost-benefit analysis over field life. Analysis to be carried out for specific sites during FEED.
Subsurface	Gravity	Early Demonstration	Time lapse seabottom gravimetry	Platform and subsea	Use of gravity to monitor changes in density of fluid resulting from CO_2 due to the fact that CO_2 is less dense than the formation water. Resolution of gravity surveys is much lower than seismic surveys. Time-lapse could track migration and distribution of CO_2 in the subsurface. Deeper reservoirs are also less suitable for gravity monitoring. Technology example: remotely-operated vehicle-deployable-deep-ocean gravimeters (ROVDOG)	Consider	Relatively low cost, but often requires a larger CO_2 plume before detection. Technology sensitivity modelling to be done during FEED to understand minimum plume detection limits.
Subsurface	Electrical Techniques	Development	Controlled-source Electomagnetic (CSEM) survey	Platform and subsea	Seabottom CSEM (Controlled Source Electro Magnetic) surveying is a novel application of a longstanding technique, currently at a quite early stage of development. It involves a towed electromagnetic source and a series of seabed receivers that measure induced electrical and magnetic fields. These can be used to determine subsurface electrical profiles that may be influenced by the presence of highly resistive CO_2. Challenges of technique in shallow water (<300m) and offshore deployment is logistically complex.	Park	Costly and challenging to deploy, still in early stages of development. However, modelling during FEED will determine whether this is likely to provide any benefit.

Monitoring Domain	Type	Field Readiness	Technology	Applicability to Offshore	Description	Boston Square Box	Comments/ rationale
Subsurface	Electrical Techniques	Early Demonstration	Electrical resistivity tomography (ERT)		Electrodes used to measure pattern of resistivity in the subsurface and can be mounted on outside of non-conductive well casing. Can have Cross-well ERT or surface-downhole ERT configurations, depending on scale of imaging	Consider	Modelling during FEED to understand the benefit of this technology
Subsurface			Monitoring well		An additional well drilled for the purpose of monitoring, with no intent to inject CO2 into it. CO2 breakthrough at the monitoring well can give insight into plume movement (rates, extent, etc) through the reservoir and pressure and temperature measurements can provide information on aquifer connectivity. The draw-back is that monitoring wells can be expensive and only give one point source measurement.	Focussed application	A redundancy well is currently considered, which will monitor when not injecting.
Subsurface	Seismic Method	Commercial	Vertical Seismic Profiling (VSP)	Platform and subsea	VSPs have seismic source in water column (offshore) or at surface (onshore) and geophones at regular intervals down the wellbore to produce a high-resolution near-wellbore image (300 to 600m away). Time-lapse VSPs are repeated over time to understand any changes. May be challenges with repeatability as reliability of sensors is a key issue	Park	Moderately expensive offshore and value of information uncertain compared with other technologies of similar or less cost - modelling during FEED.
Subsurface	Seismic Method	Early Demonstration	Cross-well seismic	Platform and subsea	Borehole seismic using seismic source in one well and receiver array in nearby well to build up a velocity map between the wells. Requires wellbore access and good coordination with other monitoring acitivies.	Park	Challenging regarding wellbore access and uncertainty over value of information.
Seabed/ water column	Seismic method	Commercial	Chirps, boomers & pingers	Platform and subsea	Very high resolution surface seismic surveys which may detect bubble streams. AUV systems have chirp transducers.	Just do it	Relatively low cost and can be used to rule out bubble streams at seabed and around abandoned/injection wellheads which may indicate loss of containment.

Monitoring Domain	Type	Field Readiness	Technology	Applicability to Offshore	Description	Boston Square Box	Comments/ rationale
Seabed/ water column	Seabed Method	Commercial	Side scan sonar	Platform and subsea	Sidescan sonar, a towed echo sounding system, is one of the most accurate tools for imaging large areas of the seabed. Sidescan sonar transmits a specially shaped acoustic beam perpendicular to the path of the support craft (which could included AUV or ROV), and out to each side. It can detect streams any bubbles, for example around abandoned or injection wellheads which penetrate the storage complex.	Just do it	Can be used to rule out bubble streams at seabed and around abandoned/injection wellheads which may indicate loss of containment.
Seabed/ water column	Seabed Method	Commercial	Underwater Video	Platform and subsea	Recording and high definition images of bubbles and other features which could indicate CO2 at seabed/ water column. Qualitative - cannot resolve size or shape of bubbles.	Consider	Consider inclusion as additional monitoring in corrective measures plan.
Seabed/ water column	Surface displacement monitoring	Development	Offshore tiltmeters	Platform and subsea	Reservoir pressure changes from CO2 injection can cause surface deformation and so vertical displacement of seabed may indicate that this has occurred. GPS system may be able to measure this to 5mm accuracy. Measuring subsistence or uplift may provide evidence of containment and conformance.	Consider	Moderate cost but modelling required to understand detectability limit for store depth and injected CO2 volumes and therefore information benefit.
Seabed/ water column	Geochemical Monitoring of water column	Commercial	Geochemical analyses of water column	Platform and subsea	CTD (conductivity, temperature and depth) probes from survey ships or platforms (for continuous measurement) can measure water column conductivity, used in addition to pH pCO2, dissolved O2 and other chemical components, any anomalous chemistry can be detected. Requires good baseline measurements and may have challenges detecting small quantities of CO2 due to dispersion.	Just do it	Relatively cheap and can be used to rule out loss of containment of CO2 to seabed over a large area and also around wellheads. Carry out survey at same time as side-scan sonar
Seabed/ water column	Tracer		Tracers		CO2 soluble compounds injected along with the CO2 into the target formation. Act as a "fingerprint" for the CO2 in case of any leakage.	Consider	Tracers are in the "Consider" box as they are of moderate cost, but low benefit as containment loss at the storage sites is not

Monitoring Domain	Type	Field Readiness	Technology	Applicability to Offshore	Description	Boston Square Box	Comments/ rationale
							expected. To explore further during FEED.
Seabed/ water column	Seabed Method		Seafloor sediment samples	Platform and subsea	Sediment samples are extracted from the seabed (for example using a Van Veen Grab, vibro corer, CPT+BAT probe, hydrostatically sealed corer) and analysed for CO2 content. The CO2 content may give insight into CO2 flux (if any) above abandoned wellbores which penetrate the storage complex. Requires a good baseline to detect CO2 above background levels.	Just do it	Relatively cheap and can be used to rule out loss of containment of CO2 to seabed over a large area and also around wellheads. Carry out survey at same time as side-scan sonar
Seabed/ water column	Seabed Method		Ecosystem response monitoring	Platform and subsea	Time-lapse sediment sampling may detect changes in seabed flora and fauna from CO2. Baseline survey key to determine normal behaviour and CO2 concentrations	Just do it	Relatively cheap and can be used to rule out loss of containment of CO2 to seabed over a large area and also around wellheads. Carry out survey at same time as side-scan sonar
Atmospheric	Optical CO2 Sensors	Commercial	e.g. CRDS, NDIR-based CO2 sensors, DIAL/ LIDAR	Platform only	All sensors optical CO2 sensors measure absorption of infrared radiation (IR) along the path of a laser beam - Cavity ring-down spectroscopy (CRDS): Sensors to measure continuous or intermittent CO2 in air. . Work better over smaller areas and may be difficult to detect any CO2 release from background CO2 emissions. Relatively cheap and portable. - Non-dispersive infrared (NDIR) spectroscopy. CO2 detectors for health and safety monitoring. - Light detection and ranging (LIDAR).	Just do it	Atmospheric CO2 sensors will be essential if platform (including unmanned) injection facilities. For health and safety of personnel inspecting or maintaining platform. Modelling required during FEED to understand which atmospheric CO2 sensors should be installed.

Table 11-8 Offshore technologies for monitoring

11.8 Appendix 8 - Geomechanics

Document Summary			
Client	The Energy Technologies Institute		
Project Title	DECC Strategic UK CCS Storage Appraisal Project		
Title:	Geomechanical Analysis for Potential CO2 Storage Sites – Bunter Closure 36		
Distribution:	Click here to enter text.	**Classification:**	Client Confidential
Date of Issue:	Click here to enter text.		
	Name	**Role**	**Signature**
Prepared by:	Tim Wynn	Project Advisor	
Approved by:		Project Manager	

Amendment Record						
Rev	**Date**	**Description**	**Issued By**	**Checked By**	**Approved By**	**Client Approval**
V01		Report received	Axis WT			
V02		Updated version	Axis WT			

Disclaimer:

Geomechanical Analysis for Potential CO_2 Storage sites

Bunter Closure 36

Energy Technologies Institute
Axis Well Technology

Tim Wynn
Abraham Salazar

December 2015

Status: Draft

Date: December 2015

Revision: 02

Prepared by:

Tim Wynn

Project Manager [first name last name]

Approved by:

Reviewer [first name last name]

Executive Summary

This study was commissioned by Axis Well Technology to perform geomechanical analyses on 5 CO2 storage sites. This report concerns the Bunter 36 structure. Three main analyses were conducted:

1. 1D analytical wellbore stability analysis of key wells on the structure to determine fracture gradient, breakout line and the mud window to drill hole with no breakouts or losses.
2. 1D empirical sanding analysis to determine the likelihood of sanding during injection shutdown & startup operations.
3. 3D geomechanical model to determine the likelihood of seal breach, fault reactivation and degree of seabed uplift.

This analysis was carried out using DrillWorks 5000 and Visage

The 1D geomechanical analysis of existing wells indicates that a SHmin gradient of around 0.73 psi/ft is valid for the Bunter Sandstone and that vertical wells can be drilled through the overburden and Bunter Sandstone with ~10 ppg mud weights.

For vertical wells in this sequence, the recommended mud weights are essentially the same as the ones used to drill the wells (around 10 ppg). Some basic analysis on required mud weights at different injector orientations has been performed within the Bunter Sandstone. In general, mud weight increases of 1 to 1.5 ppg are sufficient to prevent breakouts for the worst orientation (horizontal wells parallel to SHmax).

Although salt occurs above the Bunter Sandstone (Rot Halite) this is a relatively thin layer at shallow depths and drilling problems from dissolution or salt creep are not anticipated.

The sanding analysis indicates that the Bunter Sandstone is relatively strong and is unlikely to cause sanding due to pressure drops associated with injection related operations. Pressure changes during injection operations (e.g. CO_2/water hammer) are unlikely to result in sanding issues.

The 3D geomechanical modelling indicates that with the modelled injection scheme from 2027 to 2082 there will be minor uplift and some minor elastic strains with no shear or tensile failure of the overburden or faults.

Contents

1 Introduction

This study was commissioned by Axis Well Technology to perform geomechanical analyses on 5 CO_2 storage sites as defined below:

Site Name	Lithology	Site Type
Bunter 36	Triassic Bunter Sandstone	Aquifer only
Hamilton	Triassic St Bees Sandstone	Depleted Gas Field
Viking	Permian Leman Sandstone	Depleted Gas Field
Forties	Paleocene Forties / Mey / Maureen Sandstones	Aquifer to oilfields
Captain	Jurassic Volgan / Heather Sandstones	Aquifer to oilfields

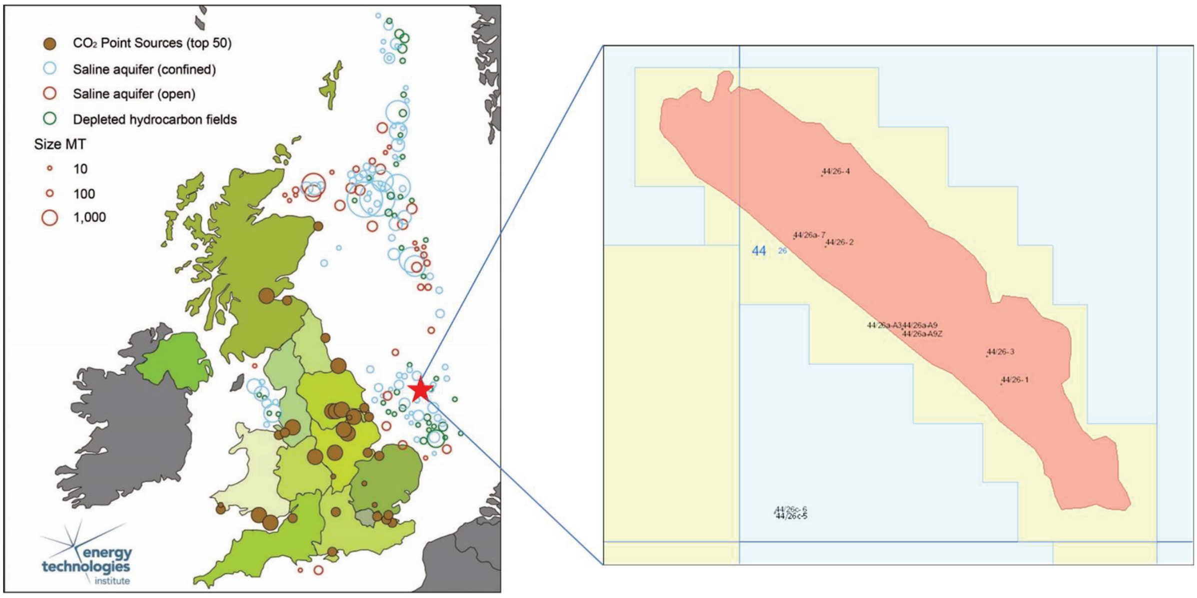
Table 11-9 ETI screening study storage sites.

This report concerns the Bunter 36 structure. Three main analyses were conducted:

4. 1D analytical wellbore stability analysis of key wells on the structure to determine fracture gradient, breakout line and the mud window to drill hole with no breakouts or losses.
5. 1D empirical sanding analysis to determine the likelihood of sanding during injection shutdown & startup operations.
6. 3D geomechanical model to determine the likelihood of seal breach, fault reactivation and degree of seabed uplift.

1.1 Bunter Closure 36 – Overview

Bunter Closure 36 is located in the South North Sea region as presented in the Figure 11-29.



Major offshore areas covered by CO2Stored (© Energy Technologies Institute)

Figure 11-29 Bunter Closure 36 location

The site details are presented in the Table 11-10

Site reference	**7**
Site description	Bunter Closure 36
UKCS Block	Quad 44, Blocks 26, 27
Region	SNS
Formation	Bunter SST, Bacton Group
Containment unit	Rot Halite Member

Table 11-10 Bunter Closure 36

The typical Bunter Closure stratigraphy is presented in Figure 11-30

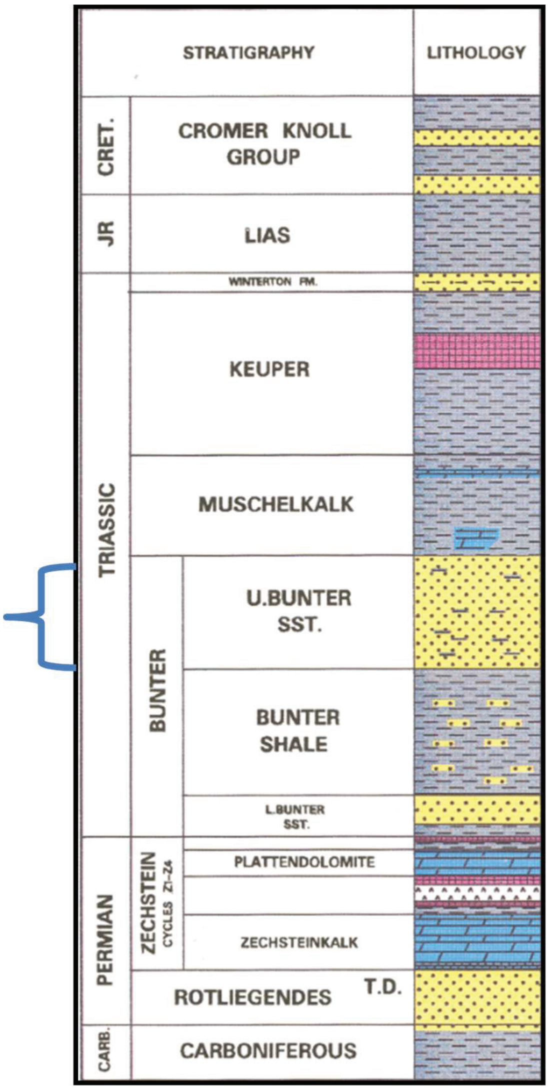


Figure 11-30 Bunter Closure 36 stratigraphy

2 Wellbore Stability Analysis

This analysis was carried out using DrillWorks 5000

The following tasks were performed for selected wells in each field (basic workflow):

- Overburden or Vertical stress (SV): based on bulk density log
- Pore pressure calculation: Bowers Sonic Method and verified with reference pore pressure value
- Fracture Gradient o minimum horizontal stress (Shmin): Eaton method and verified with reference fracture gradient value and LOT/FIT if available
- Poisson ratio: based on sonic log
- UCS: Horsrud's law correlation applied to sonic log
- Stress regime: normal assumed (SV>SH>=Shmin)
- Maximum horizontal stress (SH) calculated from SV and Shmin
- Stress orientation from the World Stress map
- Shear failure stress: Modified Lade failure condition

- Safe mud weight windows
- Optimal wellbore trajectory analysis

This process utilises log derived geomechanical properties combined with elastic stress calculations. The modified Lade shear failure criterion was applied. This utilises all three principal stresses and is generally less conservative than the Mohr-Coulomb failure criterion. The calculated fracture gradient is calibrated to well specific FIT or LOT data were available or two published results on regional analogues. The calculated breakout criterion and fracture gradient lines are combined with information on drilled mud weights and any drilling issues (tight hole, losses) to provide a qualitative calibration on the rock property / stress system. This is accounted for when making the safe mud weight range estimates. Note, these safe mud weight ranges are for zero losses and zero breakouts so they maybe somewhat conservative.

2.1 Pore Pressure and Fracture gradient reference

The following tables indicates the reference for the pore pressure gradient and fracture pressure gradient in the target layer based on a search in public domain data (full references in References section)

FIELD	CODE	Datum (ft TVDSS)	Pore pressure at datum (psi)	Pore pressure gradient (psi/ft)	Frac Pressure at datum (psi)	Frac Press gradient (psi/ft)	Source / Comment
Bunter Closure 36	139.016	3973	1756	0.442	2892	0.728	SPE 26680 / SPE 26794 / International Journal of Greenhouse Gas Control 2011, "CO2 storage in the offshore UK Bunter sandstone formation", Heinemann et al

Table 11-11 Bunter Closure 36 pore pressure and fracture gradient references

2.2 Stress Orientation

The World Stress Map is a global reference for tectonic stress data when there is no any other data available (e.g. reliable dual arm calliper or image log data). The web link is in the References section.

The regional maximum horizontal stress (SH) is aligned NW-SE, and therefore the Shmin is aligned NE-SW. The presence of the Zechstein salt may allow local structure related stress orientation variations in the overlying Bunter

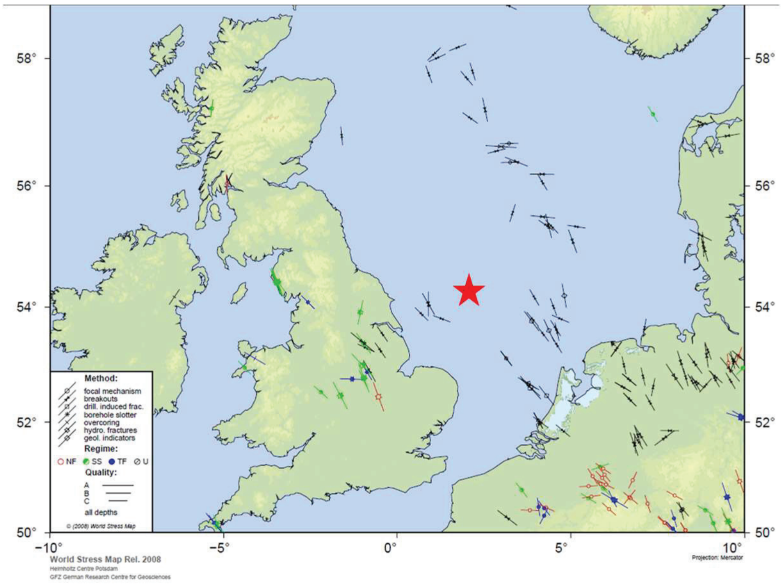


Figure 11-31 Bunter Closure 36 stress orientation

2.3 Wells evaluated

Logs available were obtained by the CDA website. The analysis was focused on three wells that include the minimum requirements of logs and location. For the well 44/26-3 the LAS files were built from image files.

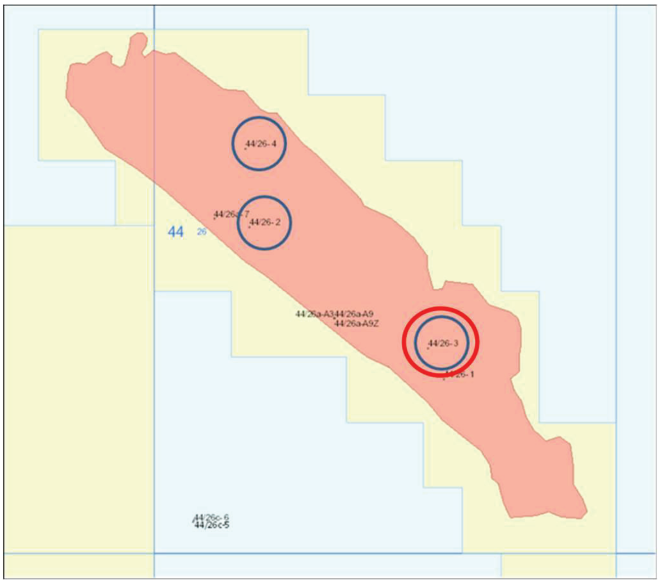


Figure 11-32 Bunter Closure 36, well evaluated locations

2.3.1 Well: 44/26-2

Figure 11-33 indicates the location of this well in the field.

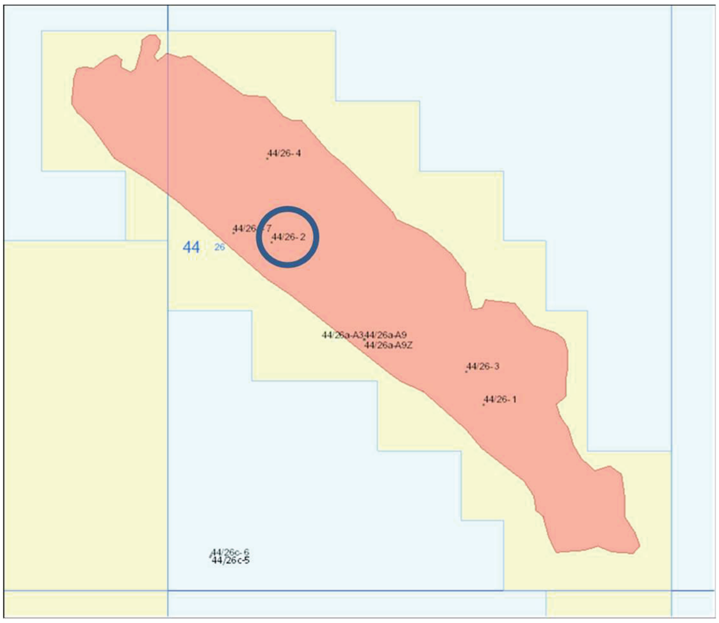


Figure 11-33 Bunter Closure 36, Well 44/26-2

Stress path and rock mechanical properties

The Figure 11-34 depicts the stress path in the well 44/26-2, showing pore pressure (orange line), minimum horizontal stress (red line), maximum horizontal stress (black line) and overburden (magenta line). The following considerations were used to calculate the stress path:

- Minimum horizontal stress (shmin) calculated by Eaton and calibrated with LOTs reported from the well (0.723 psi/ft at 20" casing shoe 3097 ftMD)
- Normal stress regime assumed. Maximum horizontal stress calculated from average of Shmin and overburden (Sv)
- Calculated Rot Halite Shmin gradient incorrect – treated as lithostatic for drilling window purposes.
- Pore pressure gradient estimated by using Sonic Bowers method and verified with reference pore pressure.

The Figure 11-35 depicts the following rock mechanical properties derived from logs:

- Poisson's ratio
- Friction angle
- Rock strength (UCS)

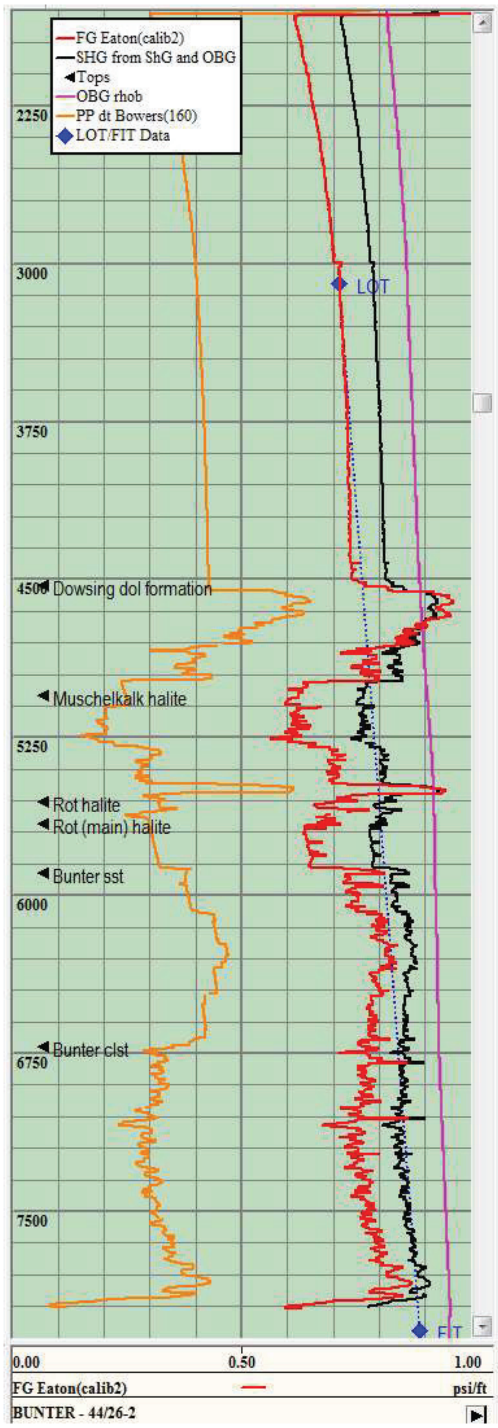


Figure 11-34 Stress path, Well 44/26-2

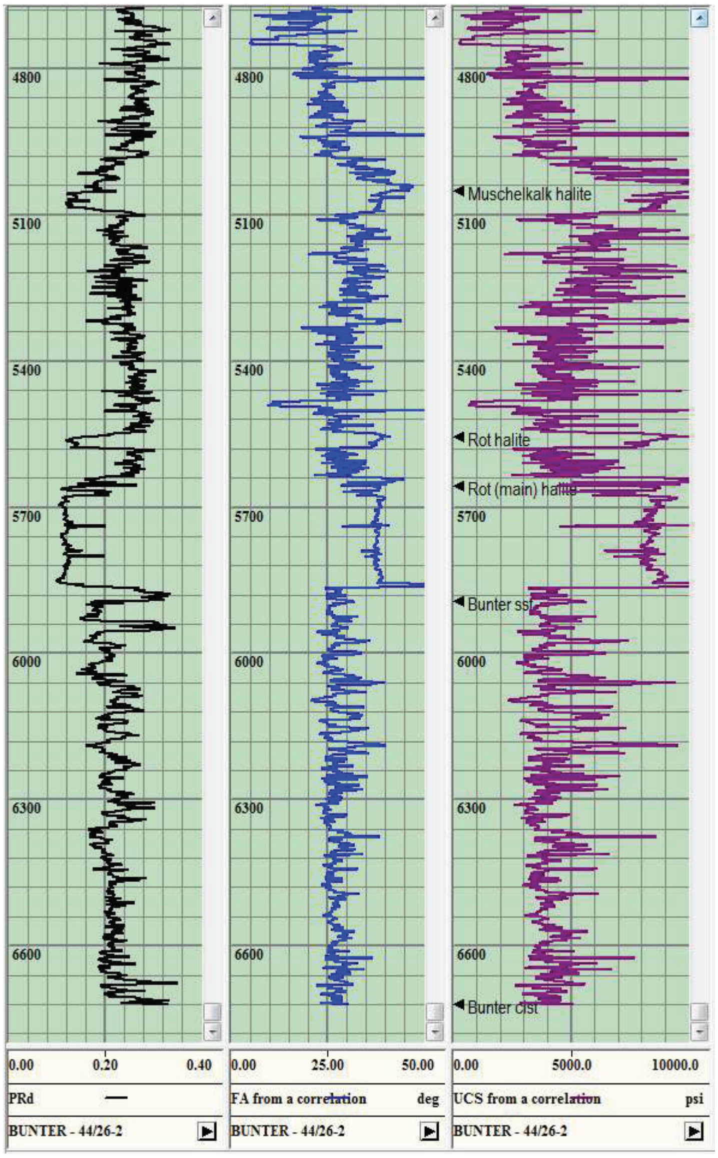


Figure 11-35 Rock mechanical properties, Well 44/26-2

Safe mud weight windows

Figure 11-36 present the recommended mud weight (MW) windows shown as blue bars. This figure plot of breakout gradient (blue line) pore pressure gradient (orange line) drilled mud weight (yellow line), fracture gradient (red line) and fracture initiation gradient (black line).

The MW used to drill this well was between 9.12 to 9.88 ppg. Some overpulls were noted at 3700 & 3659 ft when POH. Light reaming required. Based on this analysis, for the Rot Halite, Bunter sst, and Bunter clst (Bunter Shale) a safe MW would be between 9.5 to 13.5 ppg (for a vertical well). The upper limit is higher than shown in Figure 11-36 as the Rot Halite stresses are assumed to be lithostatic rather than the low values calculated from the logs.

For layers immediately above the Rot Halite a safe MW would be between 8.5 to 11 ppg (for a vertical well). For practical purposes, a MW close to that used to drill the well would be adequate for a vertical with this geomechanical profile.

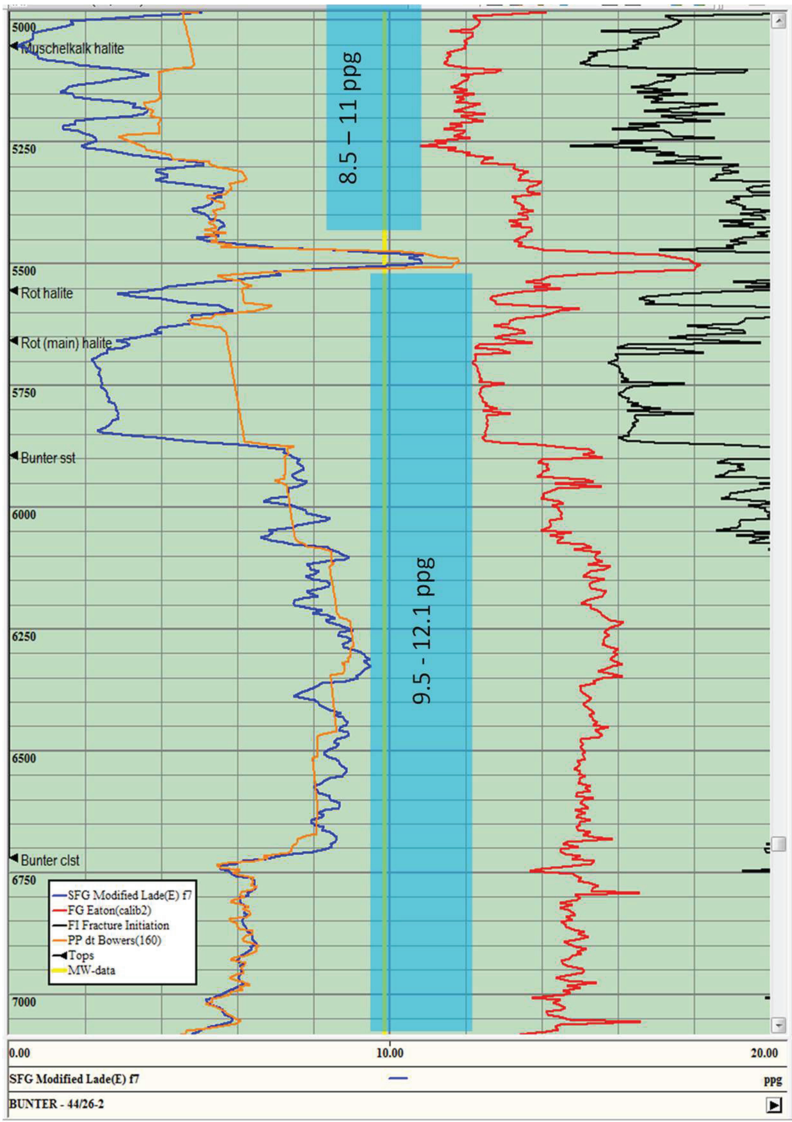


Figure 11-36 Safe mud weight analysis, Well 44/26-2

Wellbore trajectory analysis

The Figure 11-37 indicates the variation of the minimum mud weight to prevent any breakout with wellbore inclination and orientation. The Figure 11-37 show the Bunter Sandstone fm (at 6250 ft), where a horizontal well would increase the MW by up to 1 ppg (10.5ppg).

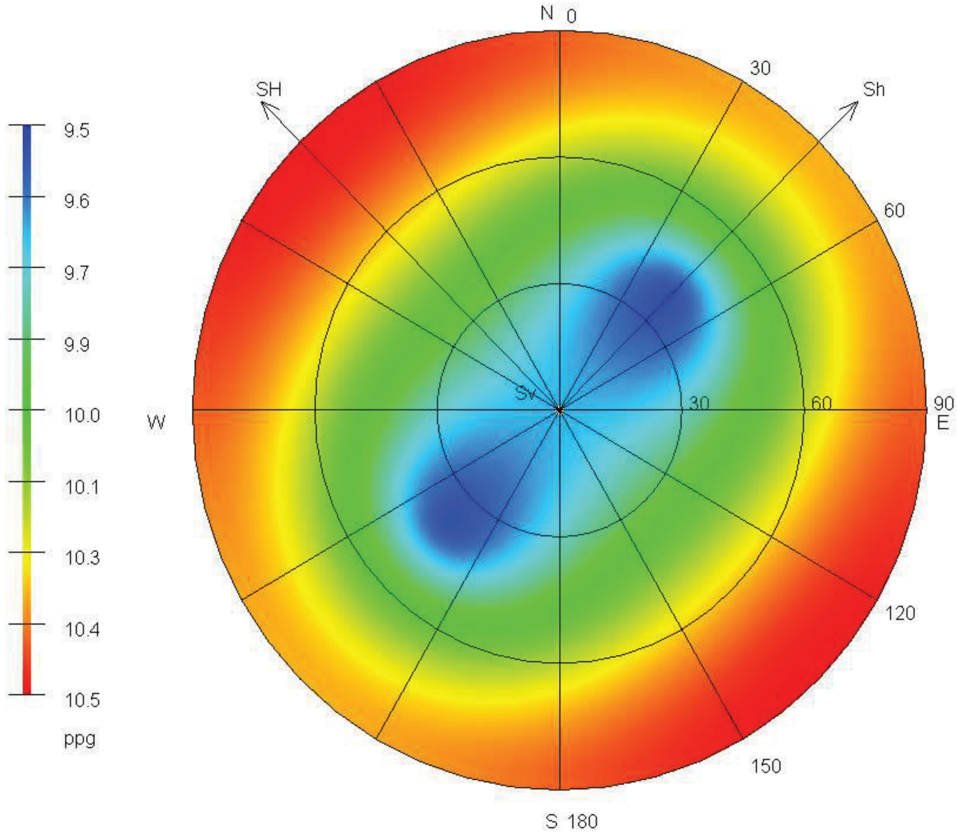


Figure 11-37 Well trajectory analysis, Well 44/26-2

2.3.2 Well: 44/26-3

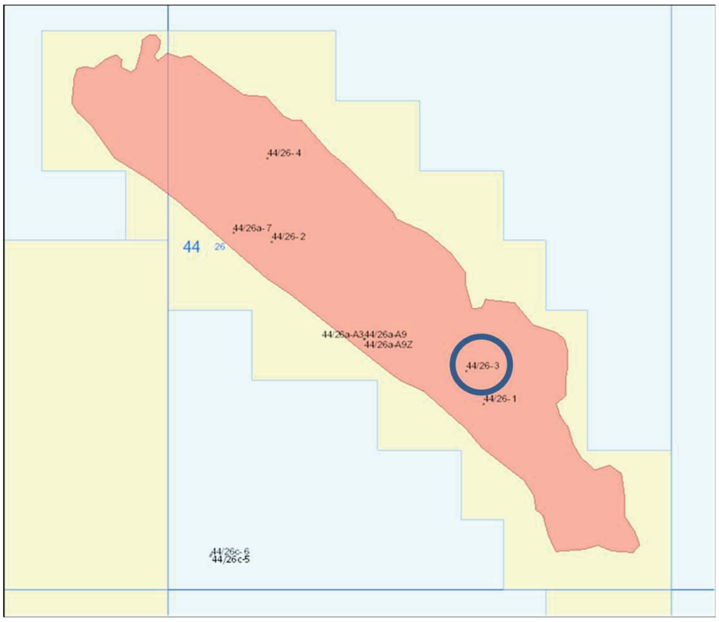


Figure 11-38 Bunter Closure 36, Well 44/26-3

Stress path and rock mechanical properties

This well did not have LAS files for RHOB and DTC. These properties were taken from the composite log plot hence the coarse data presented in analysis. The Figure 11-39 depicts the stress path in the well 44/26-3, showing pore pressure (orange line), minimum horizontal stress (red line), maximum horizontal stress (black line) and overburden (magenta line). The following considerations were used to calculate this stress path:

- Minimum horizontal stress (shmin) calculated by Eaton
- Normal stress regime assumed. Maximum horizontal stress calculated from average of Shmin and overburden (Sv)
- Calculated Rot Halite Shmin gradient incorrect – treated as lithostatic for drilling window purposes.
- Pore pressure gradient estimated by using Sonic Bowers method

The Figure 11-40 depicts the following rock mechanical properties derived from logs:

- Poisson's ratio
- Friction angle
- Rock strength (UCS)

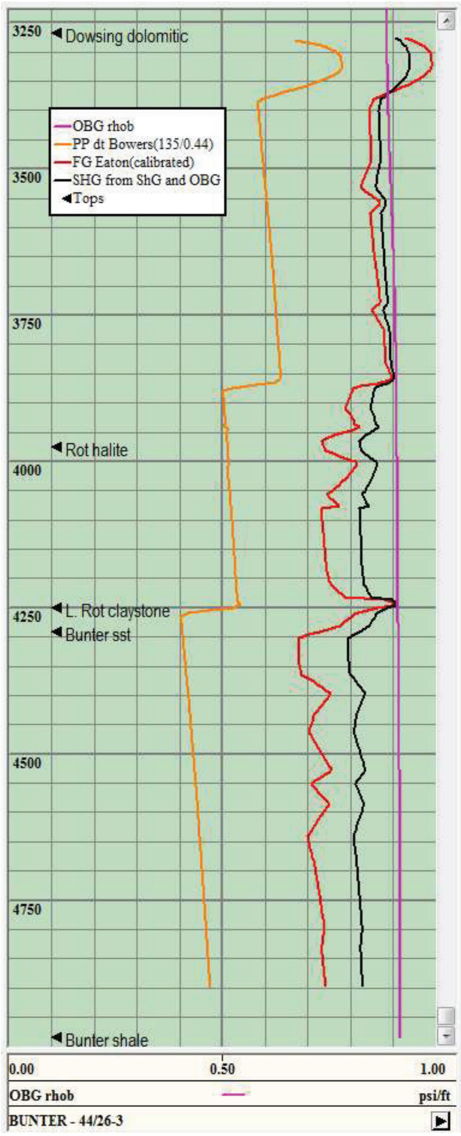


Figure 11-39 Stress path, Well 44/26-3

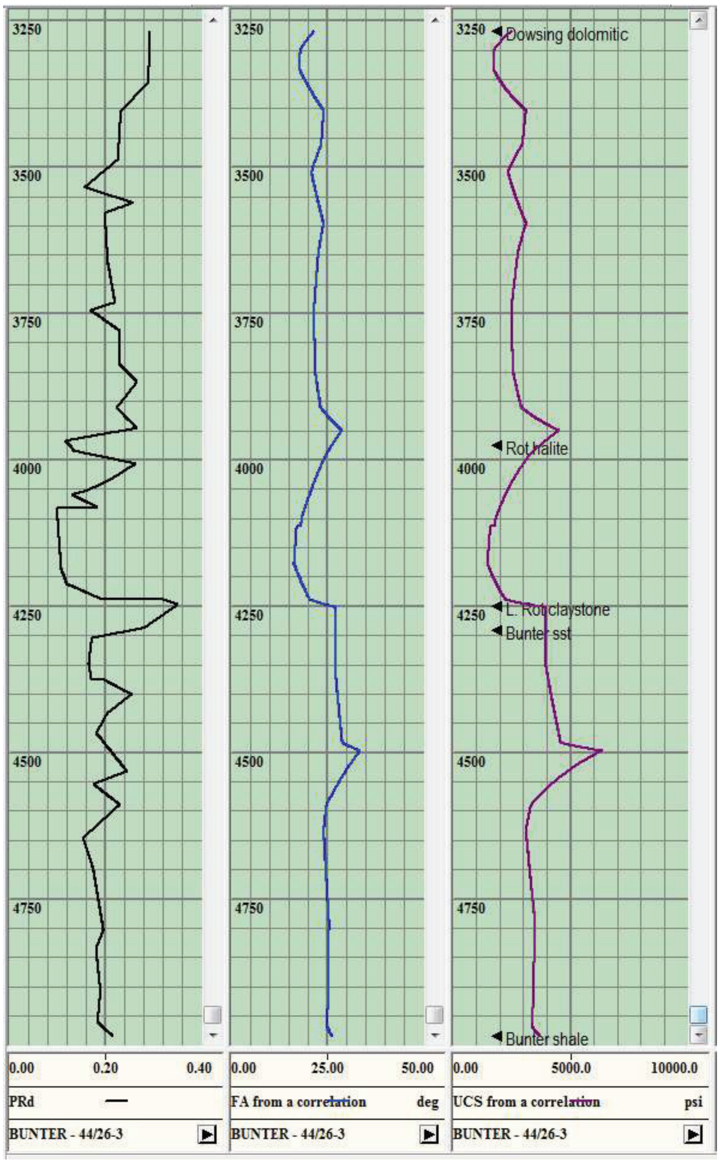


Figure 11-40 Rock mechanical properties, Well 44/26-3

Safe mud weight windows

Figure 11-41 present the recommended mud weight (MW) windows shown as blue bars. This figure plot of breakout pressure (blue line), pore pressure (orange line) drilled MW (yellow line), fracture gradient (red line) and fracture initiation gradient (black line).

The LOT at the 20” conductor shoe at 2474 ftMD was 13.85 ppg. The 13 3/8” shoe at 6464 ftMD within the Zechstein halite has a reported LOT of 18.27 ppg. This is probably an FIT but is below the interval of interest. The MW used to drill the 20” section was between 9.98 and 10.26 ppg (yellow line). Some tight spots were noted when POH at 3367, 3947 and 4382 e.g. 4080 which indicates the MW was a little low.

For the Lower Rot Claystone and Bunter sandstone a safe MW would be between 9.5 to 12.5 ppg (for a vertical well). For layers above L. Rot Claystone a safe MW would be between 12.3 to 13.8 ppg (for a vertical well). In reality, a vertical well with this geomechanical profile can probably be drilled with 9.5-10.5 ppg mud. Salt creep in the Rot Halite may require managing but it is relatively thin and shallow (i.e. cold) so this effect should be minimal during drilling.

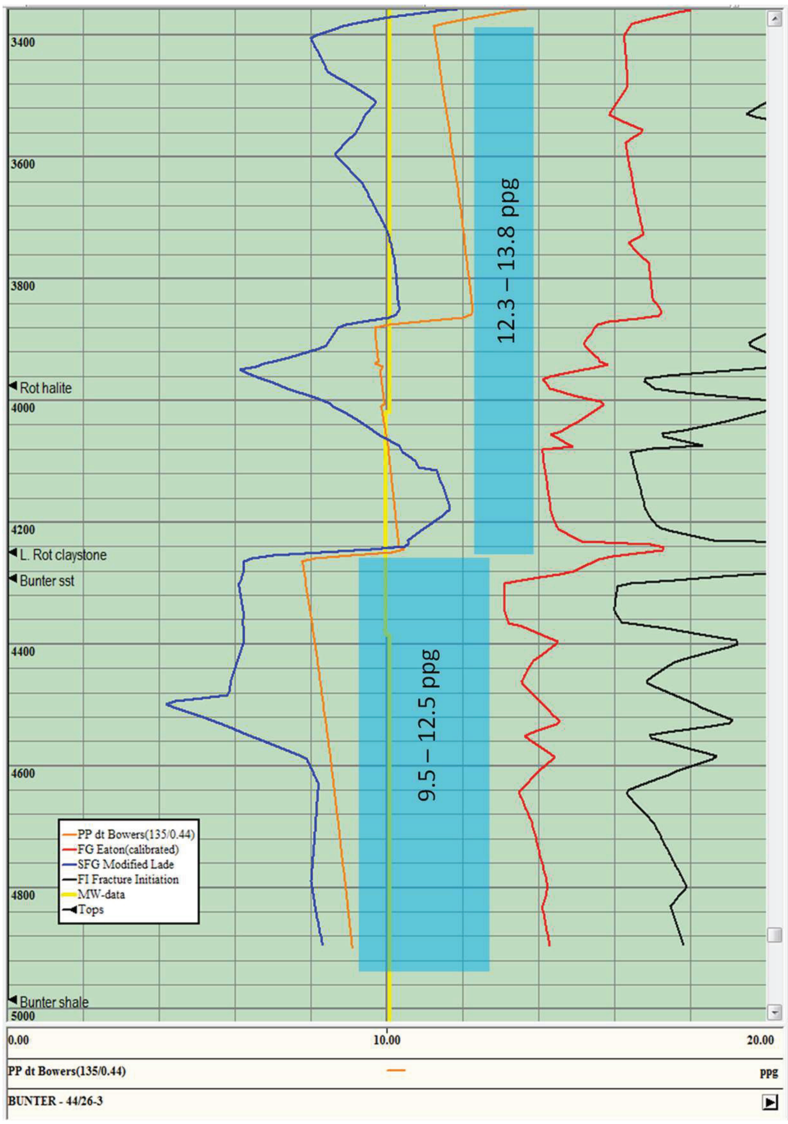


Figure 11-41 Safe mud weight analysis, Well 44/26-3

Wellbore trajectory analysis

The plot in Figure 11-42 indicates the variation of the minimum mud weight to prevent breakout with wellbore inclination and orientation. The plot shows the Bunter Sandstone fm (at 4800 ft), where a horizontal well would increase the MW by up to 1.6 ppg (11.1ppg)

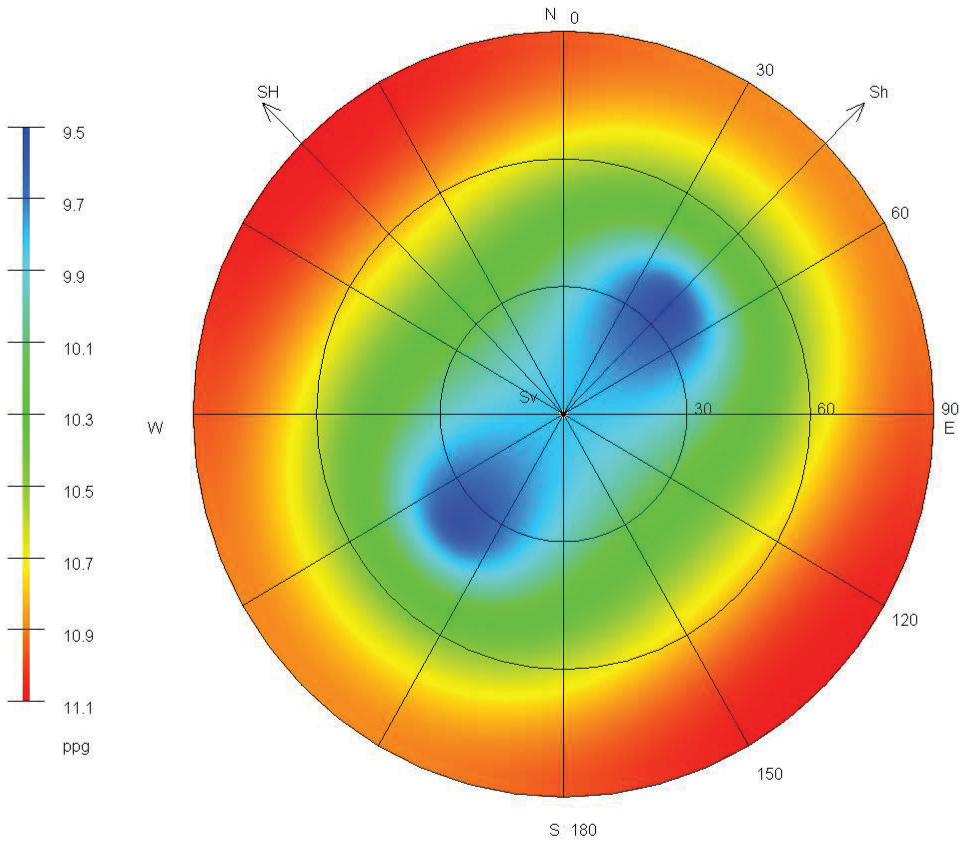


Figure 11-42 Well trajectory analysis, Well 44/26-2

2.3.3 Well: 44/26-4

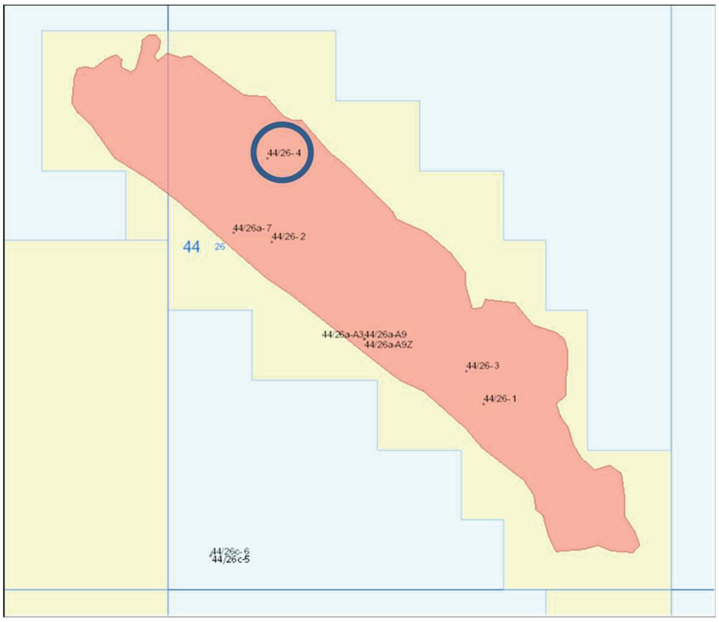


Figure 11-43 Bunter Closure 36, Well 44/26-4

Stress path and rock mechanical properties

The Figure 11-44 depicts the stress path in the well 44/26-4, showing pore pressure (orange line), minimum horizontal stress (red line), maximum horizontal stress (black line) and overburden (magenta line). The following considerations were used to calculate the stress path:

- Minimum horizontal stress (shmin) calculated by Eaton
- Normal stress regime assumed. Maximum horizontal stress calculated from average of Shmin and overburden (Sv)
- Calculated Rot Halite Shmin gradient incorrect – treated as lithostatic for drilling window purposes.
- Pore pressure gradient estimated by using Sonic Bowers method

The Figure 11-45 depicts the following rock mechanical properties derived from logs:

- Poisson's ratio
- Friction angle
- Rock strength (UCS)

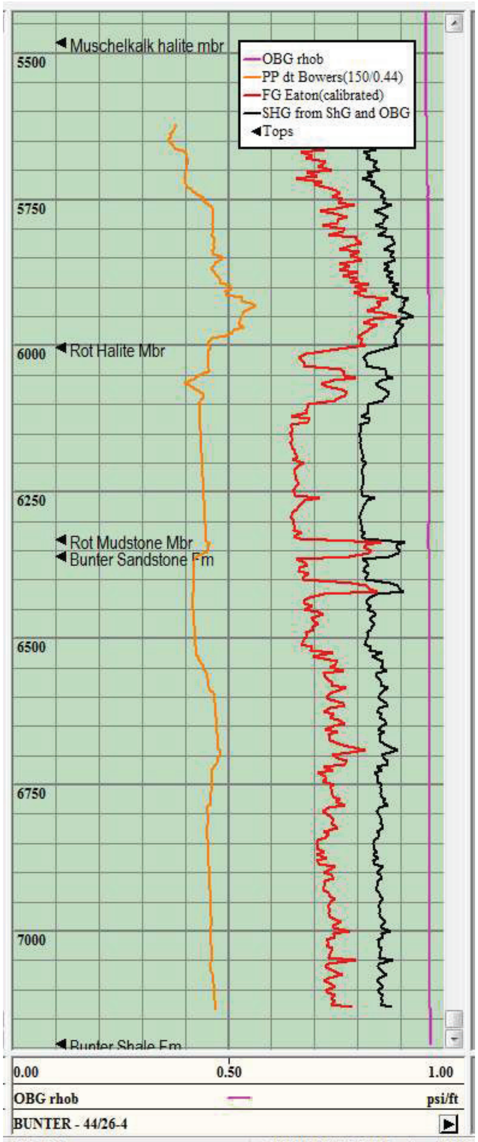


Figure 11-44 Stress path, Well 44/26-4

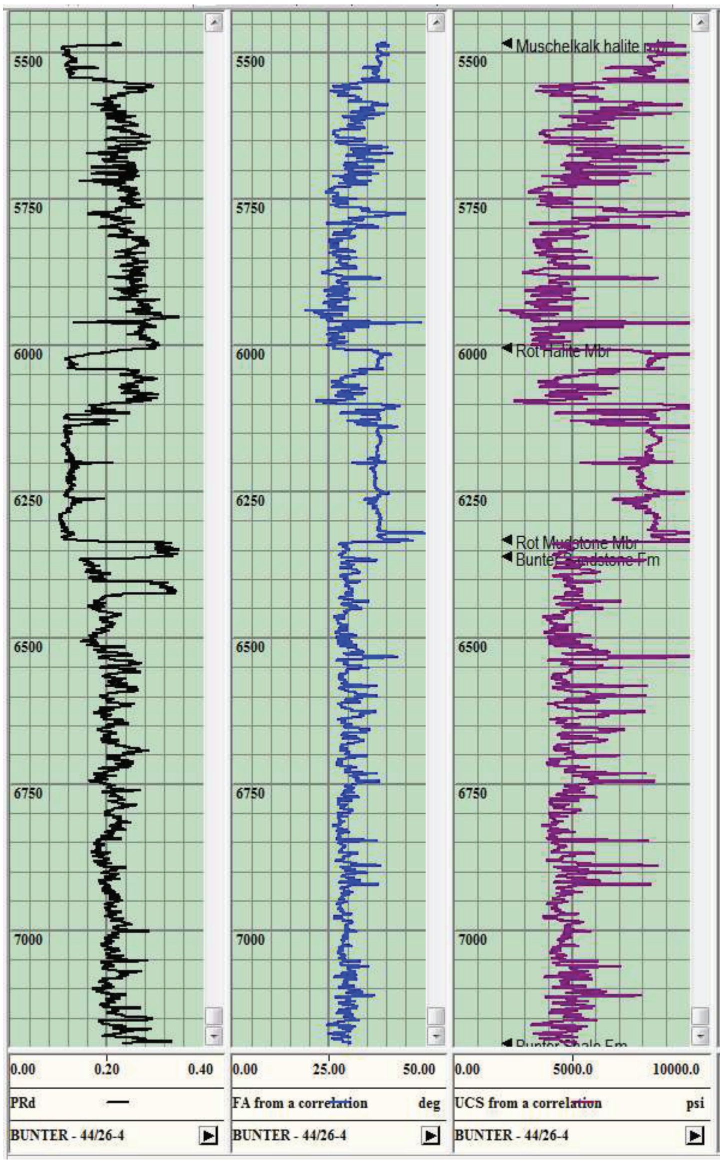


Figure 11-45 Rock mechanical properties, Well 44/26-4

Safe mud weight windows

Figure 11-46 present the recommended mud weight (MW) windows shown as blue bars. This figure plot of breakout gradient (blue) pore pressure gradient (orange) drilled mud weight (yellow), fracture gradient (red) and fracture initiation gradient (black).

The MW used to drill this well was between 9.79 to 10.07 ppg. LOT at the 20” shoe at 2139 ftMD of 0.740 psi/ft. LOT reported (FIT?) at 13/ 3/8 shoe at 8702 ftMD in the Zechstein of 0.991 psi/ft. This is close to lithostatic and is expected in this unit.

For the Bunter Sandstone and Rot Halite member a safe MW would be 9.5 to 12.2 ppg (for a vertical well). For the section above the Rot Halite member a MW of 11.4 to 12.2 ppg (for a vertical well) would produce a gun barrel hole but a lower MW is probably manageable. For practical purposes a MW close to that used to drill this well would be suitable for a vertical well with this geomechanical profile.

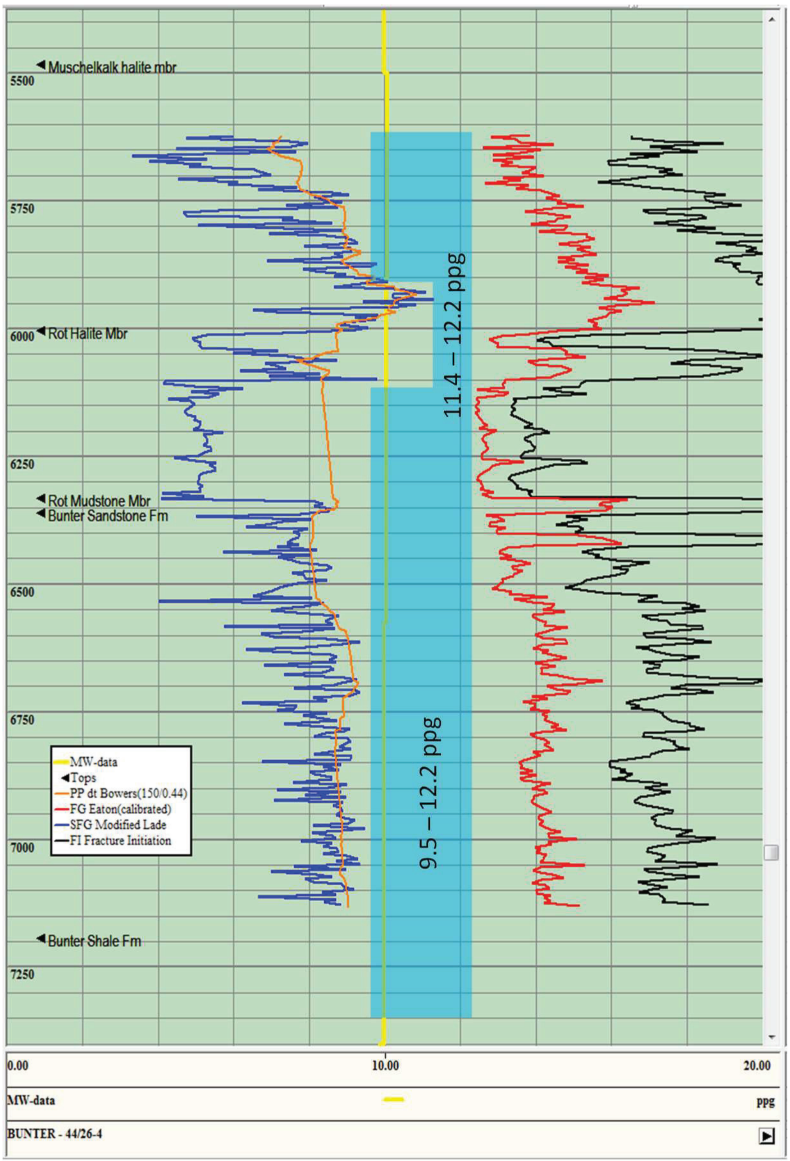


Figure 11-46 Safe mud weight analysis, Well 44/26-4

Wellbore trajectory analysis

The plot in Figure 11-47 indicates the variation of the minimum mud weight to prevent breakout with wellbore inclination and orientation. The plot shows the Bunter Sandstone fm (at 6700 ft), where a horizontal well would increase the MW by up to 1.7 ppg (11.2ppg).

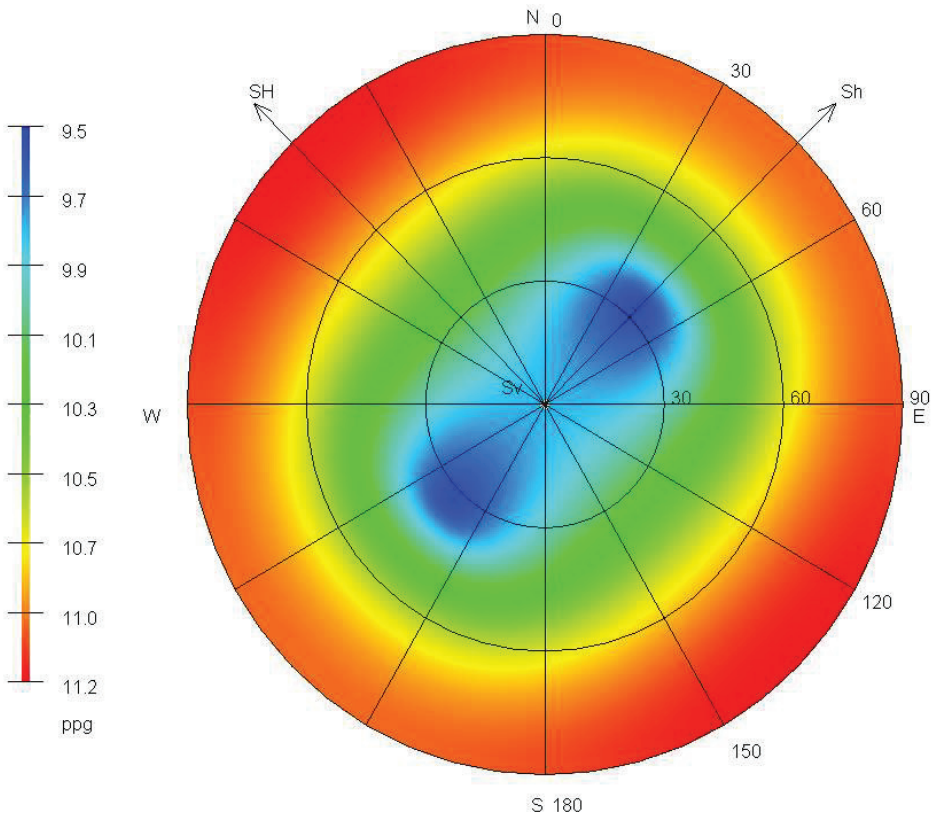


Figure 11-47 Well trajectory analysis, Well 44/26-4

3 Sanding Risk

As with water injection wells, there is a potential for sand failure in CO_2 injection wells. The principal causes of this are similar:

- Flow back (unlikely to occur in CO_2 injection wells without some form of pre-flow pad)
- Hammer effects during shut-in
- Crossflow (again unlikely since injection will be into a single formation although depleted fields offer more chances of this occurring)

The pre-requisite for sand failure is that the effective near wellbore stresses, as a result of depletion and drawdown, exceed the strength of the formation.

The in-situ stresses at the wellbore wall, while predominantly a function of the overburden and tectonic forces, will vary dependent on the trajectory (deviation and azimuth) of the proposed wellbore. So, while field wide values can be generalised, the specifics of the well can impact on the required conditions for failure of the formation.

These notes apply a generic critical drawdown process to selected well strength logs to provide a guide for the pressure drops required for failure in a CO2 injector. More detailed work would be required once the well trajectory and injection scheme parameters are better defined.

3.1 Critical drawdown for sanding

The critical drawdown for sanding was estimated using the methodology presented in Bellarby (2009) and SPE 78235.

$$p_{\mathrm{w(crit)}} = \frac{3\sigma_1 - \sigma_2 - \sigma_{\mathrm{yield}} - p_{\mathrm{r}}A}{2 - A}$$

Where:

$$A = \frac{(1-2\mu)}{(1-\mu)}\alpha$$

This method relates mechanical rock properties and the stress condition

The cumulative rock strength (UCS) in the Bunter Closure 36 structure as calculated from logs for the three analysed wells are shown in Figure 11-48.

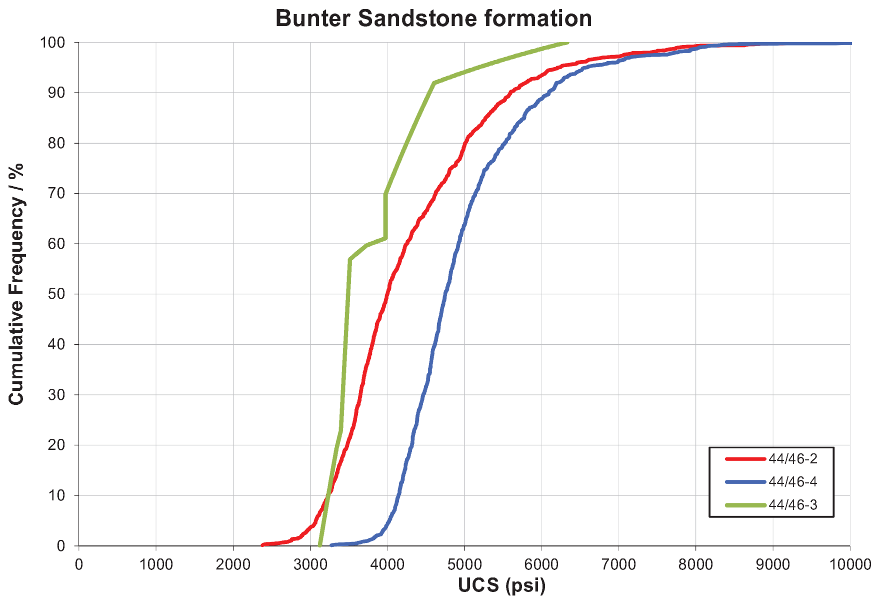


Figure 11-48 Bunter Sandstone UCS cumulative distributions

For the Bunter Closure 36 the average critical total drawdown (CTD) for sanding for the well 44/46-2 is above 5000 psi (see example in Figure 11-49). This indicates that the Bunter sandstone is competent and there is minimal risk for sanding during injection operations. However, this is based on an uncalibrated rock strength so uncertainty remains.

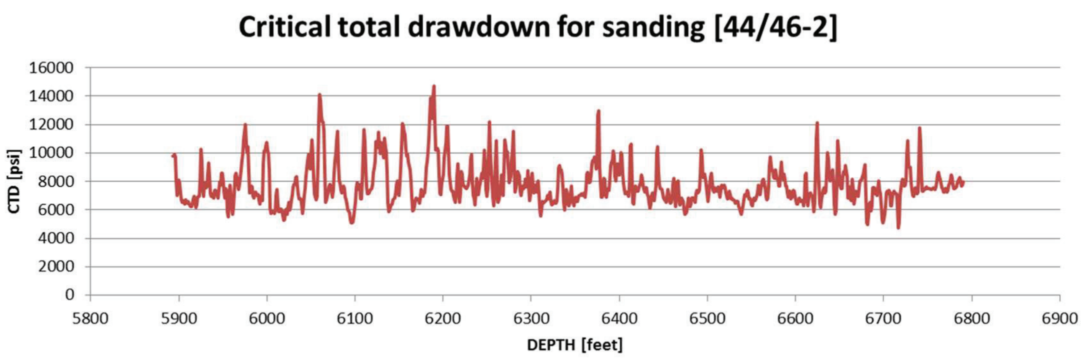


Figure 11-49 Critical drawdown pressure for the Bunter Sandstone, Well 44/26-2

3.2 Guidelines for completing injector wells

Following the guidelines from SPE 39436, the cases listed below are selected depending on the critical drawdown criteria.

Case A: Very weak or unconsolidated formation from top to bottom

- Gravel pack
- Openhole with prepacked screen – if zone isolation is not required and there is a narrow grain size distribution

Case B: Weakly consolidated formation, low injection pressure

- Selective perforation with a propped hydraulic fracture
- Selective perforation with a frac pack, without a screen

Case C: Weakly consolidated formation, high injection pressure

- Selective perforation with a high injection pressure. Injectivity enhanced by thermal cracking

Case D: Consolidated formation with limited weak zones

- Selective perforation

Case E: Uniformly strong formation

- Openhole completion, no screen

Following the guidelines from SPE 39436, the Bunter Closure 36 could be considered as a Case D.

4 3D Geomechanical Analysis

4.1 Introduction

A 3D geomechanical model was constructed to investigate the possibility of seal breach and/or fault reactivation on the crest of the Bunter 36 structure. The process involves creating a small strain finite element model (i.e. the grid is not deformed) that allows elastic stress/strain relations and plastic failure effects to be investigated as a response to the proposed injection scheme(s). These reported parameters include the following:

1. Displacement vectors to assess degree of overburden uplift
2. Failure criteria thresholds (shear or tensile) in the Bunter Sandstone or overburden
3. Matrix strains
4. Fault reactivation strains
5. Total and effective stress evolution
6. Stress path analysis (elastic response to pore pressure changes)

The Bunter 36 Petrel model supplied by Axis WT was used as a basis for building a simplified 3D geomechanical model (see Figure 11-50). This model has the same top and base as the Axis WT model within the Bunter Sandstone.

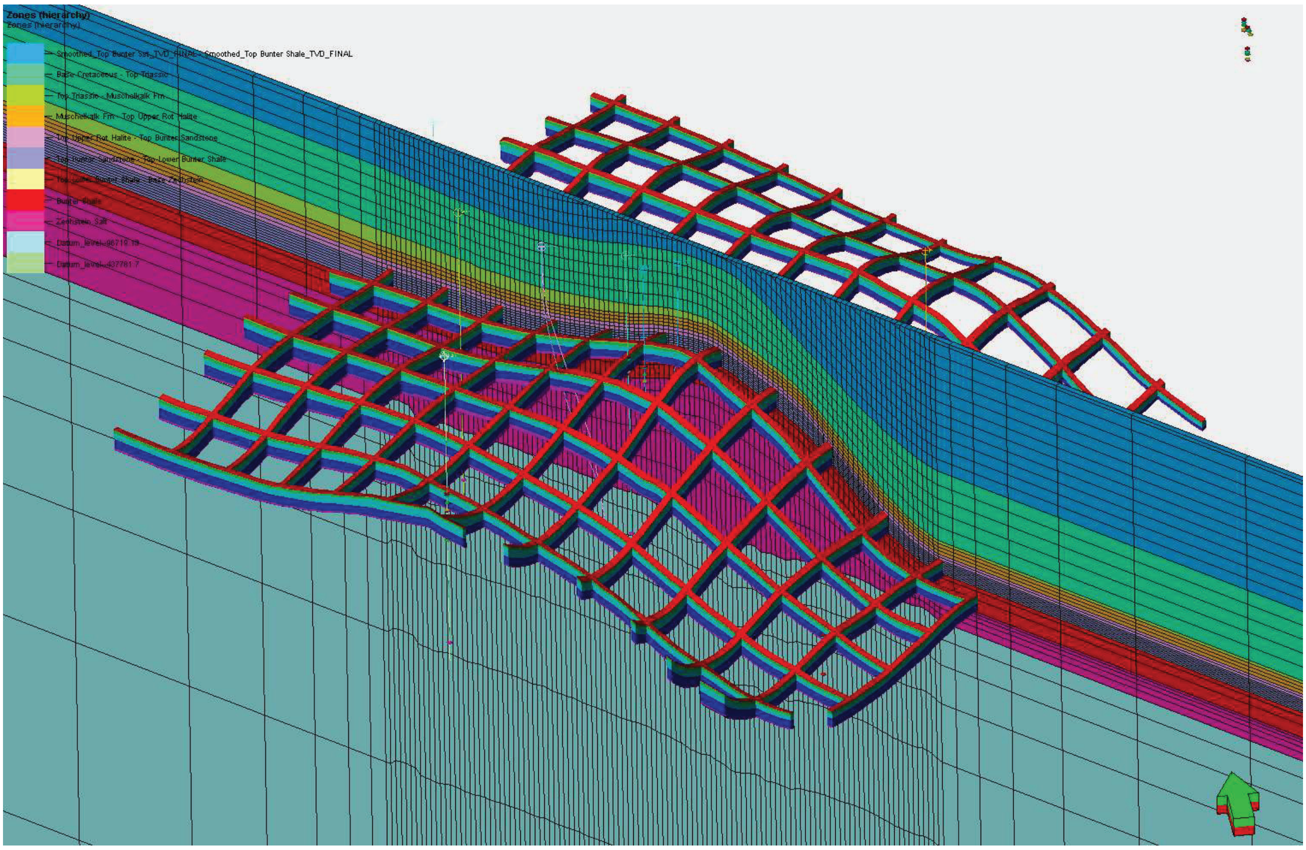


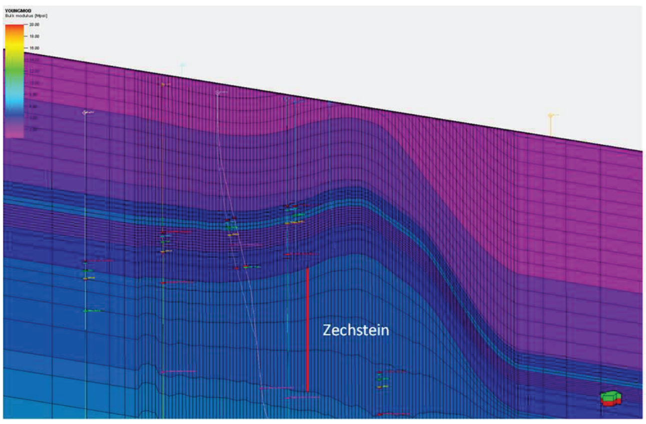
Figure 11-50. Bunter 36 structure. Original Axis WT simulation grid (Sim 3D grid multisectional view) and AGR TRACS geomechanics grid including overburden and additional side and underburdens (Sim 3D grid_AGR_geomechanical NW-SE section). Grids intersect within the Bunter Sandstone (purple)

4.2 3D geomechanical modelling process

The various steps required to construct, initialise, run and analyse a 3D geomechanical model are listed below.

1. Area selected and layering scheme identified. Layering scheme covers all units from Zechstein Salt upwards to Seabed.
2. Explicit surfaces used to generate a grid and zones over the area of interest (Sim 3D grid_AGR). Bunter Sandstone given 8 layers, other zones given 1-4 cells to allow relatively gradual changes in cell thickness (see Figure 11-50).
3. Generate a geomechanical grid. This is a semi-automated process that adds geometrically expanding cells to the model sides (sideburden) and base (underburden). The sideburdens provide a buffer between the model and the boundary conditions. Note the edges of the lateral boundaries are defined by relatively stiff homogeneous plates approximately 50m thick. The underburden thickens the model and prevents buckling.

4. Geomechanical properties were upscaled and distributed from logs in 44/26-2. Young's Modulus, Poisson's Ratio and Uniaxial Compressive Strength (UCS) values generated from logs in Drillworks were used here and distributed using kriging to create smoothly varying properties within the layers from Zechstein to Seabed (see Figure 11-51).
5. Geomechanical Materials (e.g sandstone, shale, salt, faultrock) can be selected from a library and made available to the project. These materials can be assigned to cells based on regions (reservoir, sideburden etc) or specific cell indices. The library materials are used in undefined areas in the log derived properties. The default is to create elastic properties (bulk density, Young's modulus, Poisson's ratio, Biots factor, thermal expansion coefficient and porosity). For this project, Mohr-Coulomb failure function properties for plastic failure analysis were also created (UCS, friction angle, dilation angle and tensile failure threshold) These parameters were defined over the zones from Zechstein to Seabed but with elastic properties in the outer three cells in the lateral direction and the top four cells in the seabed layer. These elastic and plastic materials can be overridden by the properties upscaled and distributed in Petrel (see point 4).
6. Salt (halite) properties were treated differently to the other units. Two variants were created – RefHal using values derived from the logs and WkHal created by assigning the material library salt properties that have a low Young's modulus and high Poisson's ratio and thermal expansion coefficient (see Figure 11-51). This was done to allow the spectrum of possible salt behaviours to be modelled. In reality salt acts as a viscous fluid over geological time and equilibrates to the lithostatic stress state. This can also occur over week to year timeframes depending on the depth and geothermal gradient. However, the instantaneous response obtained from logs or from slightly longer term laboratory tests at surface conditions indicate halite often has moderately high Young's modulus and low to moderate Poisson's ratio values. Petrel Geomechanics does not yet contain a salt creep model so the highly compliant elastic properties variant has been used as a proxy for the stress state obtained via viscous flow. This is generally regarded as adequate for small strains.
7. Fault properties are defined as shear and normal stiffness, cohesion and tensile strength in the material library. These properties are assigned to cells cut by surfaces representing the faults (see Figure 11-52). For this structure, no faults have been supplied to two notional faults (representing possible sub-seismic features) have been created on the crest of the Bunter 36 structure. The properties assigned to these faults were obtained from Zhang et. al. (2007).
8. Pressure / saturation properties are created using pressure vs depth equations and/or upscaled from Eclipse. Single steps are used for initialisation models to allow the stresses to be matched in certain layers (e.g. Bunter Sandstone and salt layers). Multiple pressure steps are used to model the geomechanical responses to the injection pressure steps. Here, steps of 5 years have been used.
9. Boundary conditions properties are created to setup the boundary condition SHmin stress magnitude, the SHmax/Shmin ratio and the SHmin orientation. These are modified to get a match to expected stress trends in the initialisation models. For the multi pressure runs, the starting stresses (6 component tensor) were defined explicitly by splicing the initialisation total stress properties from the sandstone and lithostatic salt stress cases.
10. The cases were setup by selecting the relevant properties folders from items 5 to 8 and defining the run as either linear (elastic) or non-linear (plastic). Non-linear runs utilise the Mohr-Coulomb materials defined in steps 4 and 5.



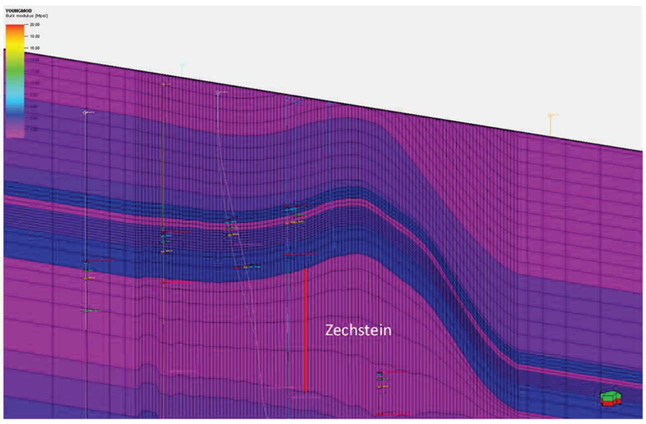


Figure 11-51. Left - Log derived Young's modulus from Drillworks analysis in well 44/26-2. Right, log derived Young's modulus and weak halite properties assigned to Rot Halite and Zechstein. Note the gradation to the constant underburden property under the Zechstein.

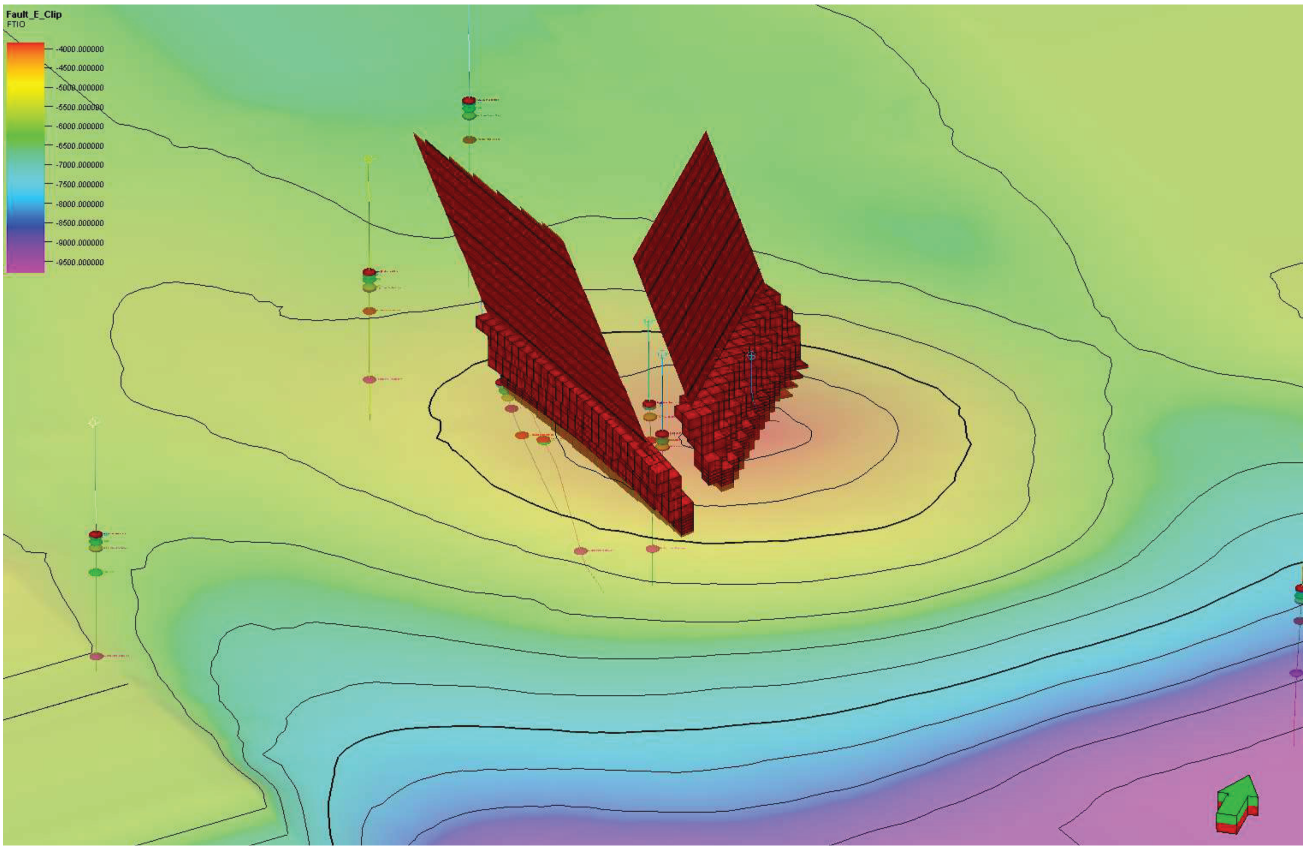


Figure 11-52. Notional sub-seismic fault properties on the Bunter 36 Structure crest. Note slight extension into the Bunter Sandstone to provide a worst case scenario leak path.

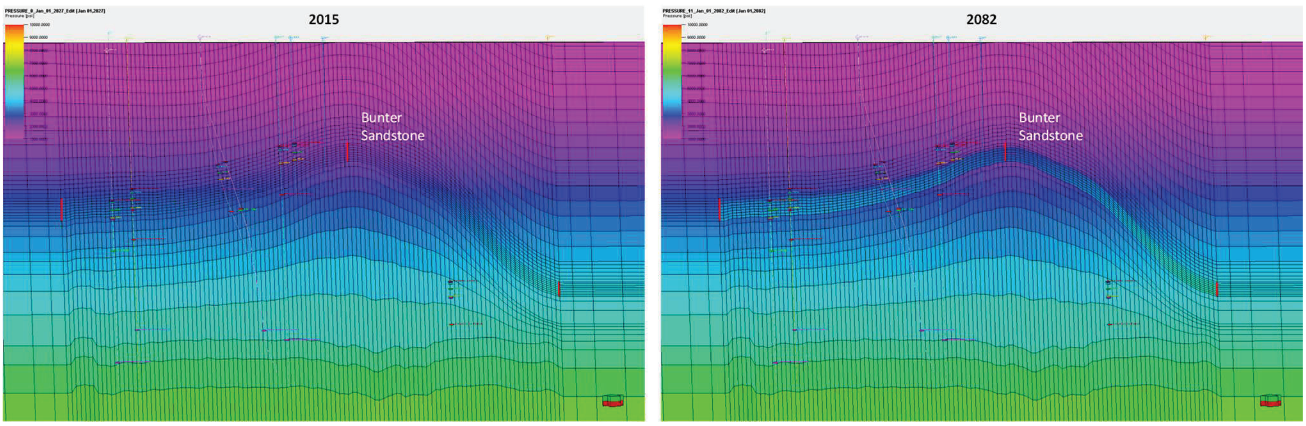


Figure 11-53. Pressure property variations within Bunter Sandstone. Left 2015, hydrostatic pressures. Right 2082 at end of injection. Note upper two layers pressure don't change due to a sealing shale layer within the upper Bunter Sandstone.

4.3 Geomechanics Results

Initial runs with the reference halite properties indicated the stress initialisation in the halite was unrealistic given the long time period of injection (55 years). These were not taken further.

The weak halite model was used with Mohr Coulomb and fault properties as defined above. Explicit stress initialisation was used after approximately matching the SHmin gradient in the Bunter Sandstone and other units to 0.73 psi/ft and setting the halite stresses to lithostatic (isotropic). Seven pressure steps were used from the Eclipse runs in the Bunter Sandstone (2027, 2032, 2042, 2052, 2062, 2072 and 2082). These cases were run in linear and non-linear modes and the following observations can be made.

1. The injection is in multiple well locations and perforation intervals within the Bunter Sandstone. Over the timesteps modelled, the pressure evolution is effectively homogeneous with equilibration over the full model area.
2. Maximum vertical displacement (uplift) at the end of injection is about 0.14 m in the Rot Halite and at the Seabed (see Figure 11-54). The uplift is smoothly distributed around the main Bunter 36 structure with no obvious changes associated with fault reactivation. Note the slight downward displacement on the flanks within the Bunter Shale and Zechstein. This is probably a result of the response of the compliant salt to the injection.
3. Strains are very low with some minor dilational (negative) strains seen in the Bunter Sandstone and even smaller contractional (positive) strains seen in the overburden (see Figure 11-55). Low elastic strains are also observed in the faults. This is partly because the faults only extend into the top 1-2 layers of the Bunter Sandstone and the modelled pressures do not increase in these layers because the injection is below an intra Bunter Sandstone sealing shale. The contractional strains in the underlying Bunter Shale and Zechstein (and associated downward displacement) probably reduce the amount of contractional strain and uplift in the overburden.
4. The non-linear run produced no plastic strains in the model indicating all deformation is elastic. Therefore, failure thresholds have not been reached in the matrix or the faultrocks.
5. CO_2 injection related temperature properties were not available for this project and cooling within the CO_2 plume may cause tensile failure in the Rot Halite. However, this is likely to be minor and wouldn’t occur in the current Bunter Sandstone model because the Upper Bunter sandstone layers are isolated from the injection intervals.

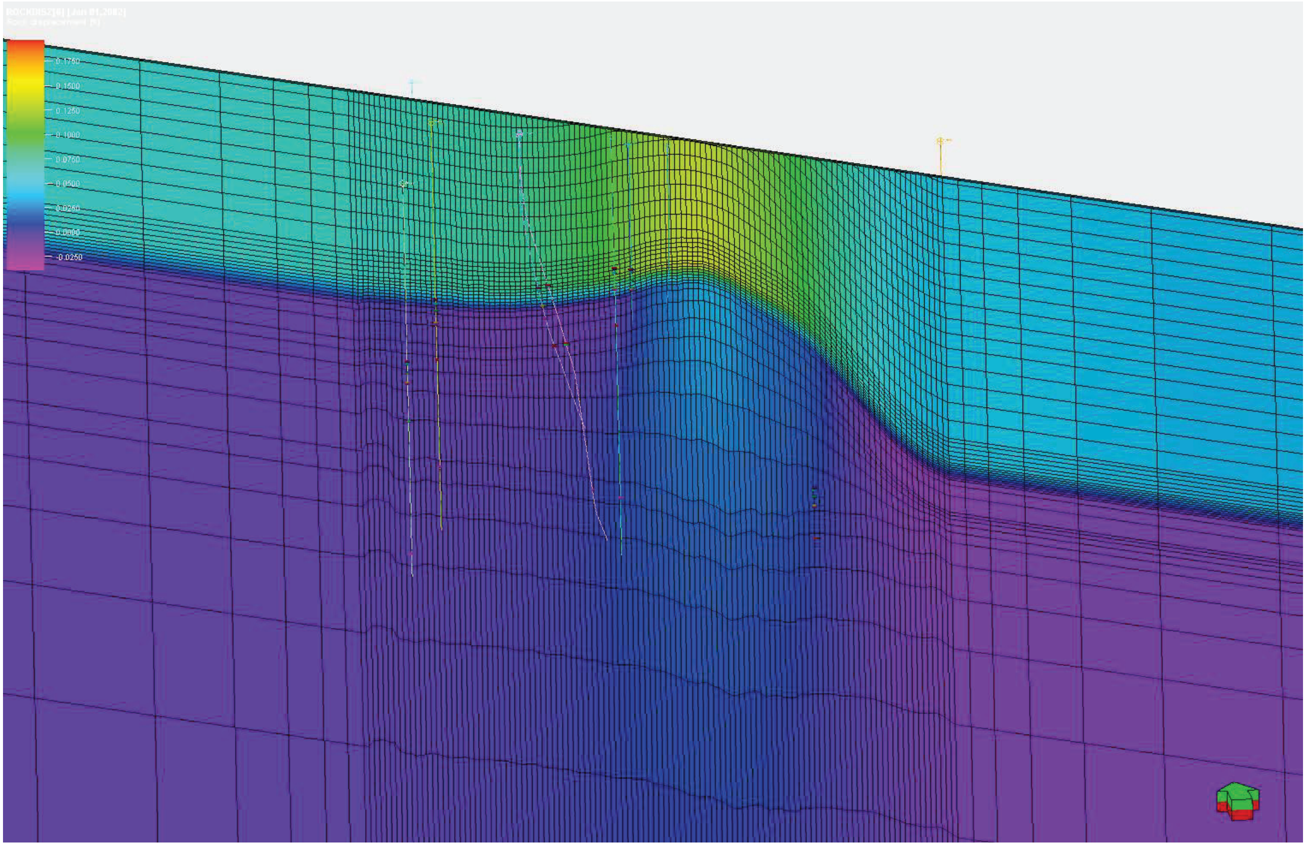


Figure 11-54. Modelled vertical displacement at 2082 in a NW-SE cross section through the Bunter 36 Structure crest.

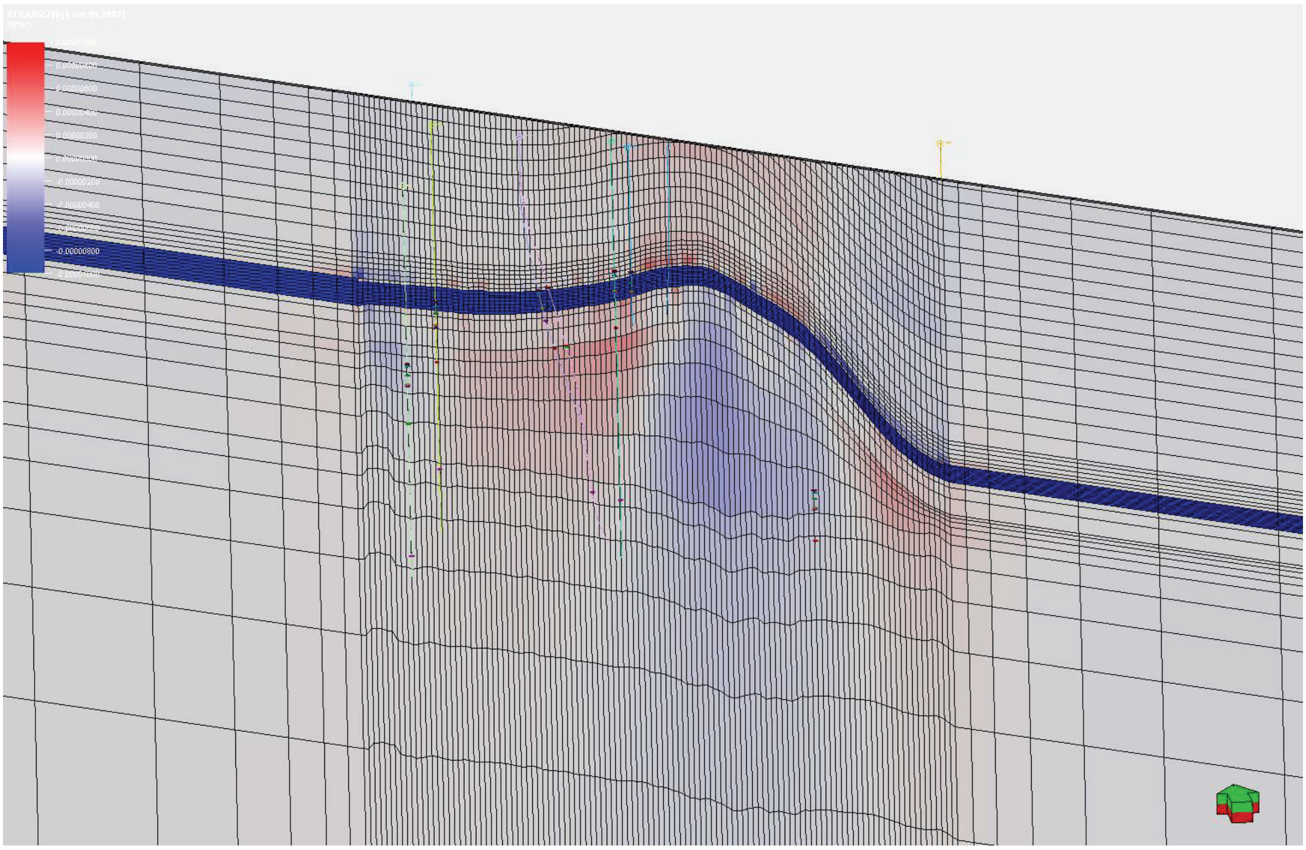


Figure 11-55. Modelled vertical strain at 2082 in a NW-SE cross section through the Bunter 36 Structure crest. Dilational strains are blue and contractional strains are red.

5 Discussion and Conclusions

Wellbore Stability

- The Bunter 36 Structure appears to have a reasonable amount of seismic and well data control.
- 1D geomechanical analysis of existing wells indicates that an SHmin gradient of around 0.73 psi/ft is valid for the Bunter Sandstone and that vertical wells can be drilled through the overburden and Bunter Sandstone with ~10 ppg mud weights.
- For vertical wells in this sequence, the recommended mud weights are essentially the same as the ones used to drill the wells (around 10 ppg). Some basic analysis on required mud weights at different injector orientations has been performed within the Bunter Sandstone. In general, mud weight increases of 1 to 1.5 ppg are sufficient to prevent breakouts for the worst orientation (horizontal wells parallel to SHmax).
- Assumptions are made that the regional NW-SE in-situ stress orientation is relevant to the Bunter 36 Structure. Real Shmax azimuth may be different.
- Focus here has been on the Bunter and immediately overlying units around 5000-6000 ftMD. However, reported experience in the 17 ½” hole sections (~3000-8000 ftMD) of selected existing wells indicate few problems.
- Note the reported static mud weight windows are for drilling ‘gun barrel’ hole with no losses. If some breakout is tolerated and or losses can be managed with LCM then the real mud window could be larger.
- No core has been available to calibrate the strength (breakout) information. This would need optimising for any planned wells.
- The wellbore trajectory analysis has been made on Bunter Sandstone levels only. For any planned wells a predicted MW window would need to be generated based on expected lithologies vs planned trajectory. This could indicate different mud weights are required to maintain stability in some of the shallower units drilled at a higher angle than existing vertical wells.
- Although salt occurs above the Bunter Sandstone (Rot Halite) this is a relatively thin layer at shallow depths and drilling problems from dissolution or salt creep are not anticipated.

Sanding Risk

- The sanding analysis indicates that the Bunter Sandstone is relatively strong and is unlikely to cause sanding due to pressure drops associated with injection related operations.
- Pressure changes during injection operations (e.g. CO_2/water hammer) are unlikely to result in sanding issues.

3D Geomechanical Analysis

- The 3D geomechanical modelling indicates that with the modelled injection scheme from 20127 to 2082 there will be minor uplift and some minor elastic strains with no shear or tensile failure of the overburden or faults.
- Cooling related effects have not been modelled but these are likely to result in minor tensile fracturing in the Bunter Sandstone only as the upper Bunter Sandstone layers have low permeability. These low permeability layers should either prevent the CO_2 plume from contacting the Rot Halite or slow down plume development such that it warms up prior to reach the top of the Bunter Sandstone.
- A worst case scenario would be no baffling/sealing units at top Bunter Sandstone, cooling effects causing local Bunter Sandstone and possible Rot Halite thermal fracturing and the presence of very weak faults propagating down from the overburden into the Bunter Sandstone.

- The development of the Bunter Sandstone dome structure from Zechstein halokinesis +/- lateral compression may be associated with some brittle fracturing or minor faulting that could affect the Bunter Sandstone permeability and/or the sealing unit effectiveness. This is regarded as a minor risk as the available data (logs, reported mud losses) do not indicate significant open fracturing was present during drilling of the Bunter Sandstone and immediate overburden. This is probably because the Bunter Sandstone is relatively porous and permeable so small scale fracturing wouldn't be noticeable and small scale faulting will probably lead to granulation seams and local baffling. The Rot Clay has not been explicitly modelled here but it could be fractured in places. However, it is a relatively thin unit and the Rot Halite would be the primary seal and would heal up any fracturing over geological time.

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11.9 Appendix 9 – Basis of Well Design

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Bunter 36 – Carbon Store

Basis of Well Design

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Contents

1. Introduction

In order to develop the Bunter 36 aquifer for carbon capture and storage, both CO_2 injection and monitoring wells will be required. The CO_2 injectors will be J-shaped, high angle wells in order to optimise dense phase CO_2 injection performance, and the monitoring well will be vertical to minimise cost and complexity. The purpose of this section of the report is to:

- Identify well design risks and drilling hazards based on the available offset well data.
- Generate a preliminary well design for the identified injection and monitoring wells.
- Provide high level time and cost estimates for each well type.

This report proposes conceptual well designs that could form the basis of a detailed well design. It should be stressed that the well designs suggested herein are not fully developed and may be subject to change following detailed engineering analysis.

2. Offset Review

Relevant well data from the CDA database has been analysed in order to identify inputs for designing the Bunter 36 CO_2 injection and monitoring wells. The key findings are as follows:

2.1 Surface Hole and Conductor

In the area, the conductor has been set using two differing techniques, these being:

- Drill a 36" or 32" hole section to approximately 80m below seabed, and then run and cement a 30" or 26" conductor.
- Drive a 26" conductor to approximately 75m.

Both techniques have been applied successfully, with no hole or installation problems occurring.

2.2 Surface Hole Section and Casing

The surface hole sections have been drilled to approximately 400m TVDSS, which is approximately 100m below the top of the Chalk formation. This setting depth was selected to provide sufficient formation strength to drill the next hole section with a weighted mud system, while minimising the length of chalk drilled in surface hole.

All surface hole sections were drilled using seawater, with bentonite sweeps being used to assist with hole cleaning.

Some surface hole sections were directionally drilled, with inclination being nudged up to 10^o. The main reason for conducting directional drilling at shallow depths was to provide separation from offset platform wells. Therefore, should anti-collision issues dictate that directional drilling in the surface hole section is a requirement in a future development application, offset data suggests that this is possible.

No major problems occurred when drilling the surface hole sections, however, the following issues were recorded as being problematic:

- The shallow Tertiary clays overlying the chalk can be reactive when drilled with seawater, and are prone to swelling.
- Overgauge hole was observed in the top chalk section, due to wash-outs.

2.3 Intermediate Hole Section and Casing

In all the offset wells, the main reservoir targets were located in the Rotliegendes Sandstone located below the Zechstein. As such, the Bunter Sand was always drilled in intermediate hole, with an intermediate casing string set upon identification of top Zechstein. Given that the CO_2 store will be in the Bunter Sandstone, this is the last relevant hole section analysed in the offset study.

The findings from the intermediate hole section offset analysis were as follows:

- The chalk section was routinely drilled with either seawater or a basic water based mud, to avoid tight hole problems associated with higher specification mud systems.
    - Increased torque levels were recorded in the Chalk formation when drilling with higher specification water based mud systems, leading to stuck pipe and drillstring failure.
- Chert was encountered in the Chalk formation, which generated high levels of vibration leading to MWD and BHA component failure.
- Upon encountering the top Speeton Clay (located directly below the base of the Chalk), the mud system was changed to a weighted oil based mud in order to provide inhibition against reactive clays and stabilise the mobile salts in the Rot Halite.

  - It should be noted that the first Schooner well attempted to drill the Speeton Clay and Rot Halite with a salt saturated water based mud. However, this was unsuccessful, and the mud was changed to an oil based system following an unsuccessful fishing operation on a stuck BHA.

- The formations below the chalk have been drilled at angles up to 55° without directional drilling related problems occurring.

- There were no significant drilling issues in the Bunter Sand or Shale. However, slow rates of penetration were recorded on some occasions, suggesting that bit and BHA selection can affect operational performance.

- No problems were recorded running and cementing casing. However, there are records of subsequent casing failure due to salt squeeze in the Rot Halite.

3. Drilling Risks and Hazards

The following drilling risks and hazards have been identified from the available offset data:

3.1 Shallow Gas

At present, it is assumed that shallow gas will not be present below the platform location. However, this will be confirmed when the results of the shallow gas survey are available. In the event that shallow gas is identified at the selected platform site, the location should be moved.

3.2 Shallow Swelling Clays

The shallow clays overlying the Chalk formation swell when exposed to seawater or water based drilling fluids. Therefore, the length of time in which they are left open should be minimised. This situation has been managed in the offset wells by setting surface casing in the Upper Chalk at a depth which provides sufficient formation strength to drill the next hole section.

3.3 Chalk Drilling

The shallow Cretaceous Chalk is expected to present the following problems:

- Losses to natural fractures in the upper sections of the formation.
- Enlarged hole and wash-outs when drilled with seawater.
- Chert presence, which eliminates the use of PDC bits.
- Torque and sticky hole when drilled with mud systems.

Of these issues, the most difficult to deal with are hole enlargement and tight, sticky hole, which has led to stuck pipe and drillpipe failures in the offset wells. Sticky hole conditions occur when enhanced mud systems are used, because the chalk fines generated when drilling get incorporated into a drilling fluid with no free water, leading to a rapid increase in viscosity. Therefore, it is preferable to drill the Chalk with seawater or a basic water based mud.

However, when drilling with seawater, hole enlargement will occur, and this can generate hole cleaning problems in directional wells. Therefore, a basic water based mud is the most suitable drilling fluid because it can be designed to:

- Reduce the extent of excessive hole enlargement.
- Provide suitable rheology for hole cleaning purposes.
- Allow chalk fines to be incorporated into the drilling fluid without leading to unmanageable increases in viscosity.

In order to minimise the issues associated with this formation, it is planned to case off the Chalk prior to drilling the reactive clays and mobile halites below the Chalk sequence.

3.4 Reactive Clay

Problems have occurred in the offset wells when drilling the Speeton Clay with water based systems, suggesting that the shales are chemically reactive. In order to avoid this problem, it is recommended that this formation is drilled with oil based mud.

3.5 Rot Halite

The Triassic halites are known to be mobile, with instances of stuck pipe having been recorded in the offset data. Two mud systems have been successfully used when drilling the Rot Halite, these being salt-saturated water-based mud and oil-based mud. Either is considered acceptable for use; however given that oil based mud is required to drill the overlying Speeton Clay, operational efficiencies would be gained by continuing to use this system.

In order to minimise salt movement, it is important to select the correct mud weight. Offset data suggests that a mud weight of 10.5 ppg will be successful in preventing salt movement in the Rot Halite, however this may be inclination dependent. It is recommended that detailed modelling be conducted during the FEED stage to confirm the mud weights required to maintain wellbore stability in the Speeton Clay and Rot Halite at the inclinations planned.

3.6 Bunter Sand

The Bunter Sand is hard and abrasive which can lead to low rates of penetration (ROP), therefore, bit selection will be a key consideration from a drilling performance perspective. Also, the abrasive nature of the formation can lead to bit and BHA wear, which can generate under-gauge hole. In order to avoid this problem, bit and BHA component selection should address the risk of tool wear by ensuring that suitable gauge protection is included in component design.

4. Directional Profiles

4.1 Reservoir Targets

The following reservoir targets have been identified for the top of the Bunter Sand:

Target Name	TVDSS (m)	UTM North (m)	UTM East (m)
Bunter INJ1	1,359.3	5,991,223.7	444,000.0
Bunter INJ4	1,394.7	5,988,107.6	441,356.9
Bunter INJ5	1,347.1	5,990,901.3	442,178.2
Bunter INJ6	1.325.8	5,989,675.0	441,661.6

The coordinate system in use is UTM, ED50 Common Offshore, Zone 31N (0° East to 6° East)

4.2 Surface Location

A central surface location has been selected, which is positioned to allow each well to be reached from a single platform. The coordinates of the surface location are:

- 5,989,400m North
- 443,400m East

The surface location and well position is shown in the spider plot below:

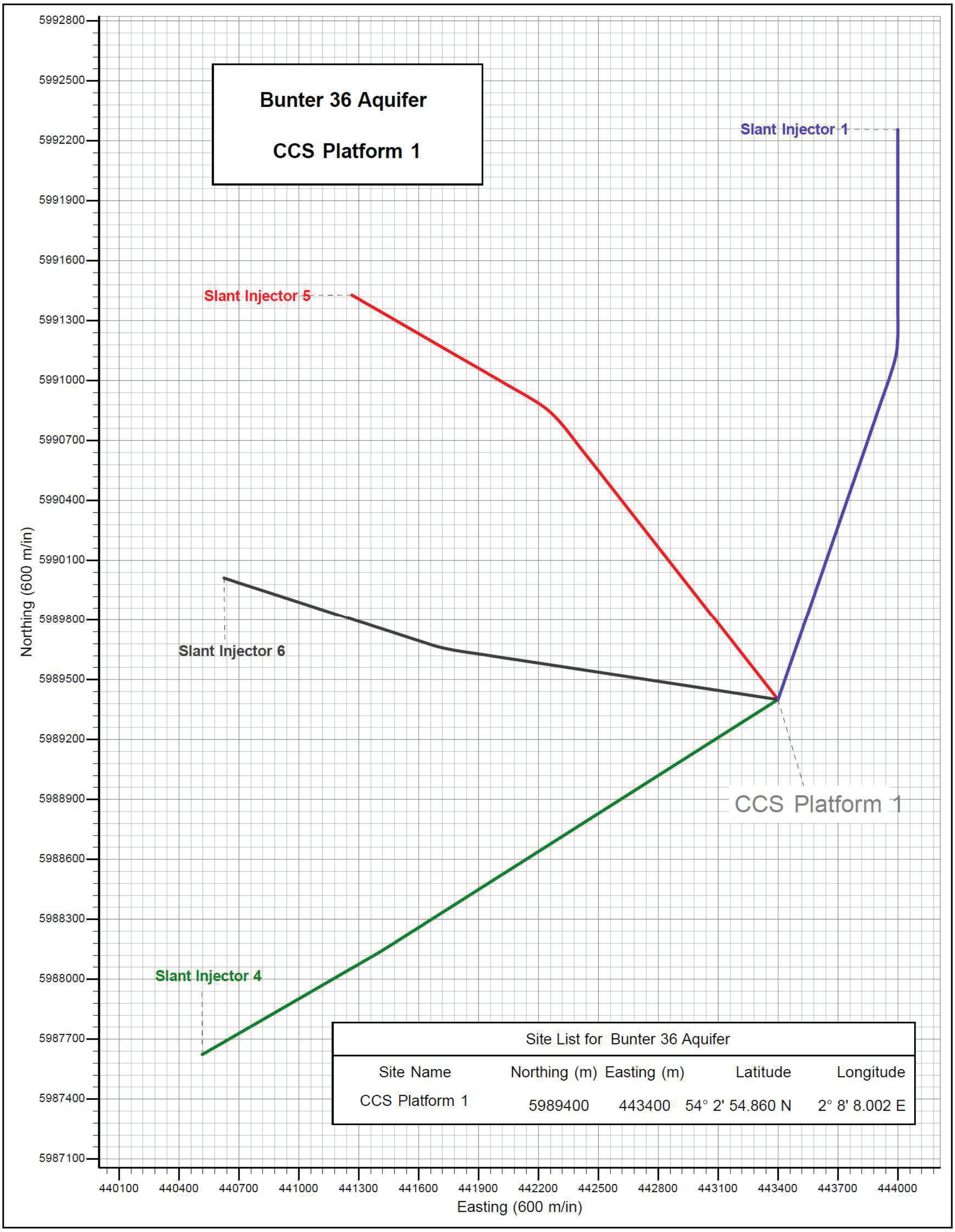


Figure 56: Directional Spider Plot

4.3 Directional Design

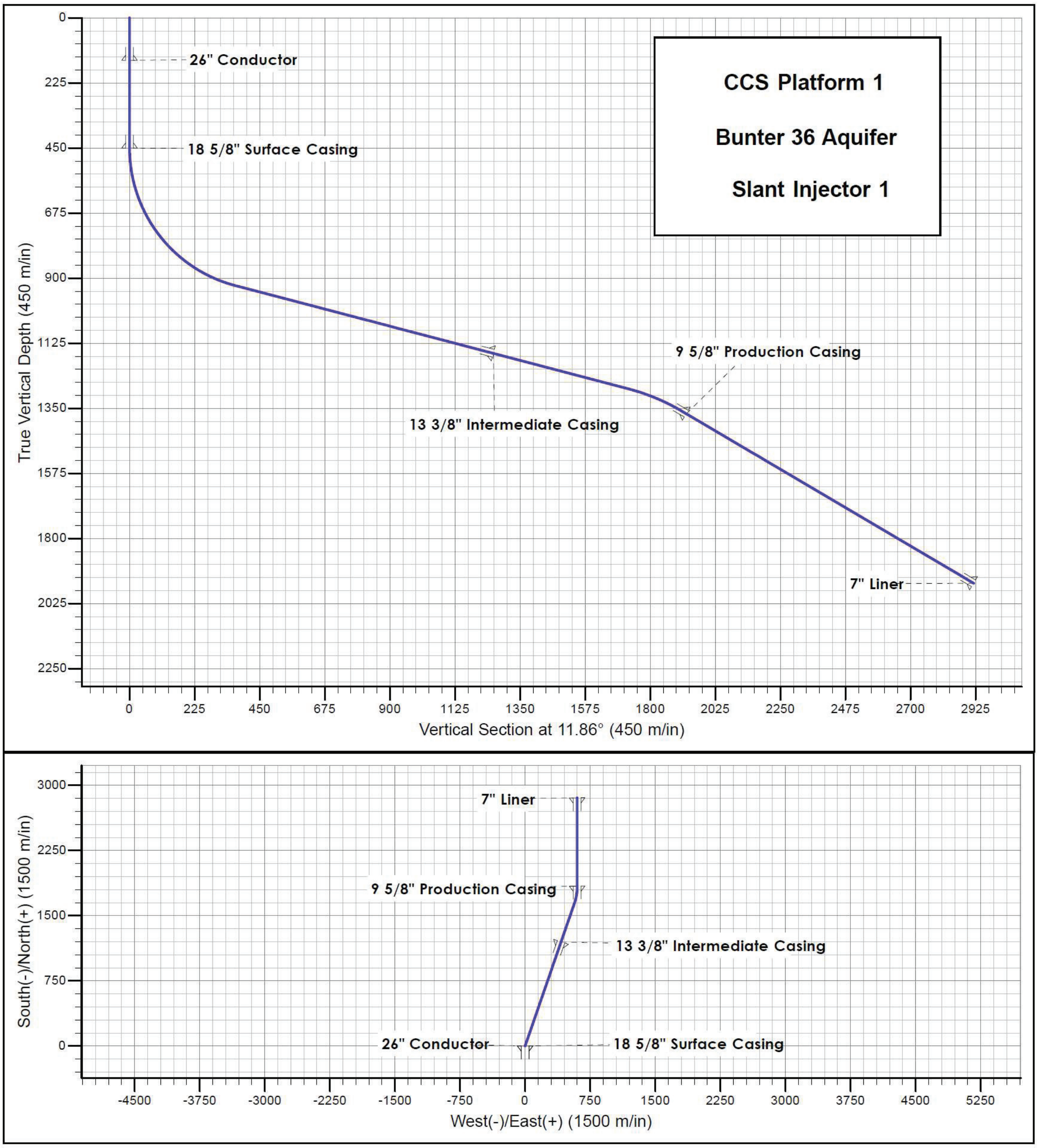
A platform surface location and well locations in the reservoir have been selected for conceptual well design purposes; however, it should be noted that these locations have not been optimised for reservoir management or directional drilling purposes. Therefore, it is recommended that the wells are re-planned and anti-collision scans conducted during the FEED stage when the target locations have been finalised.

The conceptual directional plans for the CO_2 injectors have been designed on the following basis:

- The injection wells will be drilled as high angle slant wells.
- The surface hole sections will be drilled vertically, to minimise the risk associated with shallow swelling clays and a weak Upper Chalk formation.
- All wells will be kicked off directly below the surface casing shoe, with dog leg severity kept to 3.5^{o} per 30m.
- A build section will be drilled from the surface shoe to the depth at which inclination is sufficient to reach the identified reservoir target.
- A turn and drop section will be drilled in the 12 ¼" hole section to reduce inclination to 60^{o} at the top of the Bunter Sand while turning the well path onto the desired azimuth.
- The reservoir section will be drilled as a tangent section, holding inclination at 60^{o} to TD below the base of the Bunter Sand.

The conceptual directional plan for the monitoring well assumes that a vertical well will be drilled directly below the platform location.

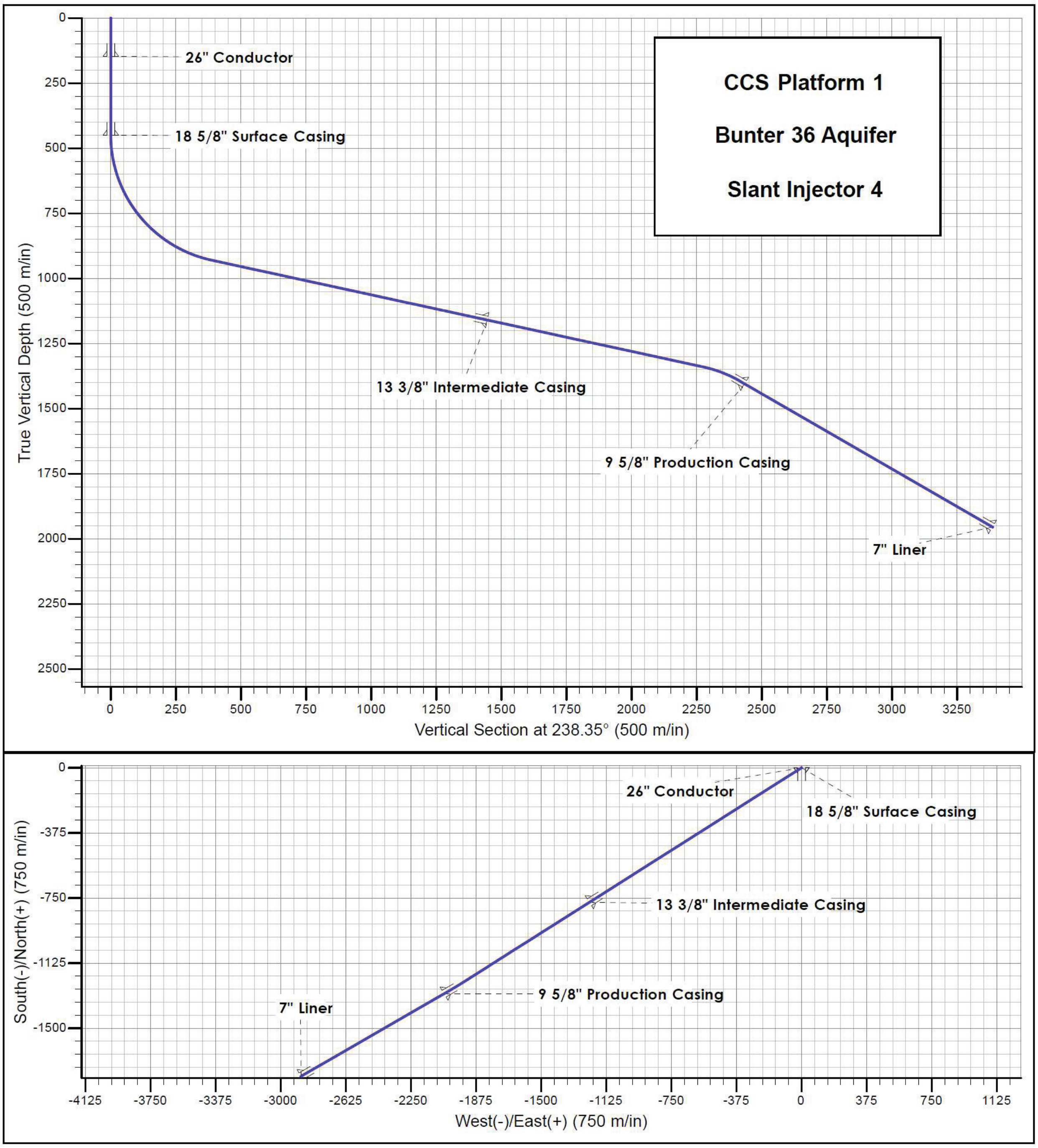
Directional profiles have been prepared for each well based on the reservoir targets and directional drilling limitations, as follows:



SECTION DETAILS

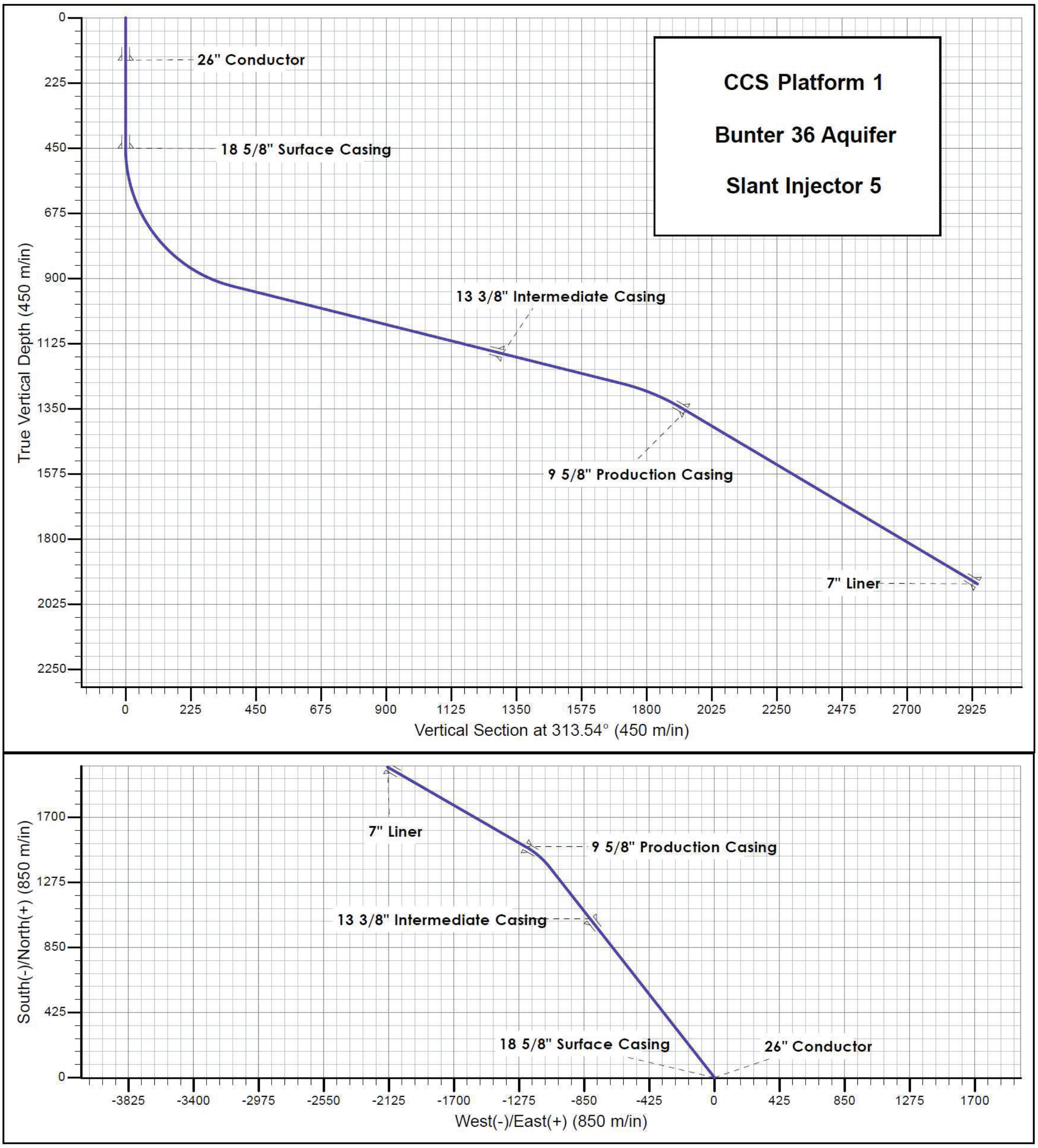
MD	Inc	Azi	TVD	+N/-S	+E/-W	Dleg	TFace	VSect
0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.00
450.00	0.00	360.00	450.00	0.00	0.00	0.000	360.00	0.00
1096.19	75.39	19.07	925.23	347.08	119.96	3.500	19.07	364.33
2513.31	75.39	19.07	1282.69	1643.13	567.93	0.000	0.00	1724.79
2713.37	60.00	360.00	1359.00	1823.75	600.00	3.500	-134.43	1908.14
3905.37	60.00	360.00	1955.00	2856.05	600.00	0.000	0.00	2918.39

Figure 57: Slant Injector 1 Directional Profile



SECTION DETAILS								
MD	Inc	Azi	TVD	+N/-S	+E/-W	Dleg	TFace	VSect
0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.00
450.00	0.00	360.00	450.00	0.00	0.00	0.000	360.00	0.00
1116.41	77.75	237.62	929.92	-207.20	-326.73	3.500	237.62	386.86
3048.67	77.75	237.62	1339.96	-1218.45	-1921.37	0.000	0.00	2274.95
3201.97	60.00	240.00	1395.00	-1292.35	-2043.10	3.500	173.27	2417.36
4321.97	60.00	240.00	1955.00	-1777.33	-2883.10	0.000	0.00	3386.91

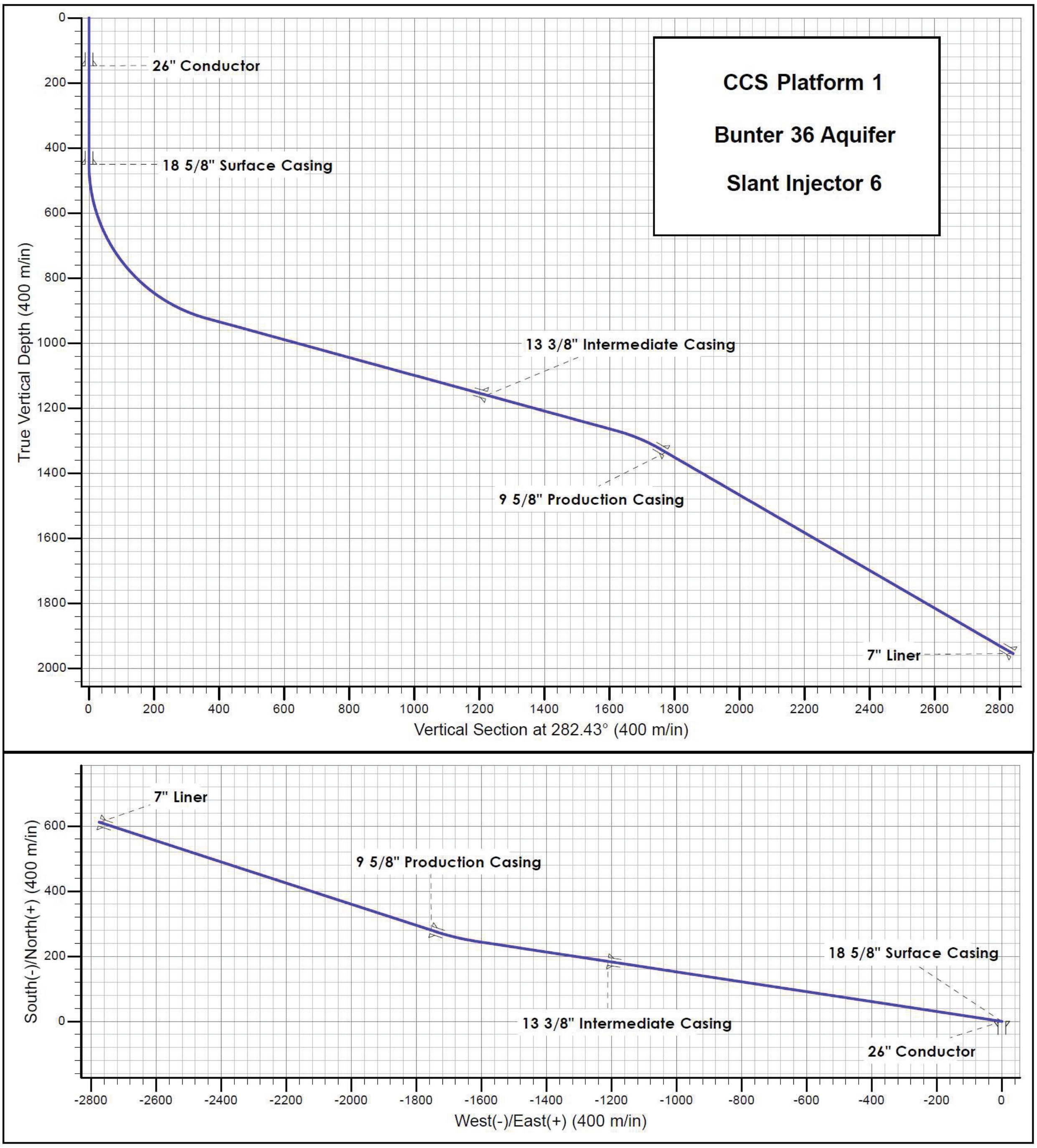
Figure 58: Slant Injector 4 Directional Profile



SECTION DETAILS

MD	Inc	Azi	TVD	+N/-S	+E/-W	Dleg	TFace	VSect
0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.00
450.00	0.00	360.00	450.00	0.00	0.00	0.000	360.00	0.00
1102.38	76.11	321.94	926.75	293.87	-230.08	3.500	321.94	369.22
2505.46	76.11	321.94	1263.55	1366.32	-1069.74	0.000	0.00	1716.66
2727.15	60.00	300.00	1347.00	1501.35	-1221.80	3.500	-132.12	1919.90
3943.15	60.00	300.00	1955.00	2027.89	-2133.80	0.000	0.00	2943.71

Figure 59: Slant Injector 5 Directional Profile



SECTION DETAILS

MD	Inc	Azi	TVD	+N/-S	+E/-W	Dleg	TFace	VSect
0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.00
450.00	0.00	360.00	450.00	0.00	0.00	0.000	360.00	0.00
1090.23	74.69	278.65	923.69	54.39	-357.35	3.500	278.65	360.68
2401.62	74.69	278.65	1269.86	244.72	-1607.81	0.000	0.00	1622.80
2547.49	60.00	288.00	1326.00	275.05	-1738.40	3.500	151.28	1756.85
3805.49	60.00	288.00	1955.00	611.71	-2774.54	0.000	0.00	2841.17

Figure 60: Slant Injector 6 Directional Profile

5. Well Design

5.1 CO_2 Injector

The conceptual well design for a CO_2 injector is as follows:

5.1.1 Conductor

To reduce the risk of shallow soil destabilisation, the conductor string is normally driven to depth on platform wells in the Southern North Sea, and this method has been selected for setting the conductors in the Bunter 36 area. The conductor setting depth has been specified as 75m below the mudline for the following reasons:

- Conductors have been successfully driven to this depth regionally.
- The formation strength at this depth should be sufficient to hold a mud weight of 10.0 ppg (recommended spud mud weight prior to running surface casing), and allow returns to be taken to the rig floor elevation.

The selected conductor size is 26” which is compatible with the selected well design, while minimising the tubular diameter for driving efficiency.

5.1.2 22” Surface Hole and 18 ⅝” Casing Setting Depth

The surface casing setting depth has been selected as 450m TVDSS in order to case off the swelling clays above the Chalk formation. This is considered to be advantageous for the following reasons:

- **Time Related Instability:** The length of time to which the shallow clays are exposed to seawater should be minimised to reduce the impact of gumbo type problems.
- **Formation Strength:** The upper sections of the Chalk are known to be weak, and it is preferable to case these off prior to conducting directional drilling activities.
- **Directional Drilling:** By setting the surface casing at 450m TVDSS, the surface hole section can be drilled vertically through the swelling clays and Upper Chalk.

5.1.3 17 ½” Intermediate Hole and 13 ⅜” Casing Setting Depth

The 13 ⅜” intermediate casing setting depth has been selected as the top of the Cromer Knoll, directly below the base of the Chalk at approximately 1,160m TVDSS. This is considered to be advantageous for the following reasons:

- **Hole Condition:** The Chalk is known to provide problematic hole conditions when drilled with an oil-based mud system. Therefore, by casing off the Chalk prior to drilling the next hole section, a basic water based mud can be used in the intermediate hole section, while allowing the reactive clays and halites below the Chalk to be drilled with oil based mud.
- **Chert:** The Chalk is known to contain chert. By casing off the Chalk, PDC bits can be selected for the next hole section, thereby providing drilling performance benefits.

5.1.4 12 ¼” Intermediate Hole and 9 ⅝” Production Casing Setting Depth

The 12 ¼” intermediate hole section will be drilled through the reactive Speeton Clay and Rot Halite formations, and will be cased off prior to drilling the reservoir section. The 9 ⅝” production casing setting depth has been selected as 20m MD below the top of the Bunter Sand for the following reasons:

- **Cement Quality:** By setting the 9 ⅝" casing shoe below the top of the Bunter Sandstone, the production casing can be cemented across the Rot Halite and Speeton Clay. This provides the following advantages:
    - The cement design can be optimised to provide isolation from the reservoir, thereby minimising the risk of CO_2 leakage from the reservoir.
    - The risk of a poor cement job across the Rot Halite is reduced, thereby minimising the risk of casing collapse due to mobile salt point loading.
    - The probability of delivering a good cement job for end of life abandonment purposes is increased.
- **Sandface Completion:** By drilling the reservoir in a dedicated hole section, the mud system and production liner can be designed to optimise well intervention access, while also increasing the probability of obtaining reservoir zonal isolation via a good cement job.

5.1.5 8 ½" Production Hole and 7" Liner Setting Depth

The 8 ½" hole section will be drilled through the Bunter Sand and into the top of the Bunter Shale in order to maximise the available injection interval across the Upper and Lower Bunter reservoir sections.

A 7" liner will be run to TD and cemented across its entire length for reservoir management and zonal isolation purposes.

The amount of Bunter Shale drilled will be dependent upon the length of the production liner shoetrack.

5.1.6 End of Field Life Well Abandonment

The casing sizes and setting depths have been selected to ensure that the well can be abandoned at the end of field life by placing cement plugs inside cemented 9 ⅝" production casing and opposite the Speeton Clay and Rot Halite. These formations have sufficient strength to contain reservoir pressure; therefore, by placing the abandonment plugs opposite these formations, store integrity will be assured.

5.2 Monitoring Well

The conceptual well design for a monitoring well is as follows:

5.2.1 Conductor

The conductor design will be as per a CO_2 injector.

5.2.2 17 ½" Surface Hole and 13 ⅜" Casing Setting Depth

The surface casing setting depth has been selected as the top of the Cromer Knoll, directly below the base of the Chalk at approximately 1,160m TVDSS. Unlike the CO_2 injector, the monitoring well will be drilled vertically, allowing the entire Chalk section to be drilled in surface hole using seawater.

5.2.3 12 ¼" Intermediate Hole and 9 ⅝" Production Casing Setting Depth

The 9 ⅝" production casing setting depth will be as per a CO_2 injector.

5.2.4 8 ½" Production Hole and 7" Liner Setting Depth

The 8 ½" hole section will be drilled through the Bunter Sand and into the top of the Bunter Shale in order to allow flexibility in the selection of the strata to be monitored.

As per the CO_2 injector design, the amount of Bunter Shale drilled will be dependent upon the length of the production liner shoetrack.

5.2.5 End of Field Life Well Abandonment

The casing sizes and setting depths have been selected to ensure that the well can be abandoned at the end of field life by placing cement plugs inside cemented production casing and opposite the Speeton Clay and Rot Halite. These formation have sufficient strength to contain reservoir pressure, therefore, by placing the abandonment plugs opposite these formations, store integrity will be assured.

It should be noted that an appraisal well may be drilled prior to the development drilling programme. In the event that this occurs, the appraisal well may be suspended and then converted to a monitoring well via a mudline suspension system tie back.

5.3 *Casing Metallurgy*

When selecting the casing materials for CO_2 injectors, the following issues should be taken into consideration:

- Corrosion caused by exposure to dense phase CO_2.
- Material selection for low temperature.

For casing strings with no direct exposure to the CO_2 injection stream, CO_2 corrosion resistant materials are not required. Therefore, the following casings strings may be specified using conventional carbon steel grades:

- 26” conductor
- 18 ⅝” surface casing
- 13 ⅜” intermediate casing
- 9 ⅝” production casing above the production packer

However, below the production packer, the casing and liner casing components will be exposed to injected CO_2. The corrosion potential will be dependent upon the water content of the injected CO_2, and/or latent water in the wellbore; however, some form of corrosion resistant alloy (CRA) will be required. The most commonly used CRA for CO_2 corrosion resistance is 13Cr and this would probably be suitable for the casing strings exposed to the injection stream below the production packer. However, it is recommended that detailed modelling be conducted during the FEED stage to confirm that this material is suitable for the injection stream specification. The casing strings to be designed using CRA materials are:

- 9 ⅝” production casing below the production packer
- 7” production liner

When selecting the casing materials, it should also be noted that all casing strings could be exposed to low temperatures. The worst case happens during transient conditions which occur when wellbore pressure is released. A reduction in wellbore pressure can occur due to planned operations (i.e. when pressure is bled off to test a downhole safety valve or during well servicing activities), or when an unplanned event occurs (i.e. there is a leak at the wellhead). When wellbore pressure is released either by design or unexpectedly, the dense phase (liquid) CO_2 will revert to its gaseous phase. At the liquid / gas interface, temperatures can be as low as -78°C, and heat transfer will lead to the near wellbore casing materials being exposed to low temperatures. In order to determine the minimum temperature that each casing string could be exposed to, modelling will be required, and this should be conducted during the detailed design phase.

When metals cool they lose toughness, which could become an issue when subjected to mechanical load. Therefore, in order to demonstrate that the selected casing grades are suitable for the modelled temperatures, low temperature impact toughness testing should be conducted by the steel suppliers, to confirm that the selected tubular is suitable for a low temperature application.

The monitoring well will not be exposed to the same concentrations of CO_2 and/or water as an injector. However, it is recommended that the selected casing grades are the same for a monitoring well as for an injector. This should provide the following benefits:

- Reservoir management flexibility is provided (i.e. it would ease conversion of a monitoring well to an injector).
- It would minimise the number of differing casing joints and string components purchased.

5.4 Wellhead Design

As with the casing materials, the wellhead components must also be designed to provide suitable low temperature performance and corrosion resistance. Wellhead component temperature rating is specified in API 6A with a class being assigned to reflect the temperature range to which the components are rated. For CO_2 injection wells, API 6A class K materials may be suitable, as the low temperature rating of these materials is -60^{o}C. This should be acceptable for CO_2 injection purposes; however, it is recommended that detailed modelling is conducted for each wellhead component to confirm the lowest temperature to which they may be exposed, and that suitable materials are being selected.

In addition, the wellhead components which are directly exposed to the CO_2 injection stream should be specified from CO_2 resistant alloys.

5.5 Negative Wellhead Growth

When CO_2 injection commences, well temperatures are expected to drop. This could lead to casing contraction and negative wellhead growth (i.e. the wellhead made up to the surface casing will move lower, and the tensile stresses in the 13 ⅜” and 9 ⅝” casing strings will decrease). This scenario should be modelled during the detailed design phase, to confirm that the selected casing strings remain within their tensile and compression design limits.

In addition, wellhead downward movement could lead to the wellhead, annulus valves and flowline clashing with the top of the conductor. Therefore, it is recommended that casing contraction is modelled during the detailed design phase to determine the movement magnitude, and to confirm that the gap between the top of the conductor and the surface casing starter wellhead is sufficient to prevent component clashes.

5.6 Drilling Fluids Selection

5.6.1 22” Surface Hole Section

This hole section should be drilled with seawater and viscous sweeps, taking returns to the rig. At section TD, the hole should be displaced to 10.0 ppg spud mud, to maintain wellbore stability prior to running the surface casing string.

The 22” hole section will be drilled primarily through the shallow swelling clays and Upper Chalk, and this formation is known to produce sticky hole conditions, and high torques. However, chalk reacts well to being drilled with seawater, as the fines produced are constantly being diluted. In addition, faster ROPs can be obtained by drilling on-balance, and should losses occur, the cost implications will be minimal.

5.6.2 17½" Hole Section

This hole section should be drilled with a basic bentonitic water based mud, taking returns to the rig.

The mud system options for drilling Cretaceous Chalk are:

- Seawater
- A simple bentonitic water based mud
- An enhanced water based mud such as KCl / polymer
- Oil-based mud

A simple bentonitic water based mud system has been selected for the following reasons:

- When drilling with seawater, hole enlargement will occur, and this can generate hole cleaning problems in directional wells. Given that high angles are required in the 17 ½" hole section to deliver the directional drilling objectives, hole cleaning problems must be avoided.
- When drilling chalk formations, fines are produced from the cutting action of the bit and borehole erosion from drillstring rotation. These fines get incorporated into the drilling fluid leading to a rise in viscosity and sticky hole conditions. This problem is exacerbated by enhanced mud systems such as oil based mud or KCl or silicate water based muds, as the fines lead to a rapid rise in viscosity.
- A simple water based drilling fluid can incorporate chalk fines into the system with a lower rise in viscosity, making the problem manageable. In addition, a simple water based mud can be designed to:
  - Reduce the extent of excessive hole enlargement.
  - Provide suitable rheology for hole cleaning purposes.

5.6.3 12¼" Hole Section

This hole section should be drilled with 10.5 ppg oil based mud, taking returns to the rig. Oil based mud has been selected to:

- Avoid the Speeton Clay reactivity problems encountered in the offset wells when drilling with water based mud.
- Maintain borehole stability in the Speeton Clay and Rot Halite (i.e. prevent mobile salt movement).
- Deliver the optimum ROPs available for these formations.
- Prevent washouts in the Rot Halite mobile salts, and maintain gauge hole.
  - This reduces the risk of hole cleaning problems and increases the probability of obtaining a good cement bond.

The offset data suggests that the formations encountered in this hole section will be drilled more efficiently using a combination of PDC bits and oil-based mud. Salt saturated water-based muds have been used in these formations, and should WBM be selected, the objectives of the hole section should be delivered. However, the differences in performance on the offset wells are characterised by the time taken to drill these formations, and the wells drilled with WBM have been significantly slower due to lower ROPs, and lost time associated with wiper trips, hole conditioning and stuck pipe.

It should be recognised that cuttings collection and management will be an important issue when using oil based mud. Therefore, this factor should be addressed early in the planning process, when selecting the rig.

5.6.4 8½" Hole Section

The 8 ½" hole section should be drilled with 10.5 ppg oil-based mud. This has been selected to:

- Minimise formation damage in the Bunter Sand by building a tight filter cake and reducing the depth of filtrate invasion.
    - It should be noted that oil-based mud can also cause damage in the Bunter Sand, if incorrectly specified. Fluid loss to the reservoir can affect porosity; therefore it is important to maintain mud system fluid loss at very low levels. In addition, filter cake deposition must be tightly controlled, to ensure that any damage that does occur is local to the wellbore, allowing the perforation tunnels to extend beyond the damaged zones.
- Deliver the optimum ROPs available for the Bunter formations.

The offset data from the surrounding wells suggests that this hole section will also be drilled more efficiently using PDC bits and oil-based mud. Faster ROPs in the Bunter Sand and Shale have been obtained using this combination, with significant performance advantages being obtained.

5.7 Cement Programme

5.7.1 18 ⅝" Surface Casing

The 18 ⅝" surface casing should be cemented back to the mudline using conventional cement slurries.

5.7.2 13 ⅜" Intermediate Casing

The purpose of the 13 ⅜" cement job is primarily to provide a strong shoe prior to drilling the Speeton Clay and Rot Halite, and a tail slurry should be used to generate the compressive strength required to meet this objective.

The 13 ⅜" casing should be cemented back to 100m inside the 18 ⅝" shoe in order to save suspension or abandonment costs, while minimising the risk of cement contamination at the mudline hanger.

Conventional lead and tail slurries should be selected for this cement job.

5.7.3 9 ⅝" Production Casing

The purpose of the 9 ⅝" cement job is to provide a strong shoe prior to drilling the Bunter Sand, as well as preventing CO_2 leakage from the reservoir, and a tail slurry should be used to generate the compressive strength required to meet this objective.

The 9 ⅝" casing should be cemented back to 200m inside the 13 ⅜" shoe in order to:

- Cement off all open formations, and minimise leak paths from the Bunter Sand.
- Optimise the end of field life abandonment design.

5.7.4 7" Production Liner

The purpose of the 7" cement job is to provide zonal isolation in the reservoir and prevent CO_2 leakage. The liner should be cemented over its entire length to the liner hanger.

5.8 Production Casing and Liner Cement Design

At present, it is planned to cement the production casing and liner strings using conventional Portland Class G cement. The interaction between Portland cement and CO_2 is as follows:

- Carbonic acid will form when water and CO_2 are present:

  $CO_2 + H_2O = HCO_3^- + H^+ = CO_3^{2-} + 2H^+$

- When cement and carbonic acid are in contact, cement dissolution and carbonate precipitation (also called cement carbonation) occurs. This process forms an insoluble precipitate and leads to lower porosity because calcium carbonate has a higher molar volume than $Ca(OH)_2$ (i.e. cement). This reduces the CO_2 diffusion rate into the cement and is therefore a self-healing mechanism (Shen and Pye, 1989). The precipitation mechanism is:

  $Ca(OH)_2 + CO_3^{2-} + 2H^+ = CaCO_3 + 2H_2O$

  $3H_2CO_3 + Ca_3Si_2O_7 * 4H_2O = 3CaCO_3 + 2\ SiO_2 * H_2O + 3\ H_2O$

Due to the carbonation effect, cement degradation is a very slow process. Lab testing has been conducted by various parties in order to determine the rate of degradation, with a summary of the test results shown below.

Test Reference	Cement Class	Test Pressure (bar)	Test Temperature (°C)	Cement degradation per 1,000 years (mm)	Cement degradation per 10,000 years (mm)
Bartlet-Gouedard	G	280	90	776	2,454
Bartlet-Gouedard	G	280	90	646	2,042
Duguid et al	H	1	23	29	92
Duguid et al	H	1	23	16	50
Duguid et al	H	1	23 / 50	99	314
Duguid et al	H	1	23 / 50	74	234
Lecolier et al	Conventional	150	120	1,648	5,211
Shen & Pye	G	69	204	3,907	12,354
Bruckdorfer	A	207	79	184	583
Bruckdorfer	C	207	79	152	480
Bruckdorfer	H	207	79	228	721
Bruckdorfer	H + flyash	207	79	250	789

Table 12: Cement degradation rates in CO_2: Laboratory test results

For comparison purposes, the Bunter reservoir pressure is predicted to be approximately 160 bar. As such, the rate of cement degradation predicted by Lecolier et al may be the most appropriate measurement to use. This suggests that cement would degrade at a rate of 5.2m per 10,000 years. Given that the length of cement behind the 9 ⅝" production casing is designed to cover approximately 800m, it may be concluded that the rate of conventional class G cement degradation makes the selection of this cementing material suitable for use.

However, the loss of integrity due to degradation is not the only factor to be considered when selecting the cement type. The creation of micro-annuli due to thermal cycling should also be taken into consideration, as the wellbore could be exposed to low temperatures at certain stages of the CO_2 management process. .

CO_2 resistant cements are available from the main cementing service providers, with the chemistry being well understood. These specialist cements have been used in CO_2 environments, however, they can be problematic to handle as they are incompatible with conventional cementing products. Therefore, when selecting the preferred cement type it is recommended that conventional cements are compared with CO_2 resistant systems, and that the selection is based on best practices and standards in place at the time of drilling.

6. Time and Cost Estimates

High level time and cost estimates have been generated for project evaluation purposes, and are based on the following assumed activity throughout field life:

BUNTER 36 AQUIFER - PROJECT SEQUENCE												
	Year											
Well Type	**-2**	**0**	**2**	**5**	**10**	**15**	**20**	**22**	**25**	**30**	**35**	**40**
Appraisal Well	1											
New Injection Well Drill		4	1				4	1				
Monitoring Well - Appraisal tieback		1										
Workover							1					
Local Sidetrack				1		1			1		1	
Abandonment												11

Figure 61: Field Life Well Activity

The time and cost estimates listed below are based on the following assumptions:

- The time estimates are based on performance data obtained from the offset wells analysed for this study.
- Well activity in a particular year will be performed in a continuous programme. Therefore, there will be one rig move to and from location per programme.
- The wells will be drilled through a normally unmanned installation (NUI) using a standard Southern North Sea jack-up rig.
- The rate for a standard Southern North Sea jack-up rig is assumed to be \$150,000 per day.
    - The exchange rate is assumed to be £1.00 = \$1.50.
- The well inclination for the CO_2 injectors is above wire lining capability. Therefore, it has been assumed that the wells will be perforated through the completion using coiled tubing as the deployment method.
    - Note: the monitoring well is vertical and will be perforated on electric line.

The time and cost estimate summary for all wells is as follows:

BUNTER 36 AQUIFER COST MODEL		
Well Cost Summary Table		
Well Name	**Days**	**Well Cost (£,000)**
Year -2		
Appraisal Well	80.6	25,787.5
Year 0		
Slant Injector 1	77.4	25,737.5
Slant Injector 2	70.9	24,112.5
Slant Injector 3	70.9	24,112.5
Slant Injector 4	70.9	24,112.5
Monitoring Well - Appraisal Tieback	27.5	13,587.5
Year 2		
Slant Injector 5	82.4	27,237.5
Year 5		
Local Sidetrack 1	80.6	24,400.0
Year 15		
Local Sidetrack 2	80.6	24,400.0
Year 20		
Slant Injector 6	77.4	25,737.5
Slant Injector 7	70.9	24,112.5
Slant Injector 8	70.9	24,112.5
Slant Injector 9	70.9	24,112.5
Workover 1	32.5	9,975.0
Year 22		
Slant Injector 10	82.4	27,237.5
Year 25		
Local Sidetrack 3	80.6	24,400.0
Year 35		
Local Sidetrack 4	80.6	24,400.0
Year 40		
Abandonment Slant Injector 1	23.4	5,850.0
Abandonment Slant Injector 2	16.9	4,225.0
Abandonment Slant Injector 3	16.9	4,225.0
Abandonment Slant Injector 4	16.9	4,225.0
Abandonment Slant Injector 5	16.9	4,225.0
Abandonment Slant Injector 6	16.9	4,225.0
Abandonment Slant Injector 7	16.9	4,225.0
Abandonment Slant Injector 8	16.9	4,225.0
Abandonment Slant Injector 9	16.9	4,225.0
Abandonment Slant Injector 10	16.9	4,225.0
Abandonment Monitoring Well	23.4	5,850.0
TOTAL	**1,406.4**	**447,300.0**

Table 13: Time and Cost Estimate Summary

Typical time and cost estimates for each identified well activity are as follows:

BUNTER 36 AQUIFER COST MODEL							
Well : Appraisal Well							
Location : Bunter 36 Platform							
Location Sequence Position : 1							
Activity	**Days**	**Rig Cost per Day (£,000)**	**Phase Rig Cost (£,000)**	**Spread Cost per Day (£,000)**	**Phase Spread Cost (£,000)**	**Tangible Costs (£,000)**	**Total Phase Cost (£,000)**
Move rig to location and jack-up	3.0	100.0	300.0	150.0	450.0		750.0
Drill 36" hole section	1.0	100.0	100.0	150.0	150.0		250.0
Run and cement conductor	1.0	100.0	100.0	150.0	150.0	300.0	550.0
Drill 22" surface hole	1.5	100.0	150.0	150.0	225.0		375.0
Run and cement 18 5/8" surface casing. Nipple up BOPE	4.0	100.0	400.0	150.0	600.0	800.0	1,800.0
Drill 17 1/2" intermediate hole	3.0	100.0	300.0	150.0	450.0		750.0
Run and cement 13 3/8" casing	3.0	100.0	300.0	150.0	450.0	800.0	1,550.0
Drill 12 1/4" hole	4.0	100.0	400.0	150.0	600.0		1,000.0
Run and cement 9 5/8" casing	3.0	100.0	300.0	150.0	450.0	1,000.0	1,750.0
Core 8 1/2" reservoir section	3.0	100.0	300.0	150.0	450.0	100.0	850.0
Drill 8 1/2" reservoir section	4.0	100.0	400.0	150.0	600.0		1,000.0
Run open hole logging programme	5.0	100.0	500.0	150.0	750.0	400.0	1,650.0
Run and cement 7" liner	3.0	100.0	300.0	150.0	450.0	700.0	1,450.0
Displace to completion fluid	2.0	100.0	200.0	150.0	300.0		500.0
Run test string and rig up to test	6.0	100.0	600.0	200.0	1,200.0	400.0	2,200.0
Perforate well on wireline	1.0	100.0	100.0	200.0	200.0	200.0	500.0
Flow well to clean up and test	5.0	100.0	500.0	200.0	1,000.0		1,500.0
Kill well	1.0	100.0	100.0	200.0	200.0		300.0
Pull test string	2.0	100.0	200.0	200.0	400.0		600.0
Run and set a 9 5/8" bridge plug	1.0	100.0	100.0	200.0	200.0		300.0
Set suspension cement plugs on top of the bridge plug	2.0	100.0	200.0	200.0	400.0		600.0
Nipple down the BOPE	1.0	100.0	100.0	200.0	200.0		300.0
Back out the 9 5/8" casing from the MLS and set TA cap	0.5	100.0	50.0	150.0	75.0		125.0
Back out the 13 3/8" casing from the MLS and set TA cap	0.5	100.0	50.0	150.0	75.0		125.0
Back out the 18 5/8" casing from the MLS and set TA cap	0.5	100.0	50.0	150.0	75.0		125.0
Back out the conductor from the MLS	0.5	100.0	50.0	150.0	75.0		125.0
Move the rig off location	3.0	100.0	300.0	150.0	450.0		750.0
Contingency at 30%	16.1	100.0	1,605.0	150.0	2,407.5		4,012.5
TOTAL	**80.6**		**8,055.0**		**13,032.5**	**4,700.0**	**25,787.5**

Table 14: Appraisal Well Time and Cost Estimate

BUNTER 36 AQUIFER COST MODEL							
Well : Slant Injector 1							
Location : Bunter 36 Platform							
Location Sequence Position : 1							
Activity	**Days**	**Rig Cost per Day (£,000)**	**Phase Rig Cost (£,000)**	**Spread Cost per Day (£,000)**	**Phase Spread Cost (£,000)**	**Tangible Costs (£,000)**	**Total Phase Cost (£,000)**
Move rig to location and jack-up over platform	5.0	100.0	500.0	150.0	750.0		1,250.0
Drive conductor	1.0	100.0	100.0	150.0	150.0	300.0	550.0
Drill 22" surface hole	1.5	100.0	150.0	150.0	225.0		375.0
Run and cement 18 5/8" surface casing. Nipple up BOPE	4.0	100.0	400.0	150.0	600.0	800.0	1,800.0
Drill 17 1/2" intermediate hole	3.0	100.0	300.0	150.0	450.0		750.0
Run and cement 13 3/8" casing	3.0	100.0	300.0	150.0	450.0	800.0	1,550.0
Drill 12 1/4" hole	4.0	100.0	400.0	150.0	600.0		1,000.0
Run and cement 9 5/8" casing	4.0	100.0	400.0	150.0	600.0	1,000.0	2,000.0
Drill 8 1/2" reservoir section	7.0	100.0	700.0	150.0	1,050.0		1,750.0
Run and cement 7" liner	4.0	100.0	400.0	150.0	600.0	700.0	1,700.0
Displace to completion fluid	3.0	100.0	300.0	150.0	450.0		750.0
Run completion	4.0	100.0	400.0	200.0	800.0	800.0	2,000.0
Nipple down BOPE. Install Xmas tree	2.0	100.0	200.0	200.0	400.0	500.0	1,100.0
Perforate well using coiled tubing	7.0	100.0	700.0	200.0	1,400.0	500.0	2,600.0
Flow well to clean up	5.0	100.0	500.0	200.0	1,000.0		1,500.0
Suspend well pending CO_2 injection	2.0	100.0	200.0	200.0	400.0		600.0
Move rig off location	0.0	100.0	0.0	200.0	0.0		0.0
Contingency at 30%	17.9	100.0	1,785.0	150.0	2,677.5		4,462.5
TOTAL	**77.4**		**7,735.0**		**12,602.5**	**5,400.0**	**25,737.5**

Table 15: New Well Time and Cost Estimate

BUNTER 36 AQUIFER COST MODEL							
Well : Monitoring Well - Appraisal Tieback							
Location : Bunter 36 Platform							
Location Sequence Position : 5							
Activity	**Days**	**Rig Cost per Day (£,000)**	**Phase Rig Cost (£,000)**	**Spread Cost per Day (£,000)**	**Phase Spread Cost (£,000)**	**Tangible Costs (£,000)**	**Total Phase Cost (£,000)**
Move rig to location and jack-up over platform	0.0	100.0	0.0	150.0	0.0		0.0
Tieback conductor	1.0	100.0	100.0	150.0	150.0	300.0	550.0
Tieback 20" casing	1.5	100.0	150.0	150.0	225.0		375.0
Tieback 13 3/8" casing	2.0	100.0	200.0	150.0	300.0	800.0	1,300.0
Tieback 9 5/8" casing	2.0	100.0	200.0	150.0	300.0		500.0
Nipple up BOPE	1.0	100.0	100.0	150.0	150.0	1,000.0	1,250.0
Drill out cement plugs	2.0	100.0	200.0	150.0	300.0		500.0
Run casing scraper. Displace to completion fluid	3.0	100.0	300.0	150.0	450.0		750.0
Run completion	4.0	100.0	400.0	200.0	800.0	800.0	2,000.0
Nipple down BOPE. Install Xmas tree	2.0	100.0	200.0	200.0	400.0	500.0	1,100.0
Displace to nitrogen / monitoring fluid	2.0	100.0	200.0	200.0	400.0	500.0	1,100.0
Suspend well pending CO_2 injection	2.0	100.0	200.0	200.0	400.0		600.0
Move rig off location	5.0	100.0	500.0	200.0	1,000.0		1,500.0
Contingency at 30%	8.3	100.0	825.0	150.0	1,237.5		2,062.5
TOTAL	**27.5**		**3,575.0**		**6,112.5**	**3,900.0**	**13,587.5**

Table 16: Appraisal Well Conversion to Monitoring Well Time and Cost Estimate

BUNTER 36 AQUIFER COST MODEL							
Well : Monitoring Well - New Well							
Location : Bunter 36 Platform							
Location Sequence Position : 6							
Activity	**Days**	**Rig Cost per Day (£,000)**	**Phase Rig Cost (£,000)**	**Spread Cost per Day (£,000)**	**Phase Spread Cost (£,000)**	**Tangible Costs (£,000)**	**Total Phase Cost (£,000)**
Move rig to location and jack-up over platform	0.0	100.0	0.0	150.0	0.0		0.0
Drive conductor	1.0	100.0	100.0	150.0	150.0	300.0	550.0
Drill 17 1/2" surface hole	1.5	100.0	150.0	150.0	225.0		375.0
Run and cement 13 3/8" surface casing. Nipple up BOPE	4.0	100.0	400.0	150.0	600.0	800.0	1,800.0
Drill 12 1/4" hole	4.0	100.0	400.0	150.0	600.0		1,000.0
Run and cement 9 5/8" casing	4.0	100.0	400.0	150.0	600.0	1,000.0	2,000.0
Drill 8 1/2" reservoir section	4.0	100.0	400.0	150.0	600.0		1,000.0
Run and cement 7" liner	3.0	100.0	300.0	150.0	450.0	700.0	1,450.0
Displace to completion fluid	3.0	100.0	300.0	150.0	450.0		750.0
Run completion	4.0	100.0	400.0	200.0	800.0	800.0	2,000.0
Nipple down BOPE. Install Xmas tree	2.0	100.0	200.0	200.0	400.0	500.0	1,100.0
Perforate well using electric line	2.0	100.0	200.0	200.0	400.0	500.0	1,100.0
Flow well to clean up	5.0	100.0	500.0	200.0	1,000.0		1,500.0
Suspend well pending CO_2 injection	2.0	100.0	200.0	200.0	400.0		600.0
Move rig off location	5.0	100.0	500.0	200.0	1,000.0		1,500.0
Contingency at 30%	13.4	100.0	1,335.0	150.0	2,002.5		3,337.5
TOTAL	**44.5**		**5,785.0**		**9,677.5**	**4,600.0**	**20,062.5**

Table 17: New Monitoring Well Time and Cost Estimate

BUNTER 36 AQUIFER COST MODEL							
Well : Workover 1							
Location : Bunter 36 Platform							
Location Sequence Position : 5							
Activity	**Days**	**Rig Cost per Day (£,000)**	**Phase Rig Cost (£,000)**	**Spread Cost per Day (£,000)**	**Phase Spread Cost (£,000)**	**Tangible Costs (£,000)**	**Total Phase Cost (£,000)**
Move rig to location and jack-up over platform	0.0	100.0	0.0	150.0	0.0		0.0
Kill well and set suspension plugs	1.0	100.0	100.0	150.0	150.0		250.0
Nipple down Xmas tree. NU BOPE	2.0	100.0	200.0	150.0	300.0		500.0
Pull suspension plugs and completion	3.0	100.0	300.0	150.0	450.0		750.0
Perform scraper run and displace to completion fluid	2.0	100.0	200.0	150.0	300.0		500.0
Run completion	4.0	100.0	400.0	200.0	800.0	800.0	2,000.0
Nipple down BOPE. Install Xmas tree	2.0	100.0	200.0	200.0	400.0	200.0	800.0
Pull plug from tailpipe	1.0	100.0	100.0	200.0	200.0		300.0
Displace well to CO_2	3.0	100.0	300.0	200.0	600.0		900.0
Suspend well pending CO_2 injection	2.0	100.0	200.0	200.0	400.0		600.0
Move rig off location	5.0	100.0	500.0	200.0	1,000.0		1,500.0
Contingency at 30%	7.5	100.0	750.0	150.0	1,125.0		1,875.0
TOTAL	**32.5**		**3,250.0**		**5,725.0**	**1,000.0**	**9,975.0**

Table 18: Workover Time and Cost Estimate

BUNTER 36 AQUIFER COST MODEL							
Well : Local Sidetrack 1 (out of 9 5/8" casing)							
Location : Bunter 36 Platform							
Location Sequence Position : 1							
Activity	**Days**	**Rig Cost per Day (£,000)**	**Phase Rig Cost (£,000)**	**Spread Cost per Day (£,000)**	**Phase Spread Cost (£,000)**	**Tangible Costs (£,000)**	**Total Phase Cost (£,000)**
Move rig to location and jack-up over platform	5.0	100.0	500.0	150.0	750.0		1,250.0
Kill well and set suspension plugs	1.0	100.0	100.0	150.0	150.0		250.0
Nipple down Xmas tree. NU BOPE	2.0	100.0	200.0	150.0	300.0		500.0
Pull suspension plugs and completion	3.0	100.0	300.0	150.0	450.0		750.0
Set abandonment cement plugs	2.0	100.0	200.0	150.0	300.0		500.0
Perform scraper run and displace to mud	2.0	100.0	200.0	150.0	300.0		500.0
Set whipstock and mill window	1.0	100.0	100.0	150.0	150.0		250.0
Drill 8 1/2" section	3.0	100.0	300.0	150.0	450.0		750.0
Run and cement 7" liner	3.0	100.0	300.0	150.0	450.0	700.0	1,450.0
Drill 6" reservoir section	8.0	100.0	800.0	150.0	1,200.0		2,000.0
Run and cement 4 1/2" liner	4.0	100.0	400.0	150.0	600.0	500.0	1,500.0
Displace to completion fluid	3.0	100.0	300.0	150.0	450.0		750.0
Run completion	4.0	100.0	400.0	200.0	800.0	800.0	2,000.0
Nipple down BOPE. Install Xmas tree	2.0	100.0	200.0	200.0	400.0	500.0	1,100.0
Perforate well using coiled tubing	7.0	100.0	700.0	200.0	1,400.0	500.0	2,600.0
Flow well to clean up	5.0	100.0	500.0	200.0	1,000.0		1,500.0
Suspend well pending CO_2 injection	2.0	100.0	200.0	200.0	400.0		600.0
Move rig off location	5.0	100.0	500.0	200.0	1,000.0		1,500.0
Contingency at 30%	18.6	100.0	1,860.0	150.0	2,790.0		4,650.0
TOTAL	**80.6**		**8,060.0**		**13,340.0**	**3,000.0**	**24,400.0**

Table 19: Local Sidetrack Time and Cost Estimate

BUNTER 36 AQUIFER COST MODEL							
Well : Injector 1 - Permanent abandonment							
Location : Bunter 36 Platform							
Location Sequence Position : 1							
Activity	**Days**	**Rig Cost per Day (£,000)**	**Phase Rig Cost (£,000)**	**Spread Cost per Day (£,000)**	**Phase Spread Cost (£,000)**	**Tangible Costs (£,000)**	**Total Phase Cost (£,000)**
Move rig to location and jack-up over platform	5.0	100.0	500.0	150.0	750.0		1,250.0
Kill well and set suspension plugs	1.0	100.0	100.0	150.0	150.0		250.0
Nipple down Xmas tree. NU BOPE	2.0	100.0	200.0	150.0	300.0		500.0
Pull suspension plugs and completion	3.0	100.0	300.0	150.0	450.0		750.0
Set abandonment plugs on top of packer	2.0	100.0	200.0	150.0	300.0		500.0
Set bridge plug in 9 5/8" casing	0.5	100.0	50.0	150.0	75.0		125.0
Cut and pull 9 5/8" casing	2.0	100.0	200.0	150.0	300.0		500.0
Set shallow abandonment cement plug	0.5	100.0	50.0	150.0	75.0		125.0
Nipple down BOPE	1.0	100.0	100.0	150.0	150.0		250.0
Cut and pull 13 3/8" casing and 26" conductor	1.0	100.0	100.0	150.0	150.0		250.0
Move rig off location	0.0	100.0	0.0	150.0	0.0		0.0
Contingency at 30%	5.4	100.0	540.0	150.0	810.0		1,350.0
TOTAL	**23.4**		**2,340.0**		**3,510.0**	**0.0**	**5,850.0**

Table 20: Well Abandonment Time and Cost Estimate

11.10 Appendix 10 – Cost Estimate

Supplied separately as a PDF

11.11 Appendix 11 - Methodologies

11.11.1 Offshore Infrastructure Sizing

Methodology:

The preliminary calculations are based on fluid flow equations as given in Crane Corporation (1988) and were performed to provide a high level estimate of pressure drop along the pipeline routes.

Erosional Velocity: $V_e = c/\sqrt{\rho}$

Where;

V_e = Erosional Velocity (m/s)

c = factor (see below)

ρ = Density (kg/m3)

Industry experience to date shows that for solids-free fluids, values of c =100 for continuous service and c = 125 for intermittent service are conservative. For solids-free fluids where corrosion is not anticipated or when corrosion is controlled by inhibition or by employing corrosion resistant alloys, values of c = 150 to 200 may be used for continuous service; while values of up to 250 may be used for intermittent service. (American Petroleum Institute, 1991).

Velocity: $V = 4Q/\pi d^2$

Where,

V = Velocity (m/s)

Q = Mass flow rate (MTPa)

Reynolds Number: $Re = \frac{\rho V d}{\mu}$

Darcy Friction Factor: The friction factor is obtained from the Serghides' solution of the Colebrook-White equation.

$$A = -2\log_{10}(\frac{\varepsilon/D}{3.7} + \frac{12}{Re}),\ B = -2\log_{10}(\frac{\varepsilon/D}{3.7} + \frac{2.51A}{Re}),\ C = -2\log_{10}(\frac{\varepsilon/D}{3.7} + \frac{2.51B}{Re}),\ f = \left(\frac{A-(B-A)^2}{C-2B+A}\right)^{-2}$$

Pressure drop for single phase fluid flow: $\Delta P = \frac{fL\rho V^2}{\mu}$

Pipeline	Pipeline OD	Mass Flow Rate	Route Length	Pipe Roughness	Fluid Phase	Pressure Drop per km	Pressure Drop
Barmston to Bunter Closure 36	20" (508mm)	7MTPa	160km	0.045	Liquid/Dense [1]	0.235 bar	39.5 bar
		8.5MTPa				0.340 bar	57.1 bar
		10.5MTPa				0.517 bar	86.8 bar

Notes

1. Density of 980.3kg/m3 and viscosity 0.1016 kg/sm.

Table 5-6 Barmston to Bunter Closure 36 Pipeline Pressure Drop

Preliminary wall thickness calculations to PD8010 Part 2 (British Standards Institution, 2015) have also been performed. As the product is dry CO2 composition, carbon steel is sufficient for the pipeline however the material specification will require particular fracture toughness properties to avoid ductile fracture propogation. The resulting pipeline configuration is summarized in the table below.

Parameter	Value
Outer Diameter	508mm
Wall Thickness	25.4mm
Corrosion Allowance	3mm
Material	Carbon Steel
Corrosion Coating	3 Layer PP
Weight Coating	Concrete Weight Coating
Pipeline Route Length	160km
Installation	S-Lay
Crossings	5

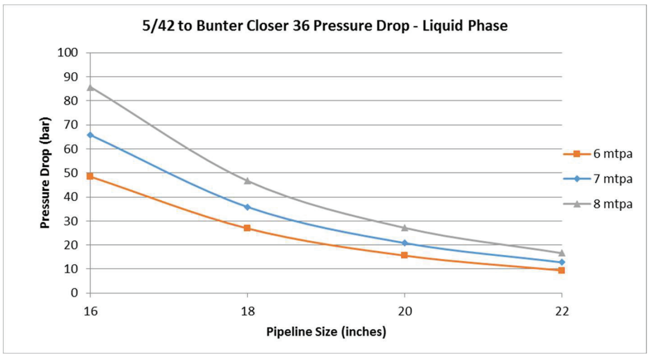


Figure 5 11 White Rose 5/42 to Bunter Closure 36 Pipeline Pressure Drop

Pipeline	Pipeline OD	Mass Flow Rate	Route Length	Pipe Roughness	Fluid Phase	Pressure Drop per km	Pressure Drop
Bunter Closure 36	18" (457.2 mm)	7MTPa	86km	0.045	Liquid/Dense [1]	0.37 bar	33.5 bar

Notes

1. Density of 980.3kg/m3 and viscosity 0.1016 kg/sm.

Table 5-8 White Rose 5/42 to Bunter Closure 36 Pipeline Pressure Drop

The 24” White Rose pipeline will be designed for a mass flow rate (maximum of) 17 MTPa, and will initially be injecting approximately 2.68 MT/Year (National Grid Carbon, et al., 2015).

Therefore assuming a constant injection rate at Bunter of 7MTPa there will be sufficient ullage in the White Rose pipeline provided injection rates there remain below 10MTPa, otherwise additional pumping will be required

Pipeline	Pipeline OD	Mass Flow Rate	Route Length	Pipe Roughness	Fluid Phase	Pressure Drop per km	Pressure Drop
White Rose	24” (609.6mm)	2.68 MTPa (Initial)	90km	0.045	Liquid/Dense [1]	0.014 bar	1.3 bar
		17 MTPa (Max)				0.525 bar	47.2 bar

Notes

1. Density of 980.3kg/m3 and viscosity 0.1016 kg/sm.

Table 5-9 White Rose 5/42 to Bunter Closure 36 Pipeline Pressure Drop

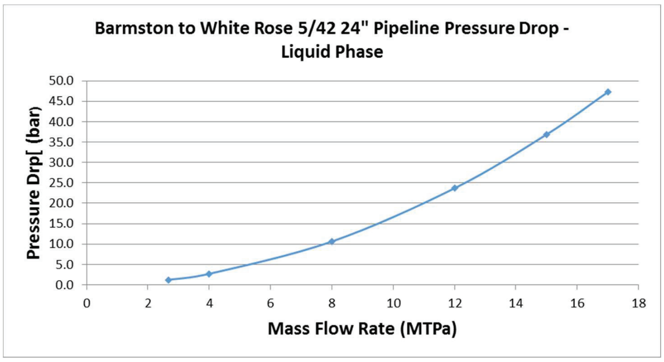


Figure 5 12 Barmston to White Rose 5/42 Pipeline Pressure Drop

The Bunter pipeline is sufficiently large (OD > 16”) that is does not require burial or rockdumping for protection purposes. Instead it is proposed the pipelines be surface laid and protected/stabilised with concrete weight coating, which necessitates installation by S-lay.

Preliminary pipeline wall thickness calculations to PD8010 Part 2 (British Standards Institution, 2015) have also been performed for this option. The resulting pipeline configuration is sumarized in the table below.

Parameter	Value
Outer Diameter	18” (457.2mm)
Wall Thickness	21.4mm
Corrosion Allowance	3mm

Material	Carbon Steel
Corrosion Coating	3 Layer PP
Weight Coating	Concrete Weight Coating
Pipeline Route Length	86km
Installation	S-Lay
Crossings	4

Table5-10 Bunter Pipeline Specification (Step Out from White Rose 5/42)

11.11.2 Cost Estimation

The CAPEX, OPEX and ABEX have been calculated for the engineering, procurement, construction, installation, commissioning, operation and decommissioning of the Bunter Closure 36 facilities. The OPEX has been calculated based on a 40 year design life.

An overview of the Bunter Closure 36 development (transportation, facilities, wells) is given in Section 5. The cost estimate is made up of the following components:

- Transportation: Pipeline, landfall and structures along the pipeline
- Facilities: NUI – Jacket / Topsides
- Wells: Drilling and the well materials and subsurface materials
- Other: Anything not covered under transportation, facilities or wells.

The cost estimate WBS adopted throughout is shown in Table 6-1. A 30% contingency has been included throughout.

CAPEX (Transport, Facilities, Wells, Other)	
Pre-FID	Pre-FEED
	FEED
Post FID	Detailed Design
	Procurement
	Fabrication
	Construction and Commissioning
OPEX (Transportation, Facilities, Wells, Other)	
Operating Expenditure 40 year design life	
ABEX (Transportation, Facilities, Wells, Other)	
Decommissioning, Post Closure Monitoring, Handover	

Table 11-21 Cost Estimate WBS

11.11.3 Petrophysics

For the purposes of quantitative evaluation of reservoir rock properties from wireline logs, a standard oilfield approach to formation evaluation has been adopted. This is outlined below and illustrated in Figure X.

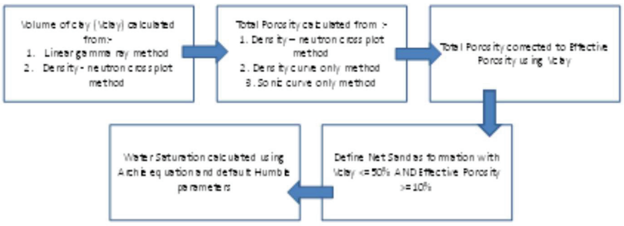


Figure 11-62 Summary of petrophysical workflow

11.11.3.1 *Parameter Definition*

A temperature gradient of 1.15 °F / 100 ft is calculated with a surface temperature of 75 °F using fixed-point linear regression of maximum recorded bottom hole temperatures from logging runs.

A default formation water resistivity value of 0.060 ohm.m @ 60 °F was used in all evaluations, with minor calibration adjustments as required. On a well by well basis the minimum value of Rwa is taken as representative of the true water resistivity for the reservoir. Cross plots of Porosity vs. Deep Formation Resistivity, (Pickett-plots) were used to check the minimum Rwa method.

These values are consistent with the published values in the 'North Sea Formation Waters Atlas' for the Triassic Bunter formation.

The deepest penetrating resistivity curve is always used as the measurement true formation resistivity. No additional environmental corrections are applied to these curves as the data archived by CDA does not give a detailed history of any resistivity post-processing

11.11.3.2 *Clay and Shale Volume Estimates*

The volume of clay in the reservoir is estimated by two independent deterministic methods.

(i) gamma ray

A linear model gamma ray method. This assumes that a clean, clay free sand is represented by the minimum gamma count within the interval and that the shales and clays are represented by the highest gamma count.

The linear model gamma ray Vclay equation is shown below:

VClay = (GRlog-GRmin)/(GRmax-GRmin)

The cumulative distribution curve for all the data has been used as a baseline calibration for sand and shales, picking the 10th percentile as the clean sand point and the 90th percentile as the shale point.

(ii) neutron – density crossplot.

A double clay indicator method. This method uses a cross-plot method that defines clean sand line and a clay point. The volume of clay is then estimated as the distance the data falls between the clay point and the clean sand line.

Figure 11-63 is a multi-well cross-plot of Neutron Porosity vs. Density data for the Bunter sandstones.

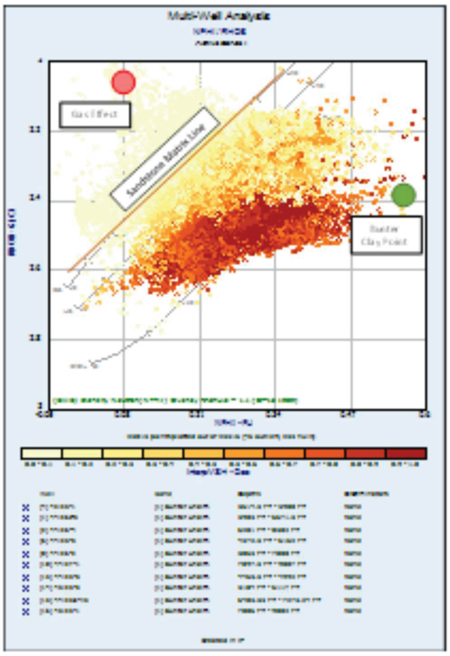


Figure 11-63 Cross plot of neutron and density log data, colour of points represents calculated Vclay

The 'clean' sand generally follows the matrix line for quartz sandstone with increasing separation of the neutron density reflecting an increase in clay content towards the 'clay' point. Note there is a cluster of data that falls to above the sandstone matrix line that is a response to gas filled sands, these are the data points from the Caister Field.

The final clay volume model carried forward to the evaluation is the minimum of the estimate from gamma and neutron density, unless the interpretive decision is made to preferentially use a particular model.

11.11.3.3 *Porosity and Water Saturation*

The estimation of Porosity and Water Saturation are coupled as an iterative process such that any parameter update during the calculation of porosity or water saturation will result in porosity and water saturation being recalculated; furthermore, if it becomes necessary to fine-tune the clay model this will cycle back to update the volume clay models for the same interval.

This linkage of parameters ensures consistency throughout all aspects of the interpretation and preserves the necessary dependency between all the variables in the analysis.

11.11.3.3.1 Porosity Model

Porosity is calculated using either the single curve Density model or Density – Neutron crossplot method with option to calculate sonic porosity if the condition of the borehole is too poor to acquire accurate density data.

Borehole conditions are estimated from limits set for the calliper and the density DRHO curves, if these limits are exceeded sonic is substituted as the most appropriate porosity method.

A clay volume fraction correction is made to estimate 'effective' porosity from the 'total' porosity calculation.

From the limited amount of core measured grain density data a high matrix density is observed, see Figure 11-64. The plot is based on 300 data points and gives a mean grain density of 2.704 g/cc, considerably higher than the 2.65 g/cc expected for a quartz sand.

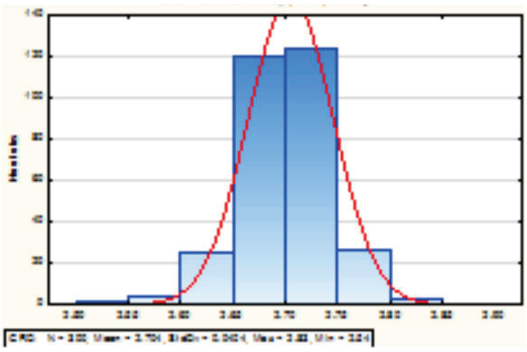


Figure 11-64 Core Grain Density Histogram of Grain density Measured in Core Plug Data

The reason for these higher matrix densities is not explained in the various core reports, however it must be expected that carbonate or anhydrite is present in the matrix and this has to be taken into account when selecting suitable parameters for any of the porosity models.

It is assumed for all interpretation the matrix of the Bunter sandstone is predominantly quartz with subordinate amounts of lithic clasts of much greater density than quartz; the matrix density is assumed to be in the range of 2.67 g/cc to 2.69 g/cc. These higher matrix assumptions lead to the best fit to the available core data.

Where core porosity data is available, the best fit porosity model to the core data is noted and then preferentially selected for un-cored intervals and wells. Figure 11-65 summarizes the distribution of the core porosity data, the plot is has 392 validated data points and gives a close fit to a normal distribution with a mean porosity of 21%.

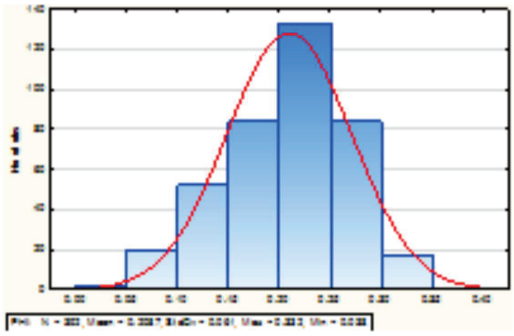


Figure 11-65 Core Porosity Histogram of Porosity Measured in Core Plug Data

This compares favourably to the porosity summary statistics generated from the petrophysical analysis (Figure 11-66).

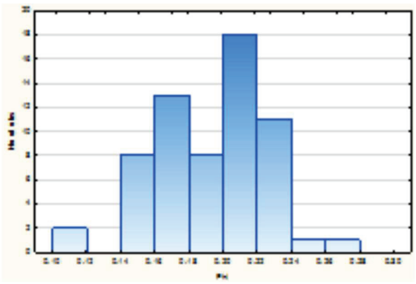


Figure 11-66 Log calculated PHIE for Net Reservoir (All Zones)

11.11.3.4 *Water Saturation*

Water Saturation is calculated in the deep zone of the reservoir (Sw) and the invaded zone (Sxo) using deep and shallow resistivity respectively; where oil based mud is used as the drilling fluid an approximation of the invaded zone saturation is made with defined limits using an Sxo ratio factor.

Archie saturation exponents, Table 11-22, validated in the water zones with Pickett plots, are consistent with the Humble parameters for a clastic reservoir:

a	0.62
m	2.15
n	2.00

Table 11-22 Saturation Equation Exponents

As most of the wells are from the Bunter aquifer the key part of this step in the evaluation was to make sure that the correct estimation of Rw and clay was applied to ensure the false presence of hydrocarbons was not calculated.

Table 11-23 details parameter used to estimate porosity and water saturation.

Well	Phi Model	Rw_a at 60	Rt_{Shale}	Sw Model
42/25-1	Density	0.060	1.260	Archie
43/23-3	Density	0.057	1.230	Indo.
43/25-1	ND-Xplot	0.058		Indo.
44/23-3	ND-Xplot	0.059	0.928	Indo.
44/23-5	ND-Xplot	0.064	0.745	Indo.
44/23a-A3	ND-Xplot	0.062	0.718	Indo.
44/26-1	Sonic	0.079	1.000	Archie
44/26-2	Density	0.050	0.842	Indo.
44/26-3	NA	NA	NA	NA
44/26-4	ND-Xplot	0.052	1.030	Indo.
44/26a-A7	NA	NA	NA	NA
44/26a-A9	NA	NA	NA	NA
44/26c-5	ND-Xplot	0.039	0.970	Indo.
44/26c-6	NA	NA	NA	NA
44/27-1	ND-Xplot	0.053	1.050	Indo.
49/21-2	ND-Xplot	0.060	1.000	Indo.
Average		0.058	0.979	

Table 11-23 Porosity and Water Saturation Parameter Selection

11.11.3.5 *Net Sand Criteria*

The following cut-offs were used to define Net Reservoir distribution in the Bunter Sandstone:

Zone Name	Porosity	Volume Clay
Bunter, All Zones	>=10%	<=50%

Table 11-24 Net reservoir Cut-offs applied

11.11.4 Geochemistry

11.11.4.1 *Objective*

Geochemical modelling of the primary reservoir and caprock at Bunter Closure 36 was carried out to assess the likely impact of CO2 injection on the rock fabric and mineralogy over both the injection period and the long term post-closure phase. The main objective was to gain a better understanding of the key geochemical risks to injection site operation and security of storage.

11.11.4.2 *Methodology*

A study methodology was developed to answer two key questions:

1. Will increasing the amount (partial pressure) of CO2 in the reservoir/aquifer lead to mineral reactions which result in either increase or decrease of porosity and permeability of the reservoir?
2. Will elevated partial pressure of CO2 compromise the caprock by mineral reaction?

The work flow followed is shown in Figure 11-67. Water and any gas geochemical data, and mineral proportion data from the reservoir and the caprock (representing the pre-CO2 injection conditions) were collected from a mix of published analogue data and CDA.

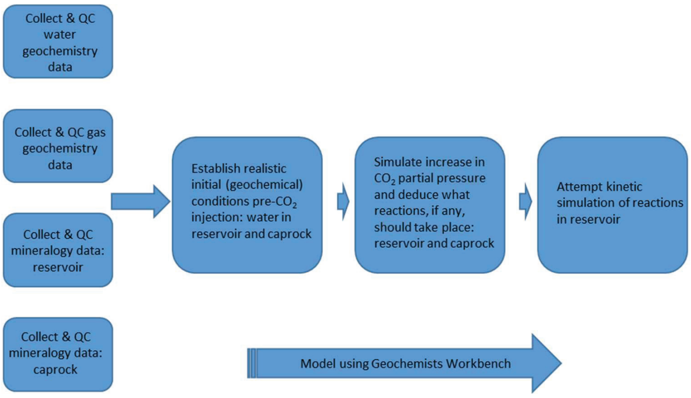


Figure 11-67 Geochemistry workflow

Following data QC, the initial gas-water-rock compositions were modelled, using a range of CO2 partial pressures and temperatures, using two approaches:

- The first, and most simple, modelling approach is to assume that there is instant *equilibrium* between minerals, aqueous solution and changing gas composition. The extent of this type of reaction is thus simply a function of the amount of CO2 that has arrived at the reaction site (as reflected in the fugacity [as stated approximately the partial pressure] of CO2]).
- A more subtle approach involves a *kinetic* approach that requires a range of further inputs including rate of reaction (e.g., dissolution), and textural controls on dissolution such as grain size (which is reflected in the specific surface area per unit mass or unit volume.

All modelling was undertaken using Geochemists Workbench.

11.11.4.3 *Data Availability*

1. No water compositional data from the Triassic part of the stratigraphy in the SNS are available in CDA. Water geochemical data from the Triassic (Bunter) sandstones in the SNS were sourced from published compilations (Warren and Smalley, 1994).
2. No gas compositional data from the Triassic part of the stratigraphy in the SNS are available in CDA. Gas geochemical data from the Triassic (Bunter) sandstones in the SNS were sourced from published compilations (Lokhurst, 1997).
3. Bunter reservoir mineral data were obtained from petrographic and sedimentology reports for well 44/23-3 (Cade et al., 1987). No quantitative mineral XRD data were found in CDA.
4. Caprock mineral data are not available in CDA. Analogue mineral data from the Mercia Mudstone (Armitage et al., 2013; Jeans, 2006) was used.

11.11.4.4 *Water Geochemistry*

The water compositional data used are shown in Table 11-25

1. Water compositional data seem to be credible given their molar charge difference is within the permissible 5%.
2. Water compositions are all highly saline and Na-Cl dominated as expected due to the presence of Triassic halite-dominated evaporites (Rot Halite) immediately overlying the Bunter and the halite-sylvite Upper Permian Zechstein evaporites deeper in the stratigraphy.
3. Waters have high Ca concentrations and low HCO3 concentrations suggesting that the waters may be susceptible to changing composition (gas-water interaction) if, or when, the CO2 partial pressure increases following CO2 injection.

11.11.4.5 *Gas Geochemistry*

Although the Bunter 36 closure is considered to be brine-filled, the presence of a small gas accumulation in the crest has been identified as a possibility. The hydrocarbon gas compositional data assumed for this closure are shown in Table 11-26

1. Gas compositions seem to be credible and not greatly different to Permian and Carboniferous gas compositions.
2. Gases are CH4- and N2-rich and generally dry.
3. Little or no CO2 is reported in the gas suggesting that an influx of CO2 following injection may cause reactions with the water-rock domain since there is little or none in the gas at present (i.e. not at equilibrium with any pre-existing CO2).

Well/Depth/Sample mg/L	Temp °C	Pressure bar	K+	Na+	Mg++	Ca++	Cl-	SO_4--	HCO_3-	pH	% Charge Difference
Esmond 43/13-a2, 1936m	66	157		104,000	2,400	7,100	190,000	380	24	6.0	-2.80
Forbes 43/8-1, 1792m	64	192	800	112,000	1,510	8,380	191,000	2,100	24	6.6	0.02
Orwell 50/26a-2, 1540m	65	167	550	59,130	500	8,300	107,710	845	74	5.6	-0.26

Table 11-25 Water geochemical composition data used in modelling

	Reservoir	Depth m	CH_4	C_2H_6	C_3H_8	i-C_4	n-C_4	C_4	i-C_5	n-C_5	C_5	C_6	N_2	CO_2	H_2S	He
Esmond 43/13	Bunter	1936	91.00	8.00	1.00											
Forbes 43/8	Bunter	1792	86.00										12.00			
Gordon 43/15	Bunter	1800	82.00										16.00			
Hewett 49/29	Bunter	1000	83.19	5.32	2.14	0.21	0.15		0.08			0.41	8.40	0.08	0.02	

Table 11-26 Gas geochemical composition data used in modelling

For 1kg Water		4596'6"	4608'2"	4643'6"	4730'0"	Mean
Quartz	cm^3	2079	2533	2087	3149	2444
K-feldspar	cm^3	105	240	422	170	238
Dolomite	cm^3	184	107	99	170	139
Calcite	cm^3	0	267	571	0	219
Illite	cm^3	1000	267	149	142	391
Anhydrite	cm^3	132	27	522	28	185
Chlorite	cm^3	500	267	149	142	265
Halite	cm^3	0	293	0	199	119
Total Mineral Volume		**4000**	**3707**	**4000**	**3801**	**3881**
Quartz average PC data	%	39.5	47.5	42	55.5	46.1
K-feldspar average PC data	%	2	4.5	8.5	3	4.5
Dolomite average PC data	%	3.5	2	2	3	2.6
Calcite average PC data	%	0	5	11.5	0	4.1
Illite average PC data	%	19	5	3	2.5	7.4
Anhydrate average PC data	%	2.5	0.5	10.5	0.5	3.5
Chlorite average PC data	%	9.5	5	3	2.5	5.0
Halite average PC data	%	0	5.5	0	3.5	2.3
Total						

Table 11-27 Reservoir (Bunter Sandstone) mineralogy data (from petrographical analysis) used in modelling

11.11.4.6 *Reservoir Mineralogy*

Bunter sandstones are quartz-rich with variable carbonate, anhydrite and clay mineral cement contents, as described by Cade et al. (1987). The petrographic data Table 11-28 describe abundant “unresolved clay”, i.e. the petrographers do not go beyond low resolution analytical techniques to study these rocks. As Triassic sandstones typically have abundant illite and chlorite, the unresolved clay has been split equally between these two minerals. No XRD data have been found to prove or disprove this assumption.

11.11.4.7 *Caprock Mineralogy*

Two caprock ‘types’ were modelled to account for the geochemical differences between the Solling Mudstone and Rot Halite, both of which may contact dissolved CO2 post-injection. An additional scenario to test the impact of a clay-rich fault gouge within a predominantly halite caprock was also tested to assess the risk of alteration to fault behaviour following injection of CO2.

Caprock type-1 is clay-rich (Table 11-28), with low porosity-permeability samples described by Cade et al. (1987). As with the coarse-grained Triassic sandstones, the petrographic description listed abundant “unresolved clay”. Triassic mudstones typically have abundant illite and chlorite (Armitage et al., 2013; Jeans, 2006) so the unresolved clay has been split equally between the two minerals. No XRD data have been found to prove or disprove this assumption.

Caprock type-2 is halite dominated. No XRD have been found to help resolve mineralogy. However a study from Rot halite equivalents in the onshore Netherlands (Schleder and Urai, 2005) reported nearly pure halite in some sections with negligible porosity. Some samples had minor anhydrite present.

11.11.4.8 *Results: Equilibrium Modelling*

Bunter Sandstone (Reservoir)

The results of the equilibrium modelling are shown in the following figures.

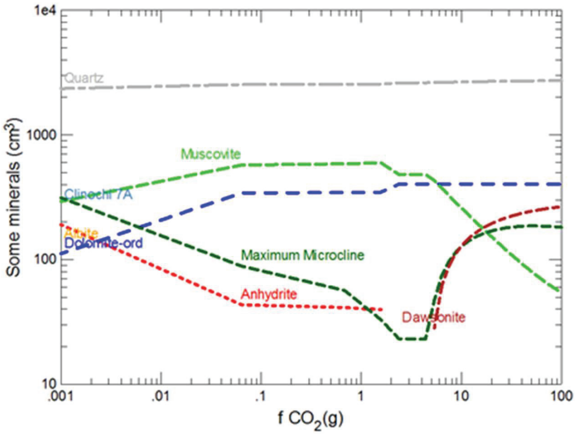


Figure 11-68 Equilibrium modelling results at 55°C: Bunter sandstone (reservoir)

For 1kg Water		4744'9"	4634'8"	4665'5"	Mean
Quartz	cm^3	4847	7270	9112	7444
K-feldspar	cm^3	485	1163	1648	1156
Dolomite	cm^3	872	388	2811	1428
Calcite	cm^3	0	0	0	0
Illite	cm^3	6204	3199	679	3535
Anhydrite	cm^3	0	872	2520	1190
Chlorite	cm^3	6301	2714	679	3399
Halite	cm^3	291	1454	679	850
Total Mineral Volume	**cm^3**	**19000**	**17061**	**18128**	**19000**
Quartz average PC data	%	25	37.5	47	36.5
K-feldspar average PC data	%	2.5	6	8.5	5.7
Dolomite average PC data	%	4.5	2	14.5	7.0
Calcite average PC data	%	0	0	0	0
Illite average PC data	%	32	16.5	3.5	17.3
Anhydrite average PC data	%	0	4.5	13	5.8
Chlorite average PC data	%	32.5	14	3.5	16.7
Halite average PC data	%	1.5	7.5	3.5	4.2
Total	**%**	**98**	**88**	**93.5**	**93.2**

Table 11-28 Caprock (type 1) mineralogy (based on petrographical analysis)

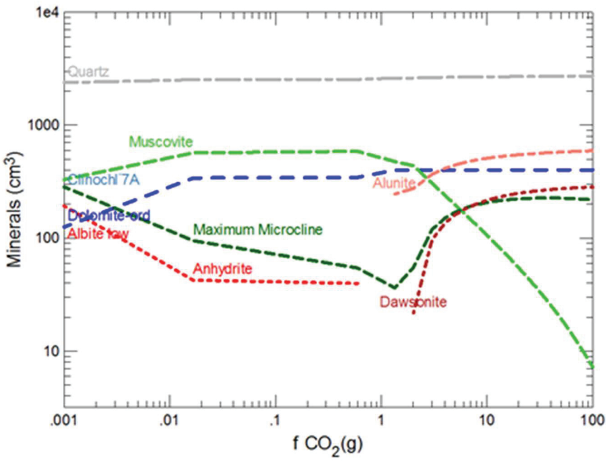


Figure 11-69 Equilibrium modelling results at 66°C: Bunter sandstone (reservoir)

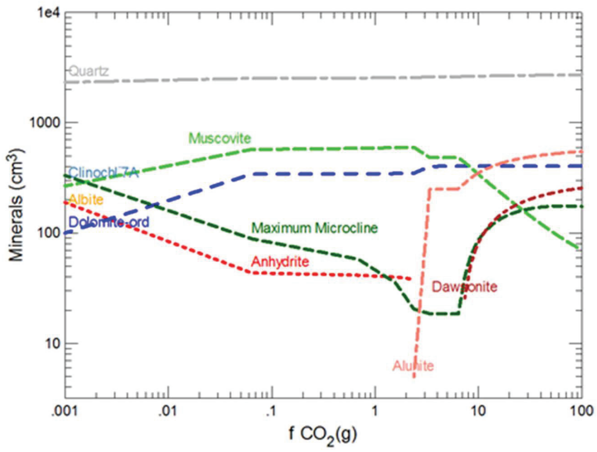


Figure 11-70 Equilibrium modelling results at 70C: Bunter sandstone (reservoir)

The key reactions which are expected to take place given the starting reservoir composition are:

Illite + Na^+ + CO_2 → quartz + dawsonite + K^+

(illite supplies Al)

Chlorite + H^+ + anhydrite + CO2 → dolomite

(chlorite supplies Mg) (anhydrite supplies Ca)

Illite + H^+ + anhydrite → quartz + alunite

(illite supplies K and Al) (anhydrite supplies SO4) (increase in H^+ due to elevated CO2 [CO2 dissolution and dissociation releases protons and carbonic acid]).

Figure 11-68 to Figure 11-70 show the evolution of the mineral content as CO2 fugacity increases in the model. Modelling was carried out at three separate temperatures: 55°C, 66°C and 70°C. The results of the modelling are relatively similar across the range, other than the appearance of alunite (a potassium-containing sulphate) at the higher temperatures:

- Average Bunter mineralogy reacted progressively as CO2 concentration increases.
- CO2 fugacity of 100 approximates to a partial pressure of 100.
- At the highest concentrations of CO2, muscovite is replaced by dawsonite.
- Chlorite and anhydrite disappear due partly to the acidic conditions and the released Mg and Ca create dolomite in the presence of increasingly concentrated CO2.
- Dawsonite grows due to the release of Al from chlorite, the abundance of Na in the saline formation water and the increasingly concentrated CO2.
- At 66°C and 70°C, Alunite grows due to SO4 released from anhydrite and K and Al released from muscovite.

Initial Mineral	log fCO_2	Quartz %	K-feldspar %	Dolomite %	Calcite %	Illite %	Anhydrite %	Chlorite %	Alunite %	Dawsonite %	Total Volume %	Porosity
Bunter Sandstone 55°C	-1	50.38	4.91	2.87	4.51	8.05	3.82	5.46	0.00	0.00	80.00	20.00
Bunter Sandstone 55°C	2	56.22	4.51	8.29	0.00	0.14	0.00	0.00	12.27	5.83	87.26	12.74
Bunter Sandstone 60°C	-1	50.38	4.91	2.87	4.51	8.05	3.82	5.46	0.00	0.00	80.00	20.00
Bunter Sandstone 60°C	2	56.24	3.73	8.31	0.00	1.13	0.00	0.00	11.54	5.46	86.42	13.58
Bunter Sandstone 70°C	-1	50.38	4.91	2.87	4.51	8.05	3.82	5.46	0.00	0.00	80.00	20.00
Bunter Sandstone 70°C	2	56.15	3.59	8.33	0.00	1.44	0.00	0.00	11.32	5.28	86.11	13.89

Table 11-29 Equilibrium modelling summary of results for the Bunter sandstone (reservoir)

Table 11-29 shows a summary of the equilibrium modelling results. The modelling work suggests that the diagenetic changes induced by CO2 flooding of the Bunter sandstone will, at equilibrium, lead to a net reduction in porosity of the rock from an initial 20% to a final 13-14% (as a function of temperature and the specific diagenetic reactions that occur.

11.11.4.9 *Caprock*

The results of the equilibrium modelling for the **Caprock Type-1** (clay-rich) are shown in Figure 11-71 to Figure 11-73

The key reactions which are expected to take place given the starting clay-rich composition are:

- Illite + Na^+ + $CO_2 \rightarrow$ quartz + dawsonite + K^+

  (illite supplies Al)

- Chlorite + H^+ + anhydrite + CO2 $\rightarrow$ dolomite

  (chlorite supplies Mg) (anhydrite supplies Ca)

The following figures show the evolution of the mineral content as CO2 fugacity increases in the model. Modelling was carried out at three separate temperatures: 55°C, 66°C and 70°C. The results of the modelling are relatively similar across the range, other than the appearance of minor alunite (a potassium-containing sulphate) at the lowest temperature:

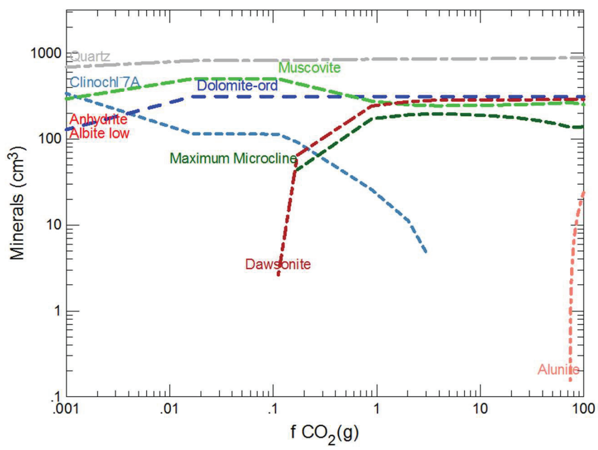


Figure 11-71 Equilibrium modelling results at 55°C: caprock type 1 (clay-rich)

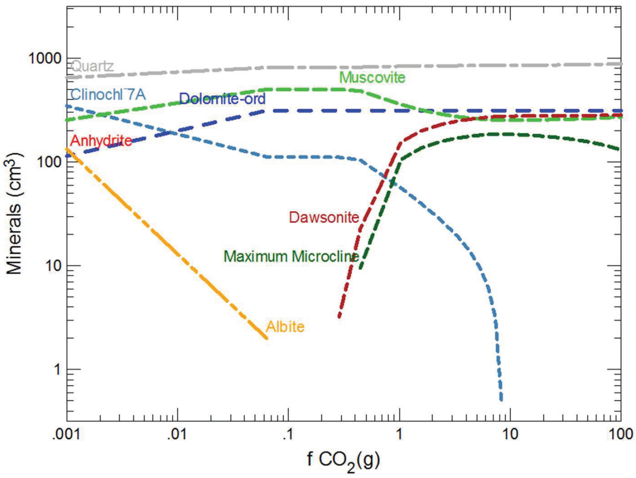


Figure 11-72 Equilibrium modelling results at 55°C: caprock type 1 (clay-rich)

- Average Triassic mudstone mineralogy reacted progressively across the range of temperatures as CO2 concentration increases.
- CO2 fugacity of 100 approximates to a partial pressure of 100.
- At the highest concentrations of CO2, muscovite is replaced by dawsonite and K-feldspar

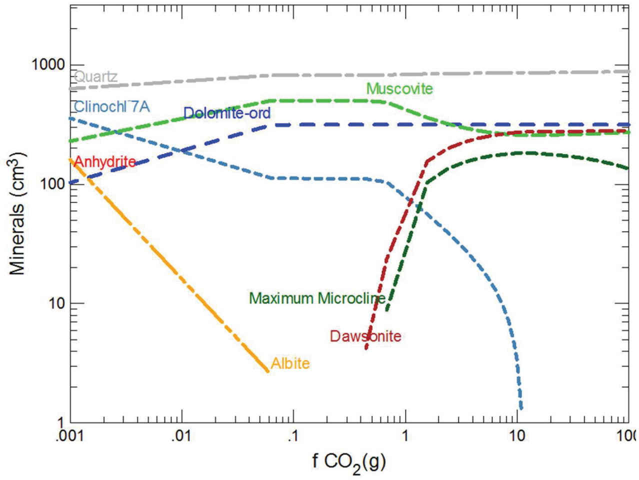


Figure 11-73 Equilibrium modelling results at 70°C: caprock type 1 (clay-rich)

- Chlorite and anhydrite disappear due partly to the acidic conditions and the released Mg and Ca create dolomite in the presence of increasingly concentrated CO2
- Dawsonite grows due to the release of Al from chlorite, the abundance of Na in the saline formation water and the increasingly concentrated CO2.
- At 55°C , Alunite grows due to SO4 released from anhydrite and K and Al released from muscovite.
- The models for 66°C and 70°C are relatively similar.

Initial Material	log fCO_2	Quartz %	K-feldspear %	Dolomite %	Calcite %	Illite %	Anhydrate %	Chlorite %	Alunite %	Dawsonite %	Total Volume %	Porosity %
Bunter Shale Seal 55°C	-1	36.91	5.73	7.08	0.00	17.53	5.90	16.85	0.00	0.00	90.00	10.00
Bunter Shale Seal 55°C	2	43.93	6.89	15.52	0.00	12.59	0.00	0.00	1.04	14.38	94.36	5.64
Bunter Shale Seal 60°C	-1	36.91	5.73	7.08	0.00	17.53	5.90	16.85	0.00	0.00	90.00	10.00
Bunter Shale Seal 60°C	2	43.69	6.64	15.62	0.00	13.49	0.00	0.00	0.00	14.08	93.52	6.48
Bunter Shale Seal 70°C	-1	36.91	5.73	7.08	0.00	17.53	5.90	16.85	0.00	0.00	90.00	10.00
Bunter Shale Seal 70°C	2	43.59	6.79	15.62	0.00	13.49	0.00	0.00	0.00	13.93	93.42	6.58

Table 11-30 Equilibrium modelling summary of results for the caprock type 1 (clay-rich)

Table 11-30 shows a summary of the equilibrium modelling results. The modelling work suggests that the diagenetic changes induced by CO2 flooding of the mudstones sitting immediately above the Bunter sandstone will, at equilibrium, lead to a net reduction in porosity of the rock from an initial 10% to a final 5.6 to 6.6% (as a function of temperature and the specific diagenetic reactions that occur, i.e., there is no net creation of new porosity simply by the action of increasing the CO2 partial pressure (fugacity) of the pore fluids.

The results of the equilibrium modelling for the **Caprock Type-2** (halite-rich with minor anhydrite) are shown inFigure 11-74 Equilibrium modelling results for caprock type 2 (halite-rich) Figure **11-74**. The geochemical model was run to simulate the effect of elevated partial pressures of CO2 on a halite-anhydrite-calcite rock in the presence of typical Bunter formation water.

The model reveals no geochemical reaction of the top seal with the modified gas composition following CO2 injection. This is not particularly surprising as, in general, significant reactions only happen when aluminosilicate minerals (clays and feldspars) are present in the rock however this is a possible scenario should any faults containing a typical silicate and calcite (Worden et al., 2015) gouge cut the Rot halite caprock.

A geochemical model was run with a **fault gouge** composition with dominant halite, subordinate calcite, and minor amounts of quartz and muscovite. The results are shown in Figure 11-75. Once aluminosilicates are introduced, the elevated CO2 partial pressure leads to reactions that mop up acid. Muscovite reacts with CO2 and Na from dissolved halite, creating dawsonite. However, there is only a negligible solid volume change suggesting that even this reaction in a fault-gouge bearing Rot Halite will have negligible effect on seal quality.

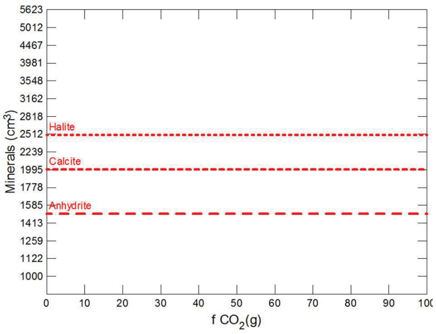


Figure 11-74 Equilibrium modelling results for caprock type 2 (halite-rich)

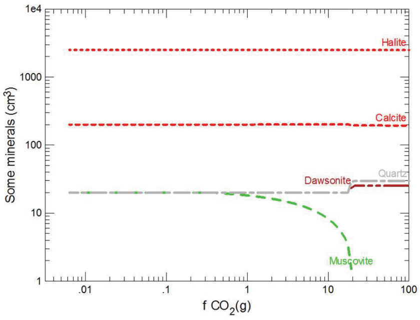


Figure 11-75 Equilibrium modelling results for caprock type 2 (halite-rich)

11.11.4.10 *Results: Kinetic Modelling*

In order to evaluate the kinetic effects on the reservoir, models reacting 5 mol CO_2(g) over 20000 years at 66°C for an average Bunter reservoir mineralogy were run for the following conditions:

- ***No*** Kinetic constraints placed on silicate dissolution reactions; and
- ***With*** kinetic constraints placed as follows
  - Microcline dissolution kinetics, rate constant 1x10^{-17} mol/cm2.s, 500 cm^2/g surface area.
  - Illite dissolution kinetics, rate constant 1x10^{-17} mol/cm2.s, 2000 cm^2/g surface area.
  - Chlorite dissolution kinetics, rate constant 1x10^{-17} mol/cm2.s, 3000 cm^2/g surface area.

Without kinetic considerations in place a variety of reactions take place (Figure 11-76), mirroring those indicated by equilibrium modelling, i.e. Feldspar and muscovite breakdown with Al being used by the growth of dawsonite. Note that these mineral changes lead to a negligible porosity decrease in the reservoir.

Putting kinetic considerations in place slows down the mineral reaction rate (Figure 11-77). Feldspar reaction slows down hugely (due to the small specific surface area), while the illite to dawsonite reaction also slows down but still occurs over the 20,000 year timeframe modelled. Note that again, these mineral changes lead to negligible porosity decrease.

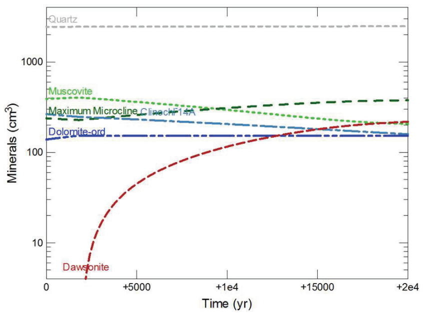


Figure 11-76 Kinetic modelling results for the Bunter sandstone (reservoir) with no kinetic constraints placed on silicate dissolution reactions

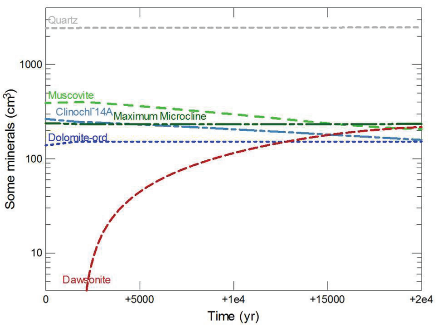


Figure 11-77 Kinetic modelling results for the Bunter sandstone (reservoir) with kinetic constraints (dissolution rate and surface area) in place

11.11.4.11 *Conclusions*

Reservoir

The relatively low temperature of the Bunter Sandstone reservoir means that all reactions will be slow (low rate constants for dissolution). The mineralogy of the reservoir is not especially reactive to the CO2. The main conclusion from this quick analysis is that the Bunter Sandstone reservoir will not undergo major mineral volume (porosity) changes due to CO2 injection.

However some reactions will occur in the reservoir sandstones with injected CO2; illite reacts with the CO2 and the Na-rich formation water to make the newly-formed mineral dawsonite. However the reaction is still slow given the CO2 injection and storage timescale – relatively little dawsonite is precipitated even on the 1000's year timeframe.

The vast dominance of unreactive quartz means that there can be relatively little effect on porosity. The modelling with kinetic constraints shows a negligible porosity-loss - there should be negligible effects on a production timescale and only very minor effects even after 10,000 years.

The effect on the permeability of the sandstone is unknown since it is not possible to predict the fabric of the artificially altered rock (by CO2 injection). It seems likely that the newly formed minerals will sit in pores and block pore throats suggesting that there could be a minor loss of permeability (on a 10,000 year time-scale). It is unlikely that reactions in the near-well bore area will impact (reduce) the injectivity.

Caprock

The most effective top seal is probably the Rot Halite. The model reveals no geochemical reaction of the top seal with the modified gas composition following CO2 injection.

The clay-rich caprock is more reactive to the elevated CO2 than the halite-rich type. Similar reactions to those in the reservoir sandstone occur (illite and K-feldspar replaced by dawsonite and alunite). There is a similar net reduction in porosity for the clay-rich caprock than for the Bunter sandstone. In the illite-rich, finest grained parts of the system, it possible that elevated CO2 could lead to a less porous (less permeable) caprock as a result of geochemical interactions but this would only occur on the very long term storage-scale.

It is worth noting that the dynamic modelling study indicated that for the development scenario selected, 73% of the injected CO2 remained structurally-trapped in the crest (i.e. with limited water-rock interaction) after 1000 years, and only 5% of the CO2 had undergone dissolution (and thus allowing reaction to occur). This places additional limits on the geochemical impact of the CO2.

11.11.4.12 *References*

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Pale Blue Dot. AXIS

RISK REGISTER

Bunter Closure 36 - Saline Aquifer site

Risk ID	Risk description/ event	Consequence of risk/ impact on project	Likelihood	Impact	Likelihood x impact	Comments (if applicable)	Controls (mitigation actions)	Potential remediation options	High level cost
1	Storage and injectivity of Bunter Closure 36 different (poorer) than forecast	Significant uncertainty over final cost of project, potential to reduce timescale of injection operations, reputational impact and fines	2	4	8		Appraisal well and well test to understand injectivity	Work-over/ stimulate wells. Drill additional wells	
2	Drilling activities near the storage site (either for O&G or CO2 storage)	Potential to compromise caprocks of storage site and provide an additional migration pathway to the near-surface/surface	1	4	4		Work closely with DECC to understand future drilling activities in the area and then work closely with Operators to ensure their drilling operations do not compromise storage integrity		
3	Future O&G extraction operations hindered by presence of CO2 in storage site	Presence of injected CO2 may hinder extractive operations near the storage site by obscuring seismic traces (eg in prospective formations below the storage site) or making drilling process more difficult. Drilling through formation with supercritical CO2 might cause blow out or loss of containment. May be requirement to pay compensation	1	4	4		Work closely with DECC to understand future drilling activities in the area and then work closely with Operators to ensure their drilling operations do not compromise storage integrity		
4	Accidental or intentional damage to injection process or storage site that disrupts storage site	Depending on scale of damage, could result in release of CO2 to seabed via well bores, injection being stopped, reputational and financial implications	1	4	4	Very low probability event but could have significant impact on storage system by disrupting expected evolution of the system	Monitoring of site to ensure operations are as expected	Shut in wells, further work to understand the scale of the damage, potentially require new injection site.	
5	Seismic event compromises store integrity	In the highly unlikely event that a large-scale seismic event occurred, the thickness, continuity and self-healing properites of the Rot Halite caprock ensure the impact will be negligible	1	1	1	The North Sea is a fairly quiescent area and far from plate boundaries so likelihood of large-scale seismicity is very low	Monitoring of site to ensure operations are as expected	Shut in wells, further work to understand the scale of the damage, potentially require new injection site.	
6	Loss of containment from primary store to overburden through caprock & P&A wells		1	3	3			Re-entry into an abandoned well is complex, difficult and has a very low chance of success. A relief well is required.	
7	Loss of containment from primary store to overburden through caprock & inj wells	Unexpected movement of CO2 outwith the storage site, but within the storage complex in the overburden, considerable reputational impact, large fine likely	1	3	3				
8	Loss of containment from primary store to overburden through via P&A wells	Unexpected movement of CO2 outwith the storage site, but within the storage complex in the overburden, considerable reputational impact, large fine likely	1	3	3	10 producing or suspended wells for deeper Schooner field and 5 P&A wells; location of wells in the crest of structure and within CO2 plume; annular cement job in the 13-3/8" casing - Top Of Cement is unknown and class B cement was used; for well A8 there is annular cement in the 13-3/8" casing across the Bunter which is a single, untested barrier. So if there is a leak path through this annular cement the CO2 could potentially travel directly up the 13-3/8" annulus to surface. Alternatively the CO2 could move down past the 13-3/8" shoe and up the 9-5/8" annulus. If the CO2 in the annulus of well 44/26a-A8 corrodes the casing there is then no barrier to the production bore and hence to surface. Only a leak to the biosphere will be detected.	Well A8 is a platform well and so assumed that the top hole is yet to be abandoned and a surface cement plug would be installed;	Re-entry into an abandoned well is complex, difficult and has a very low chance of success. A relief well is required.	Relief well: $55 million (60 days & tangibles).
9	Loss of containment from primary store to overburden through via injection wells	Unexpected movement of CO2 outwith the storage site, but within the storage complex in the overburden, considerable reputational impact, large fine likely	1	3	3		Injection wells designed to have low risk of loss of containment; downhole P/T gauges and DTS along the wellbore as part of monitoring plan to detect first signs of loss of integrity.		
10	Loss of containment from primary store to upper well/ seabed via P&A wells	CO2 to seabed. Environmental, international rep and cost implications	3	4	12	10 producing or suspended wells for deeper Schooner field and 5 P&A wells; location of wells in the crest of structure and within CO2 plume; annular cement job in the 13-3/8" casing - Top Of Cement is unknown and class B cement was used; for well A8 there is annular cement in the 13-3/8" casing across the Bunter which is a single, untested barrier. So if there is a leak path through this annular cement the CO2 could potentially travel directly up the 13-3/8" annulus to surface. Alternatively the CO2 could move down past the 13-3/8" shoe and up the 9-5/8" annulus. If the CO2 in the annulus of well 44/26a-A8 corrodes the casing there is then no barrier to the production bore and hence to surface. Only the final event – leak to the biosphere – will be detected.	Well A8 is a platform well and so assumed that the top hole is yet to be abandoned and a surface cement plug would be installed; monitoring plan in place focuses around bubble detection from P&A wells	Re-entry into an abandoned well is complex, difficult and has a very low chance of success. A relief well is required.	Relief well: $55 million (60 days & tangibles).
11	Loss of containment from primary store to upper well/ seabed via injection wells	CO2 leaks to seabed. Environmental, PR and cost implications	1	4	4	Injection wells designed to have low risk of loss of containment	Injection wells designed to have low risk of loss of containment; downhole P/T gauges and DTS along the wellbore as part of monitoring plan to detect first signs of loss of integrity.		
12	Loss of containment from primary store to underburden (Zechstein or lower)	If CO2 was to flow downwards in the wellbore zone, impact would be Medium as the Schooner reservoirs are considered to be outside the defined storage complex.	2	3	6	All legacy wells have been abandoned to prevent hydrocarbon leakage from the deeper reservoir (Schooner targets) to any shallower reservoir (e.g. Bunter). There are tested (verifiable) plugs between the two units. The potential for downward leakage is therefore significantly lower (but not negligible, as some of these plugs rely on good annular isolation which, even if tested - does not necessarily guarantee over lifetime) CO2 in modelling only reaches top of Bunter 5 sand, which has low NTG and under which lies the Bunter Shale bottom seal (store flow) --> 100s of metres thick. For leakage outwith the storage complex, the CO2 would need to get into the Zechstein or lower via thickness of shale thicker than reservoir itself and is v unlikely that Bunter shales have permeability that would enable this. In addition, the geometry of the storage site makes this highly improbable.	Work with existing Schooner operators to ensure robust well abandonment techniques; monitor using 4D seismic	Stop injection; corrective measures plan	
13	Fault reactivation through primary caprock	Impact v low as even if risk scenario happened, very unlikely for CO2 to get to Base Chalk so still within storage complex.	1	2	2	No obvious seismic Top Bunter faults that offset the primary caprock, although there could always be small subseismic faults. Even if the subseismic faults are reactivated, they are very small and will not go through caprock. Rot Halite (caprock) is also self healing --> low likelihood.	Maximum reservoir pressure during injection set to 90% of fracture pressure	Stop injection, corrective measures plan, inject at reduced pressure, limit injection volumes	
14	CO2 flow through unreactivated, permeable fault in primary caprock	Impact v low as even if risk scenario happened, very unlikely for CO2 to get to Base Chalk so still within storage complex.	1	2	2	Very low likelihood of there being a permeable fault and very low impact if there was as Rot Halite caprock is "self healing"	n/a		
15	Thermal fracturing of primary caprock from injection of cold CO2 into a warm reservoir	Impact v low as even if risk scenario happened, very unlikely for CO2 to get to Base Chalk so still within storage complex.	1	2	2	Although likely to have thermal fractures within the reservoir during injection, there is a very low likelihood of thermal fractures being created in the Rot Halite caprock due to:	(i) two barriers of Bunter reservoir (Bunter 1 and 2) and layer of claystone between injection layers (Bunter 3 and 4) and caprock (Rot Halite) and (ii) Rot Halite is a poor heat conductor so reduces likelihood of thermal fractures occurring.	Stop injection, corrective measures plan, limit injection volumes/rate	
16	CO2 and brine react with minerals in caprock and create permeability pathway	Even in the unlikely event that the CO2 managed to migrate through the primary caprock, the volumes would be small and it would be trapped by the secondary store and still within the Storage Complex	1	2	2	Halite (primary caprock) is insoluable in CO2 and so therefore unreactive --> very low likelihood.	None required		
17	Buoyant CO2 exposes caprock to pressures beyond the capillary entry pressure enabling it to flow through primary caprock	Even in the unlikely event that the CO2 managed to migrate through, the volumes would be small and it would be trapped by the secondary store and still within the Storage Complex --> low impact.	1	2	2	The Rot Halite primary caprock has a very very low permeability --> very low likelihood.		Stop injection, corrective measures plan, inject at reduced pressure, limit injection volumes to reduce column height of CO2,	
18	Geology of caprock lithology is variable and lacks continuity such that its presence cannot be assured across the whole site	Unexpected CO2 migration within storage complex	1	2	2	Even in the unlikely event that the CO2 managed to migrate through, the volumes would be small and it would be trapped by the secondary store and still within the Storage Complex --> low impact.	Rot Halite primary caprock is very thick (80-100m), with 800-1000m of total seal thickness if incl all shales above it. The Rot Halite is well developed on logs across an extensive area --> very low likelihood that the primary caprock is patchy.	Stop injection, corrective measures plan	
19	Relative permeability curves in the model move the CO2 too slowly within the primary store relative to reality	In the unlikely event that CO2 did migrate faster than expected and laterally exited the primary store, this would be unexpected migration but at reservoir level. Considerable impact on reputation and large fine likely.	2	3	6	In general, there is significant uncertainty regarding the relative permeability curves used in modelling CO2 movement in the Bunter 36 as they are based on CO2 core analysis, which has not been carried out for this site. However, the rel perm curves used capture a range of known data & have an end point of 1.6 which is v v high compared to normal oil and gas end points of around 1. This means the rel perm curves used in the simulation modelling move the CO2 much faster than usual, and so the rel perms are thought to be very conservative --> likelihood of these curves being too low is low. Uncertainty regarding likelihood: relative permeability is a massive uncertainty and very few data exist for CO2.	Site specific relative permeability study from core in appraisal well to constrain curves	Stop injection, corrective measures plan, re-model expected CO2 plume movement with new data and re-assess injection volumes to ensure containment integrity	
20	Depth conversion uncertainty around dip and spill point	In the unlikely event that the depth conversion uncertainty caused CO2 to laterally exit the primary store, this would be unexpected migration but at reservoir level. Considerable impact on reputation and large fine likely.	2	3	6	There is good well control around structure for depth conversion, including near the saddles --> low likelihood	Appraisal well drilled on flank of greatest uncertainty to reduce uncertainty		
21	Depletion or pressure gradient from nearby fields (push from 5/42 or pull from Caister)	In the unlikely event that depletion or pressure gradient from nearby fields caused CO2 to laterally exit the primary store, this would be unexpected migration but at reservoir level. Considerable impact on reputation and large fine likely.	2	3	6	It is likely that there will be some kind of pressure depletion from Caister, but very unlikely that it will be enough for CO2 in BC36 to be pulled towards it during CO2 injection operations --> low likelihood. Location of Caister is known so could potentially model this.	Model impacts; good engagement with other operators in the area to understand impact	Stop injection until situation understood; further detailed work	
22	Impact of injection and CO2 storage on nearby fields (e.g. 5/42 Endurance) is greater than expected	Pressure build up quicker than expected so reduces storage capacity, potential loss of credibility of CCS project			0		Draft process for dispute resolution with nearby subsurface users	Stop injection until situation understood; further detailed work	
23	Well placement error	In the unlikely event that the well was drilled at the edge of the storage complex and caused CO2 to laterally exit the primary store, this would be unexpected migration but at reservoir level. Considerable impact on reputation and large fine likely.	2	3	6	Due to current technology and set procedures used during drilling campaigns, this is very unlikely, but not improbable --> Low likelihood			
24	Inject in wrong zone of reservoir or damage reservoir	In the unlikely event that CO2 was injected into the wrong zone or the reservoir was damaged and caused CO2 to laterally exit the primary store, this would be unexpected migration but at reservoir level. Considerable impact on reputation and large fine likely.	2	3	6	If CO2 was injected into the wrong zone or the reservoir was damaged, it would be known from the injectivity of the well that this had occurred and so very unlikely that injection would continue to enable CO2 to laterally exit the primary store. --> low likelihood.	Downhole P/T gauges and DTS along the wellbore as part of monitoring plan to detect first signs of loss of integrity.		
25	CO2 becomes dissolved in water and laterally exits the primary store	Even if it exits the primary store laterally, the impact would be limited as will be gravitationally stable.	2	2	4	Dynamic modelling shows that some CO2 will dissolve into the brine			
26	Blowout during drilling	Possible escape of CO2 to the biosphere.					Mapping of shallow gas, understanding subsurface pressure regime for appropriate mud weight, drilling procedures	Standard procedures: shut-in the well and initiate well control procedures.	$3-5 million (5 days & tangibles).

27	Blowout during well intervention	Possible escape of CO_2 to the biosphere.					Mapping of shallow gas, understanding subsurface pressure regime for appropriate mud weight, drilling procedures	Standard procedures: shut-in the well and initiate well control procedures.	$2-3 million (3 days & tangibles).
28	Tubing leak	Pressured CO_2 in the A-annulus. Sustained CO_2 annulus pressure will be an unsustainable well integrity state and require remediation.					Downhole P/T gauges and DTS along the wellbore as part of monitoring plan to detect first signs of loss of integrity.	Tubing replacement by workover.	$15 -20 million (16 days & tangibles).
29	Packer leak	Pressured CO_2 in the A-annulus. Sustained CO_2 annulus pressure will be an unsustainable well integrity state and require remediation.						Packer replacement by workover.	$15 -20 million (16 days & tangibles).
30	Cement sheath failure (Production Liner)	Sustained CO_2 annulus pressure will be an unsustainable well integrity state and require remediation.				Requires: - a failure of the liner packer or - failure of the liner above the production packer before there is pressured CO_2 in the A-annulus.		Repair by cement squeeze (possible chance of failure). Requires the completion to be retrieved and rerun (if installed).	$3-5 million (5 days & tangibles). $18-25 million (if a workover required).
31	Production Liner failure	Sustained CO_2 annulus pressure will be an unsustainable well integrity state and require remediation.				Requires: - a failure of the liner above the production packer and - a failure of the cement sheath before there is pressured CO_2 in the A-annulus.		Repair by patching (possible chance of failure) or running a smaller diameter contingency liner. Requires the completion to be retrieved and rerun (if installed). Will change the casing internal diameter and may have an impact on the completion design and placement. Repair by side-track.	$3-5 million (3 days & tangibles). $18-25 million (if a workover required). Side-track estimated to be equal to the cost of a new well - $55 million (60 days & tangibles).
32	Cement sheath failure (Production Casing)	Sustained CO_2 annulus pressure will be an unsustainable well integrity state and require remediation.				Requires: - a failure of the Production Liner cement sheath or - a pressurised A-annulus and - failure of the production casing before there is pressured CO_2 in the B-annulus.		Repair by cement squeeze (possible chance of failure). Requires the completion to be retrieved and rerun (if installed).	$3-5 million (5 days & tangibles). $18-25 million (if a workover required).
33	Production Casing Failure	Sustained CO_2 annulus pressure will be an unsustainable well integrity state and require remediation.				Requires: - a pressurised A-annulus and - a failure of the Production Casing cement sheath before there is pressure CO_2 in the B-annulus.		Repair by patching (possible chance of failure). Requires the completion to be retrieved (if installed). Will change the casing internal diameter and may have an impact on the completion design and placement.	$3-5 million (3 days & tangibles). $18-25 million (if a workover required). Side-track estimated to be equal to the cost of a new well - $55 million (60 days & tangibles).
34	Safety critical valve failure – tubing safety valve	Inability to remotely shut-in the well below surface. Unsustainable well integrity state.						Repair by: - installation of insert back-up by intervention or - replacement by workover	£1 million to run insert (1 day & tangibles). $18-25 million (if a workover required).
35	Safety critical valve failure – Xmas Tree valve	Inability to remotely shut-in the well at the Xmas Tree. Unsustainable well integrity state.						Repair by valve replacement.	Dry Tree: < $1 million (costs associated with 5 days loss of injection, tangibles and man days). Subsea: $5-7 million (vessels, ROV, dive support & tangibles).
36	Wellhead seal leak	Seal failure will be an unsustainable well integrity state and require remediation.				Requires: - a pressurised annulus and - multiple seal failures before there is a release to the biosphere.		Possible repair by treatment with a replacement sealant or repair components that are part of the wellhead design. Highly dependent on the design and ease of access (dry tree or subsea). May mean the well has insufficient integrity and would be abandoned.	Dry Tree: <$3 million (costs associated with 7 days loss of injection, tangibles and man days). Abandonment $15-25 (21 days & tangibles).
37	Xmas Tree seal leak	Seal failure will be an unsustainable well integrity state and require remediation.				Requires multiple seal failures before there is a release to the biosphere.		Possible repair by specific back-up components that are part of the wellhead design. Highly dependent on the design and ease of access. May mean the Xmas Tree need to be removed/recovered to be repaired. This is a time consuming process for a subsea tree.	Dry Tree: <$3 million (costs associated with 7 days loss of injection, tangibles and man days). Subsea: $12-15 million (12 days & tangibles).

Impact categories (CO2QUALSTORE)

No.	1	2	3	4	5
Name	Very Low	Low	Medium	High	Very High
Impact on storage integrity	None	Unexpected migration of CO2 inside the defined storage complex	Unexpected migration of CO2 outside the defined storage complex	Leakage to seabed or water column over small area (<100m2)	Leakage seabed water column over large area (>100m2)
Impact on local environment	Minor environmental damage	Local environmental damage of short duration	Time for restitution of ecological resource <2 years	Time for restitution of ecological resource 2-5 years	Time for restitution of ecological resource such as marine Biosystems, ground water >5 years
Impact on reputation	Slight or no impact	Limited impact	Considerable impact	National impact	International impact
Consequence for Permit to operate	None	Small fine	Large fine	Temporary withdrawal of permit	Permanent loss of permit

Likelihood categories (CO2QUALSTORE)

No.	1	2	3	4	5
Name	Very Low	Low	Medium	High	Very High
Description	Improbable, negligible	Remotely probably, hardly likely	Occasional, likely	Probable, very likely	Frequent, to be expected
Event (E)	Very unlikely to occur during the next 5000 years	Very unlikely to occur during injection operations	Likely to occur during injection operations	May occur several times during injection operations	Will occur several times during injection operations
Frequency	About 1 per 5000 years	About 1 per 500 years	About 1 per 50 years	About 1 per 5 years	About 1 per year or more
Feature (F)/ Process (P)	Disregarded	Not expected	50/50 chance	Expected	Sure

PROJECT	Strategic UK Storage Appraisal Project
TITLE	SITE 7: BUNTER CLOSURE 36
CLIENT	ETI
REVISION	A01
DATE	03/12/2015

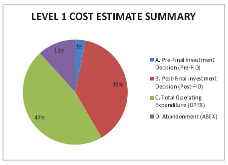
LEVEL 2 COST ESTIMATE

Pale Blue Dot. COSTAIN AXIS WELL TECHNOLOGY FROM CONCEPT TO COMPLETION

	Category	Comment	Primary Cost (£ MM)	Overheads (£ MM)	Total Cost excl. Contingency (£ MM)	Contingency (%)	Total Cost inc. Contingency (£ MM)
A. Pre-Final Investment Decision (Pre-FID)		including Pre-FEED / FEED Design and Engineering	**35.7**	**4.9**	**40.7**		**51.7**
A1.1	**Transportation**	CO2 Pipeline System Pre-FEED/FEED Design	0.5	0.2	0.7		0.8
A1.2	**Facilities**	Design of Platforms, Subsea Structures, Umbilicals, Power Cables	4.5	2.0	6.5		8.5
A1.3	**Wells**	Pre-Feed / FEED Wells Engineering Design	2.0	0.2	2.2		2.9
A1.4	**Other**		28.8	2.5	31.3	30%	39.5
A1.4.1	Seismic and Baseline Survey	Data Acquisition & Interpretation	4.0	0.4	4.4		5.7
A1.4.2	Appraisal Well	Procurement for, and Drilling of, Appraisal Well(s)	21.8	0.9	22.7		28.4
A1.4.3	Engineering and Analysis	Additional subsurface analysis and re-engineering if required	2.0	0.2	2.2		2.9
A1.4.4	Licencing and Permits	Licenses, Permissions Permit, PLANC	1.0	1.0	2.0		2.6
B. Post-Final Investment Decision (Post-FID)			**455.8**	**22.2**	**478.0**	**-**	**617.5**
B1.1	**Transportation**		170.4	6.0	176.4	-	229.4
B1.1.1	Detailed Design	Detailed Design of CO2 Pipeline System	1.0	0.2	1.2		1.6
B1.1.2	Procurement	Long lead items (linepipe, coatings etc)	85.2	5.6	90.8	30%	118.0
B1.1.3	Fabrication	Spoolbase Fabrication and Coating etc	15.4	0.2	15.6		20.3
B1.1.4	Construction and Commissioning	Logistics, Installation, WX, Function Testing and Commissioning	68.8	0.0	68.8		89.5
B1.2	**Facilities**		64.2	8.2	72.4	-	94.1
B1.2.1	Detailed Design		10.0	3.0	13.0		16.9
B1.2.2	Procurement	Jacket, Topsides, Templates, Umbilicals, Power Cables, etc	16.1	4.3	20.4	30%	26.5
B1.2.3	Fabrication	Platform/NUI and Subsea Structures Fabrication	15.6	0.9	16.6		21.5
B1.2.4	Construction and Commissioning	Logistics, Transportation, Installation, HUC	22.4	0.0	22.4		29.1
B1.3	**Wells**		220.3	7.0	227.2	-	291.5
B1.3.1	Detailed Design	including submission of OPEP (or CO2 equivalent)	2.0	0.2	2.2		2.9
B1.3.2	Procurement	Wells long lead items - Trees, Tubing Hangers, etc	64.0	0.0	64.0		83.2
B1.3.3	Fabrication	-	0.0	0.0	0.0		0.0
B1.3.4	Construction and Commissioning	Drilling/Intervention, WX	154.3	6.8	161.0	30%	205.4
		Well 1-4	59.8	2.7	62.5		80.0
		Well 5	17.4	0.9	18.3		23.0
		4 Rep. Wells	59.8	2.3	62.0		79.4
		5th Rep. Well	17.4	0.9	18.3		23.0
B1.4	**Other**		1.0	1.0	2.0	30%	2.6
B1.4.1	Licencing and Permits	Licenses, Permissions Permit, PLANC	1.0	1.0	2.0	30%	2.6
C. Total Operating Expenditure (OPEX)			**539.4**	**43.1**	**582.5**	**-**	**751.4**
C1.1	**OPEX - Transportation**	Inspections, Maintenance, Repair (IMR)	87.5	4.6	92.1		119.7
C1.2	**OPEX - Facilities**	Manning, Power, IMR, Chemicals	225.6	20.5	246.1		319.9
C1.3	**OPEX - Wells**	Workovers, Sidetracks, Power, Chemicals	87.1	4.1	91.2		112.7
C1.3.1	**Well Sidetracks and Workovers**	Local Sidetrack 1	19.8	0.9	20.7		25.6
		Local Sidetrack 2	19.8	0.9	20.7	30%	25.6
		Workover1	8.1	0.5	8.6		10.4
		Local Sidetrack 3	19.8	0.9	20.7		25.6
		Local Sidetrack 4	19.8	0.9	20.7		25.6
C1.4	**Other**		139.2	13.9	153.12	-	199.1
C1.4.1	Measurement, Monitoring and Verification	includes data management and interpretation	28.0	2.8	30.8		40.0
C1.4.2	Financial Securities		111.2	11.1	122.32	30%	159.0
C1.4.3	Ongoing Tariffs and Agreements	assume supplier covers 3rd party tariffs	0.0	0.0	0		0.0
D. Abandonment (ABEX)			**131.1**	**13.7**	**144.8**	**-**	**188.2**
D1.1	**Decommissioning - Transportation**	10% Transportation CAPEX	23.0	2.3	25.3		32.9
D1.2	**Decommissioning - Facilities**	Que$tor	40.9	4.1	44.9	30%	58.4
D1.3	**Decommissioning - Wells**		38.3	5.4	43.7		56.7
D1.4	**Other**		29.0	1.9	30.88	-	40.1
D1.4.1	Post Closure Monitoring	includes data management and interpretation	19.3	1.9	21.23	30%	27.6
D1.4.2	Handover	additional 10 years of coverage	9.7	0.0	9.65		12.5

FIELD LIFE (YEARS)	40
CO2 STORED (MT)	280

DEFINITIONS	
TRANSPORTATION	CO2 PIPELINE SYSTEM (LANDFALL & OFFSHORE PIPELINE)
FACILITIES	NUI's, SUBSEA STRUCTURES, UMBILICALS, POWER CABLES
WELLS	ALL COSTS ASSOCIATED WITH CO2 INJECTION WELLS
OTHER	ANY AND ALL COSTS NOT COVERED WITHIN ABOVE
PRIMARY COST	PRIMARY CONTRACT COSTS
OVERHEAD	ADDITIONAL OWNER'S COSTS COVERING OWNER'S PROJECT MANAGEMENT, VERIFICATION, ETC



CAPEX / OPEX / ABEX BREAKDOWN SUMMARY

COST	TOTAL COST (£ MM)	CATEGORY	COST (£ MM)
CAPEX [A + B]	669.2	TRANSPORTATION	230.2
		FACILITIES	102.5
		WELLS	294.3
		OTHER	42.1
OPEX [C]	751.4	TRANSPORTATION	119.7
		FACILITIES	319.9
		WELLS	112.7
		OTHER	199.1
ABEX [D]	188.2	TRANSPORTATION	32.9
		FACILITIES	58.4
		WELLS	56.7
		OTHER	40.1
TOTAL	1608.8	-	1608.8

LEVEL 1 COST ESTIMATE SUMMARY

Category	Primary Cost (£ MM)	Overheads (£ MM)	Total Cost excluding Contingency (£ MM)	Total Cost inc. Contingency (£ MM)
A. Pre-Final Investment Decision (Pre-FID)	35.7	4.9	40.7	51.7
B. Post-Final Investment Decision (Post-FID)	455.8	22.2	478.0	617.5
C. Total Operating Expenditure (OPEX)	539.4	43.1	582.5	751.4
D. Abandonment (ABEX)	131.1	13.7	144.8	188.2
TOTAL COST (CAPEX, OPEX, ABEX)			1245.9	**1608.8**
COST CO2 INJECTED (£ PER TONNE)			£4.45	**£5.75**

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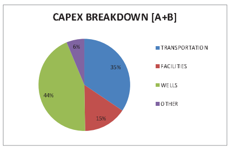

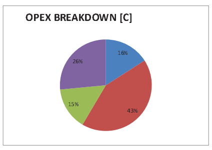

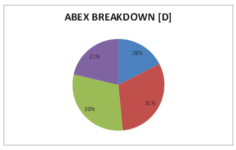

PROJECT	Strategic UK Storage Appraisal Project	**TRANSPORTATION: PROCUREMENT & FABRICATION**	Pale Blue Dot. COSTAIN AXIS WELL TECHNOLOGY FROM CONCEPT TO COMPLETION
TITLE	SITE 7: BUNTER CLOSURE 36		
CLIENT	ETI		
REVISION	A01		
DATE	03/12/2015		

Pipeline	**Trunk Pipeline(s)**	**Infield Pipeline(s)**
Number	1	
Route Length (km)	160	
Route Length Factor	1.05	
Pipeline Crossings	5	
Tee Structures	1	
Outer Diameter (mm)	508	
Wall Thickness (mm)	25.4	
Anode Spacing (m)	500	

No.	Item	Description	Unit Cost (£)	Unit	Qty	Total (£MM)	Overhead (£)	Description (Overheads)	Total Cost (£)
A. Pre-FID									
A1.1	**Transportation - Pre FID**								**£652,500**
A1.1.1	Pre-FEED	Lump Sum	£200,000	LS	1.00	£200,000	£90,000	*Company Time Writing, Contractor Surveillance*	£290,000
A1.1.2	FEED	Lump Sum	£250,000	LS	1.00	£250,000	£112,500	*Company Time Writing, Contractor Surveillance*	£362,500
B. Post FID									
B1.1	**Transportation - Post FID**								**£107,594,258**
B1.1.1	Detailed Design	Lump Sum	£1,000,000	LS	1.00	£1,000,000	£200,000	*Company Time Writing, IVB, SIT, Insurance etc*	£1,200,000
B1.1.2	Procurement		-	-	-	-	-		**£90,804,258**
B1.1.2.1	Insurance and Certification		-	-	-		£500,000	*Insurance and Certification*	£500,000
B1.1.2.2	Geotechnical Testing		£2,000	km	168	£336,000	£28,000	*Documentation etc*	£364,000
B1.1.2.3	*Procurement - Linepipe (Trunk)*	*API 5L X65, OD 457.2mm, WT 21.4mm*	£1,500	Te	50,787	£76,180,500	£4,570,830	*Logistics/Freight @ 6%*	£80,751,330
B1.1.2.4	*Procurement - Coating (Trunk)*	*Corrosion Coating*	£20	m	168,000	£3,360,000	£201,600		£3,561,600
B1.1.2.5	*Procurement - Coating (Trunk)*	*Concrete Coating*	£30	m	176,400	£5,292,000	£317,520		£5,609,520
B1.1.2.6	*Procurement - Anodes (Trunk)*	*CP Protection*	£50	Each	336	£16,800	£1,008		£17,808
B1.1.3	Fabrication		-	-	-	-	-		**£15,590,000**
B1.1.3.1	SSIV	Subsea Isolation Valve Structure	£1,500,000	LS	1	£1,500,000	£100,000	*Contractor Surveillance*	£1,600,000
B1.1.3.2	*Spoolbase Fabrication*	*Coating Only (S Lay)*	£50	m	168,000	£8,400,000	£50,000	*Contractor Surveillance*	£8,450,000
B1.1.3.3	*Crossing Supports*	*Concrete Crossing Plinth/Supports*	£100,000	Per Crossing	5	£500,000	£20,000	*Contractor Surveillance*	£520,000
B1.1.3.4	*Tee-Piece Structure*	*To Facilitate Future Expansion*	£5,000,000	Each	1	£5,000,000	£20,000	*Contractor Surveillance*	£5,020,000
						Total (Excluding Contingency)			**£108,246,758**
						Pre-FID Contingency (%)		**30%**	**£195,750**
						Post-FID Contingency (%)		**30%**	**£32,278,277**
						Total (Including Contingency)			**£140,720,785**

PROJECT	Strategic UK Storage Appraisal Project	**TRANSPORTATION: CONSTRUCTION AND COMMISSIONING**
TITLE	SITE 7: BUNTER CLOSURE 36	
CLIENT	ETI	
REVISION	A01	
DATE	03/12/2015	

Pale Blue Dot. COSTAIN AXIS WELL TECHNOLOGY FROM CONCEPT TO COMPLETION

Pipeline	**Trunk Pipeline(s)**	**Infield Pipeline(s)**
Number	1	
Route Length (km)	160	
Route Length Factor	1.05	
Pipeline Crossings	5	
Outer Diameter (mm)	508	
Wall Thickness (mm)	25.4	
Anode Spacing (m)	500	
Landfall Required?	YES	-

Activity	**Vessel**	**Dayrate (£)**	**Working Rate (m/hr)**
Pipeline Route Survey	Survey Vessel	£100,000	750
Pipelay (Reel)	Reel Lay Vessel	£150,000	500
Pipelay (S-Lay)	S-Lay Vessel (14000Te)	£350,000	100
Trenching and Backfill	Ploughing Vessel	£100,000	400
Crossing Installation	Survey Vessel	£100,000	-
Spoolpiece Tie-ins	DSV	£150,000	-
Commissioning	DSV	£150,000	-
Pipelay (Carrier)	Pipe Carrier (1600Te)	£50,000	-
Structure Installation	DSV	£150,000	-

Landfall Cost	£25,000,000

No.	**Activity**	**Breakdown**	**Vessel**	**Day Rate (£)**	**Days**	**Sub-Total (£)**	**Total Cost (£)**
B. Post FID							
B1.1	**Transportation - Post FID**						
B1.1.4	**Construction and Commissioning**						
B1.1.4.1	Pipeline Route Survey	Mobilisation	Survey Vessel	£100,000	2	£200,000	£1,400,000
		Infield Operations			10	£1,000,000	
		Demobilisation			2	£200,000	
B1.1.4.2	Pipelay (S-Lay)	Mobilisation	S-Lay Vessel (14000Te)	£350,000	5	£1,750,000	£26,950,000
		Infield Operations			70	£24,500,000	
		Demobilisation			2	£700,000	
B1.1.4.3	Crossing Installation	Mobilisation	Survey Vessel	£100,000	2	£200,000	£1,900,000
		Infield Operations - 3 day per Crossing			15	£1,500,000	
		Demobilisation			2	£200,000	
B1.1.4.4	Spoolpiece Tie-ins	Mobilisation	DSV	£150,000	2	£300,000	£2,100,000
		Infield Operations			10	£1,500,000	
		Demobilisation			2	£300,000	
B1.1.4.5	Commissioning	Mobilisation	DSV	£150,000	2	£300,000	£1,650,000
		Infield Operations			7	£1,050,000	
		Demobilisation			2	£300,000	
B1.1.4.6	Structure Installation	Mobilisation	DSV	£150,000	2	£300,000	£1,050,000
		Infield Operations -SSIV and Tee			3	£450,000	
		Demobilisation			2	£300,000	
B1.1.4.7	Pipelay (Carrier)	Mobilisation	Pipe Carrier (1600Te)	£50,000	2	£100,000	£4,800,000
		Roundtrip Operations - 4 days per Trip			92	£4,600,000	
		Demobilisation			2	£100,000	
B1.1.4.8	Construction Project Management and Engineering		-	Lump Sum (10%)	-	£3,985,000	£3,985,000
B1.1.4.9	Landfall		-	Lump Sum	-	£25,000,000	£25,000,000
					Total (Excluding Contingency)		**£68,835,000**
					Contingency	**30%**	**£20,650,500**
					Total (Including Contingency)		**£89,485,500**

PROJECT	Strategic UK Storage Appraisal Project	Facilities: PROCUREMENT & FABRICATION
TITLE	SITE 7: BUNTER CLOSURE 36	
CLIENT	ETI	
REVISION	A01	
DATE	03/12/2015	

Pale Blue Dot. COSTAIN AXIS WELL TECHNOLOGY FROM CONCEPT TO COMPLETION

COSTS EXTRACTED FROM QUESTOR

Exchange Rate (£:$) 1.50

No.	Item	Description	Unit Cost (£)	Unit	Qty	Total (£MM)	Overhead (£)	Description (Overheads)	Total Cost (£)
A. Pre-FID									
A1.2	**Facilities - Pre FID**								**£6,525,000**
A1.2.1	Pre-FEED	4 Legged Jacket, Topsides	£1,500,000	LS	1	£1,500,000	£675,000	*Company Time Writing, Contractor Surveillance*	£2,175,000
A1.2.2	FEED	4 Legged Jacket, Topsides	£3,000,000	LS	1	£3,000,000	£1,350,000	*Company Time Writing, Contractor Surveillance*	£4,350,000
B. Post FID									
B1.2	**Facilities - Post FID**								**£72,355,094**
B1.2.1	Detailed Design	4 Legged Jacket, Topsides	£10,000,000	LS	1	£10,000,000	£3,000,000	*Company Time Writing, IVB, SIT etc*	**£13,000,000**
B1.2.2	Procurement		-	-	-		-	-	**£20,361,062**
	Jacket	4 Legged Jacket	-	-	-		-	-	***£8,864,985***
B1.2.2.1.1	Insurance and Certification		-	-	-		£2,010,000	*Insurance and Certification*	£2,010,000
B1.2.2.1.2	*Jacket Steel*		£1,333	Te	3,000	£4,000,000	£240,000		£4,240,000
B1.2.2.1.3	*Piles*		£1,301	Te	1,200	£1,560,800	£93,648	*Logistics/Freight @ 6%*	£1,654,448
B1.2.2.1.4	*Anodes*		£3,685	Te	200	£737,067	£44,224		£781,291
B1.2.2.1.5	*Installation Aids*		£1,127	Te	150	£169,100	£10,146		£179,246
	Topsides		-	-	-		-	-	***£11,496,077***
B1.2.2.2.1	Insurance and Certification		-	-	-		£1,278,667	*Insurance and Certification*	£1,278,667
B1.2.2.2.2	*Primary Steel*		£1,087	Te	230	£249,933	£14,996		£264,929.33
B1.2.2.2.3	*Secondary Steel*		£900	Te	150	£135,000	£8,100		£143,100.00
B1.2.2.2.4	*Piping*		£10,733	Te	40	£429,333	£25,760		£455,093.33
B1.2.2.2.5	*Electrical*		£19,200	Te	20	£384,000	£23,040		£407,040.00
B1.2.2.2.6	*Instrumentation*		£36,333	Te	20	£726,667	£43,600		£770,266.67
B1.2.2.2.7	*Miscellaneous*		£8,800	Te	20	£176,000	£10,560		£186,560.00
B1.2.2.2.8	*Manifolding*		£14,733	Te	50	£736,667	£44,200		£780,866.67
B1.2.2.2.9	*Control and Communications*	*Sat Comms*	£460,733	Te	5	£2,303,667	£138,220		£2,441,886.67
B1.2.2.2.10	*General Utilities*	*Drainage, Diesal Storage etc*	£50,000	Te	4	£200,000	£12,000	*Logistics/Freight @ 6%*	£212,000.00
B1.2.2.2.11	*Vent Stack*	*Low Volume (venting done at beach)*	£6,933	Te	35	£242,667	£14,560		£257,226.67
B1.2.2.2.12	*Diesel Generators*	*Power Generation*	£52,067	Te	18	£937,200	£56,232		£993,432.00
B1.2.2.2.13	*Power Distribution*		£36,067	Te	5	£180,333	£10,820		£191,153.33
B1.2.2.2.14	*Emergency Power*		£34,733	Te	2	£69,467	£4,168		£73,634.67
B1.2.2.2.15	*Quarters and Helideck*	*50 Te Helideck plus TR*	£23,333	Te	70	£1,633,333	£98,000		£1,731,333.33
B1.2.2.2.16	*Crane*	*Mechanical Handling*	£19,267	Te	30	£578,000	£34,680		£612,680.00
B1.2.2.2.17	*Lifeboats*	*Freefall Lifeboats*	£24,400	Te	7	£170,800	£10,248		£181,048.00
B1.2.2.2.18	*Chemical Injection*	*Chemicals, Pumps, Storage*	£46,600	Te	10	£466,000	£27,960		£493,960.00
B1.2.2.2.19	*PLR*	*Pig Reciever*	£10,000	Te	2	£20,000	£1,200		£21,200.00
B1.2.3	Fabrication		-	-			-		**£16,571,475**
	Jacket		-	-			-		***£12,407,053***
B1.2.3.1	*Jacket Steel*		£3,245	m	3,000	£9,734,000	£584,040		£10,318,040
B1.2.3.2	*Piles*		£1,022	m	1,200	£1,226,400	£73,584	*Logistics/Freight @ 6%*	£1,299,984
B1.2.3.3	*Anodes*		£755	Each	200	£151,067	£9,064		£160,131
B1.2.3.4	*Installation Aids*		£3,955		150	£593,300	£35,598		£628,898
	Topsides		-		-		-	-	***£4,164,422***
B1.2.3.2.1	*Primary Steel*		£5,467	Te	230	£1,257,333	£75,440		£1,332,773
B1.2.3.2.2	*Secondary Steel*		£7,200	Te	150	£1,080,000	£64,800		£1,144,800
B1.2.3.2.3	*Equipment*		£1,513	Te	125	£189,167	£11,350		£200,517
B1.2.3.2.4	*Piping*		£14,867	Te	40	£594,667	£35,680	*Logistics/Freight @ 6%*	£630,347
B1.2.3.2.5	*Electrical*		£26,467	Te	20	£529,333	£31,760		£561,093
B1.2.3.2.6	*PLR*	*Pig Reciever*	£25,000	Te	2	£50,000	£3,000		£53,000
B1.2.3.2.7	*Miscellaneous*		£10,867	Te	21	£228,200	£13,692		£241,892
B1.2.4	Construction and Commissioning		-	-	-		-	-	**£22,422,557**
B1.2.4.1	Installation Spread	Jacket Installation	£596,206	Days	28	£16,693,768	£0	-	£16,693,768
B1.2.4.2	Installation Spread	Topsides Installation	£135,533	Days	7	£948,733	£0	-	£948,733
		Mobilisation	£57,236	Days	4	£228,944	£0	-	£228,944
B1.2.4.3	*Tug Transport - Jacket*	*Infield Operations*	£57,236	Days	16	£915,776	£0	-	£915,776
		Demobilisation	£57,236	Days	4	£228,944	£0	-	£228,944
		Mobilisation	£8,672	Days	4	£34,688	£0	-	£34,688
B1.2.4.4	*Barge Transport - Jacket*	*Infield Operations*	£8,672	Days	56	£485,632	£0	-	£485,632
		Demobilisation	£8,672	Days	4	£34,688	£0	-	£34,688
		Mobilisation	£57,236	Days	4	£228,944	£0	-	£228,944
B1.2.4.5	*Tug Transport - Topsides*	*Infield Operations*	£57,236	Days	30	£1,717,080	£0	-	£1,717,080
		Demobilisation	£57,236	Days	4	£228,944	£0	-	£228,944
		Mobilisation	£8,672	Days	4	£34,688	£0	-	£34,688
B1.2.4.6	*Barge Transport - Topsides*	*Infield Operations*	£8,672	Days	70	£607,040	£0	-	£607,040
		Demobilisation	£8,672	Days	4	£34,688	£0	-	£34,688
				Total (Excluding Contingency)					**£78,880,094**
				Pre-FID Contingency (%)				**30%**	**£1,957,500**
				Post-FID Contingency (%)				**30%**	**£21,706,528**
				Total (Including Contingency)					**£102,544,122**

PROJECT	Strategic UK Storage Appraisal Project	WELLS: COST SUMMARY
TITLE	SITE 7: BUNTER CLOSURE 36	
CLIENT	ETI	
REVISION	A01	
DATE	42341	

Well Cost Summary (including 30% Contingency)

Well Name	Days	Well Cost (£,000)
Year -2		
Appraisal Well	80.6	26687.5
Year 0		
Slant Injector 1	77.4	26637.5
Slant Injector 2	70.9	24562.5
Slant Injector 3	70.9	24562.5
Slant Injector 4	70.9	24562.5
Monitoring Well - Appraisal Tieback	0.0	0.0
Year 2		
Slant Injector 5	82.4	28137.5
Year 5		
Local Sidetrack 1	80.6	25300
Year 15		
Local Sidetrack 2	80.6	25300
Year 20		
Slant Injector 6	77.4	26637.5
Slant Injector 7	70.9	24562.5
Slant Injector 8	70.9	24562.5
Slant Injector 9	70.9	24562.5
Workover 1	32.5	10425
Year 22		
Slant Injector 10	82.4	28137.5
Year 25		
Local Sidetrack 3	80.6	25300
Year 35		
Local Sidetrack 4	80.6	25300
Year 40		
Abandonment Slant Injector 1	23.4	6750
Abandonment Slant Injector 2	16.9	4675
Abandonment Slant Injector 3	16.9	4675
Abandonment Slant Injector 4	16.9	4675
Abandonment Slant Injector 5	16.9	4675
Abandonment Slant Injector 6	16.9	4675
Abandonment Slant Injector 7	16.9	4675
Abandonment Slant Injector 8	16.9	4675
Abandonment Slant Injector 9	16.9	4675
Abandonment Slant Injector 10	16.9	4675
Abandonment Monitoring Well	23.4	6300
TOTAL	1378.9	450362.5

Note: This figure does not include the PM & Eng costs.

Drilling Overhead Cost Summary

Drilling Campaign	Overhead (£MM)
Well 1-4	2.70
Well 5	0.90
4 Rep. Wells	2.25
5th Rep. Well	0.90

OPEX Overhead Cost Summary

OPEX Campaign	Overhead (£MM)
Local Sidetrack 1	0.90
Local Sidetrack 2	0.90
Workover1	0.45
Local Sidetrack 3	0.90
Local Sidetrack 4	0.90

Wells Cost Estimate - Primary Cost Summary

Activity	Drilling Costs			Procurement Costs (£,000)		Total Cost (£,000)
	Phase Rig Cost (£,000)	Phase Spread Cost (£,000)	Contingency (£,000)	Procurement (£,000)	Contingency (£,000)	
Appraisal Well - CAPEX Breakdown						
Appraisal Well	6450	10625	4012.5	4700	1410	27197.5
Development Wells - CAPEX Breakdown						
Slant Injector 1	5950	9925	4462.5	6400	1920	28657.5
Slant Injector 2	5450	9175	4087.5	6400	1920	27032.5
Slant Injector 3	5450	9175	4087.5	6400	1920	27032.5
Slant Injector 4	5450	9175	4087.5	6400	1920	27032.5
Monitoring Well (Appraisal)	0	0	0	0	0	0
Slant Injector 5	6450	10925	4462.5	6400	1920	30157.5
Slant Injector 6	5950	9925	4462.5	6400	1920	28657.5
Slant Injector 7	5450	9175	4087.5	6400	1920	27032.5
Slant Injector 8	5450	9175	4087.5	6400	1920	27032.5
Slant Injector 9	5450	9175	4087.5	6400	1920	27032.5
Slant Injector 10	6450	10925	4462.5	6400	1920	30157.5
Wells - OPEX Breakdown						
Local Sidetrack 1	6200	10550	4650	3000	900	25300
Local Sidetrack 2	6200	10550	4650	3000	900	25300
Workover 1	2500	4600	1875	1000	300	10275
Local Sidetrack 3	6200	10550	4650	3000	900	25300
Local Sidetrack 4	6200	10550	4650	3000	900	25300
Wells - ABEX Breakdown						
Abandonment Slant Injector 1	1530	2970	1350	0	0	5850
Abandonment Slant Injector 2	1105	2145	975	0	0	4225
Abandonment Slant Injector 3	1105	2145	975	0	0	4225
Abandonment Slant Injector 4	1105	2145	975	0	0	4225
Abandonment Slant Injector 5	1105	2145	975	0	0	4225
Abandonment Slant Injector 6	1105	2145	975	0	0	4225
Abandonment Slant Injector 7	1105	2145	975	0	0	4225
Abandonment Slant Injector 8	1105	2145	975	0	0	4225
Abandonment Slant Injector 9	1105	2145	975	0	0	4225
Abandonment Slant Injector 10	1105	2145	975	0	0	4225
Abandonment Monitoring Well	1530	2970	1350	0	0	5850

	CAPEX Summary	Excluding Contingency (£MM)	Overhead (£MM)	Overhead Description	Sub-Total (£MM)	Contingency %	Contingency £MM	Total Cost (£MM)
A1.4.2	Appraisal Well (inc Procurement)	21.8	0.9	Well Management Fees. Insurance. Site Survey. Studies etc	22.7	30%	5.7	28.4
A1.3	Pre-FEED / FEED PM & E	2.0	0.2	Company Time Writing, IVB, SIT. Insurance etc	2.2	30%	0.7	2.86
B1.3.1	Detailed Design PM & E	2.0	0.2		2.2	30%	0.7	2.9
B1.3.2	Procurement	64.0	0		64.0	30%	19.2	83.2
B1.3.4	Construction and Commissioning (Drilling)	154.3	6.75	Well Management Fees. Insurance. Site Survey. Studies etc.	161.0	30%	44.4	205.4
	Total	244.0	0		252.1	-	70.6	322.7

OPEX Summary	Excluding Contingency (£MM)	Overhead (£MM)	Overhead Description	Sub-Total (£MM)	Contingency %	Contingency £MM	Total Cost (£MM)
OPEX	87.1	4.05	Well Management Fees. Insurance. Site Survey. Studies etc.	91.2	30%	21.7	112.8

ABEX Summary	Excluding Contingency (£MM)	Overhead (£MM)	Overhead Description	Sub-Total (£MM)	Contingency %	Contingency £MM	Total Cost (£MM)
ABEX	38.3	5.4	Well Management Fees. Insurance. Site Survey. Studies etc.	43.7	30%	13.1	56.7

Level 1 Cost Estimate Summary - Wells

	Total CAPEX (£MM)	322.69
C1.3	Total OPEX (£MM)	112.8
D1.3	Total ABEX (£MM)	56.7
	TOTAL (£MM)	492.3

Notes

1	Additional 1M added to allow for DTS procurement
2	Appraisal well no longer converted to monitoring well
3	Abandonment of Appraisal well assumed same as the abandonment of the monitoring well
4	Pre-FEED and FEED increased to £2M