CHAPTER 3
DEFINING THE STORE; GEOLOGICAL INTERPRETATION AND STORAGE MODELLING

Martin Smith*
David Lawrence
David McInroy
Alison Monaghan
British Geological Survey, Murchison House,
West Mains Road, Edinburgh EH9 3LA

Mike Edwards
Mark Naylor
School of Geosciences, Grant Institute,
University of Edinburgh, West Mains Road,
Edinburgh EH9 2JT

Jon Ford
Stephanie Bricker
British Geological Survey, Kingsley Dunham Centre,
Keyworth, Nottingham, NG12 5GG

**Corresponding Author*

3.1 INTRODUCTION

The identification of a suitable storage site for CO_2 is fundamental to a viable CCS methodology. In this chapter we describe a workflow for the process of identification, interpretation and geological modelling of a potential aquifer storage site.

The construction of a valid and testable geological model is an essential pre-requisite to carrying out any reservoir simulation of CO_2 flow and storage capacity modelling.

A well constructed model enhances confidence in the numerical simulations and monitorability assesment and importantly, also delivers a visual understanding of the sub-surface to the non-geologist.

Geologists visualise geology in 3D and previously have translated this onto 2D maps and sections. Modern technology now permits the routine construction of digital models at all scales and for these to be exported to other software packages. The construction of models based on limited data is, by necessity, open to multiple interpretation; and one of the key outcomes of our investigation has been to recognise the importance of the development and early application of a set of first response tools for geological interpretation and storage modelling. Use of this methodology and tool set should lead to best available data analysis, improved decision making and confidence in reservoir simulation (see Glossary for a full definition of terms used in this chapter).

3.2 WORKFLOW

Workflow design

The workflow (Figure 3.1), based around an asset team approach, was developed from an evaluation of the geological characterisation of two areas defined by the CASSEM project. The two areas (Figure 3.2) differ markedly in geological complexity, volume and quality of data and in potential environmental impacts (onshore vs near-shore), and thus provide complementary information for methodological development and contrasting outcomes and insights into aspects of CO_2 aquifer storage.

The geological modelling workflow described here encompasses site screening and selection, data acquisition, evaluation and compilation, leading to storage characterisation and the construction of 3D geological framework models. These models and data underpin primary estimates of (1) storage capacity and (2) the spatial behaviour of CO_2 and are applied to numerical simulations of dynamic flow and monitorability in Chapters 4 and 5. An additional aim has been to explore the quantification of uncertainty and improve our understanding of risk at each stage in the workflow (Chapter 6).

The workflow comprises four main stages separated by Evaluation/Decision gates (E/D G1 etc.) (Figure 3.1) that define a critical path approach to informed decision making. The use of E/D gates ensures that sufficient data are in place at critical stages, and, importantly, are visible to all members of the asset team. With a significant emphasis on the testing and validation in the early stages, this workflow aims to identify the key challenges early in the assessment process.

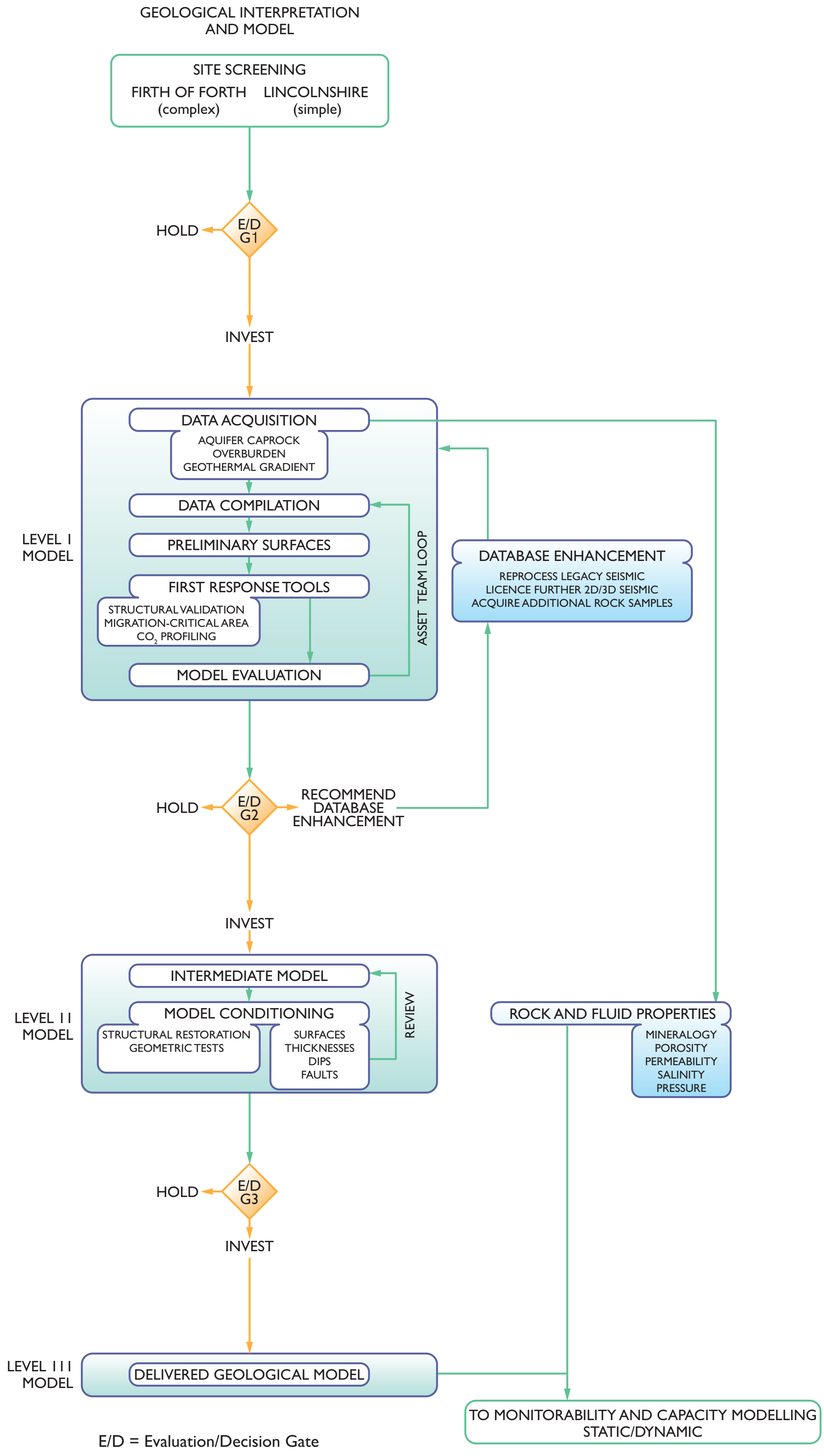


Figure 3.1 Workflow diagram for geological interpretation and modelling of a potential CO_2 store.

The four stages are:

- Site screening (geological scoping within the designated area; evaluate, rank and select potential sites based on agreed criteria).
- Level I: the basic geological model (data compilation, assessment, initial surfaces proposed and risk evaluated by the asset team, with iterative workflow loop between seismic-picking and geological interpretation via first response tools).
- Level II: the intermediate model (completed geological surfaces and faults, structural restoration, evaluation, migration and geometric testing).
- Level III: the high-level model (final geological model, attributed and validated).

The storage workflow builds on published methodologies and best practice, including Chadwick et al. (2008), the EU GeoCapacity project, and parallels the methodologies for '…the realisation of a CO_2 storage operation', as described as part of the CO2ReMoVe Project (Groenenberg et al., 2008). The steps outlined below broadly correspond, in part, to the basin-scale assessment and structural and stratigraphic modelling steps of Kaldi and Gibson-Poole (2008) and to the Phase 1 screening and part of Phase 2 site investigation of Groenenberg et al. (2008).

A key element to success and efficiency is the early establishment and resourcing of an asset team to complete a rapid analysis of data quality. Effective communication and feedback loops during initial model surface construction (Figure 3.1) are essential. As data and the models are progressively refined, they are delivered to other workflows (e.g. reservoir simulation and monitorability assessment), either at an E/D gate, if early assessment is required, or at the Level III geological model stage. Examples from the two exemplar sites of how the methodology works are presented below.

3.3 DATA AND WORKFLOW TOOLS

A wide range of commercial software tools are available to manipulate geological data and construct spatial 3D models. For the CASSEM project work, geological models were built using GOCAD® (Paradigm) and Petrel (Schlumberger) software. 2D and/or 3D baseline seismic data were rendered using Geographix® Seisvision, WellBase and Landmark™, and incorporated with other data from wells, fault pattern information, underground mine records and surface outcrops. The first response tools for geological interpretation and storage modelling implement features and algorithms of the commercial software suites: Move (Midland Valley Exploration Ltd) and MPath (Permedia Research Group Inc). Additional original code (termed CO_2 Depth Profile, University of Edinburgh) was compiled for specific tasks.

Other considerations: model equivalence

Where the geology is complex and/or interpretation of the data equivocal, then the final Level III model presented is but one representation of the available data. Other equally valid interpretations may be identified and result in parallel workflows for two or more other model outcomes. This model equivalence would commonly be identified during the Level I stage of initial risking and structural validation of surfaces but, theoretically, could occur at any stage.

Clearly, not all models of a single parent can be correct. Where there is no consensus on which is most likely, a quantification of uncertainty and risk should be allocated to each initial model. This is complicated by the fact that the risk metrics of each parallel workflow are not independent as they would be, for example, for competing, separate storage sites. Whilst acknowledging the issue of model equivalence, this is not discussed here.

3.4 SITE SCREENING AND GEOLOGICAL SCOPING

Initial site selection

A basic requirement for the subsurface storage of CO_2 is the identification of candidate porous saline aquifer formations (the hydraulic unit) at depths greater than c.800 m below mean sea level, with sufficient knowledge of the geometry and areal extent of the lithological and geomechanical properties of the aquifer, overburden, cap rock, and surrounding stratigraphies. Combined, these data permit calculation of potential storage capacity and predictions of CO_2 behaviour.

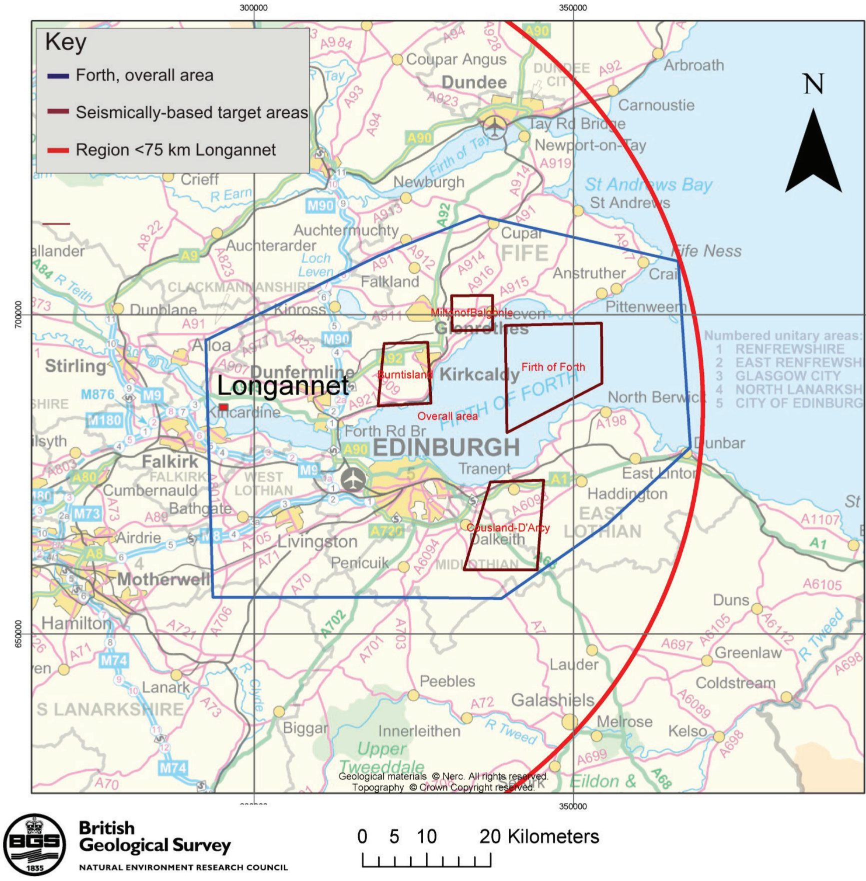
Using GIS functionality, the criteria for site selection (Table 3.1) are combined with an assessment of parameters (including tolerances on porosity, thickness, cap rock, capacity, etc) to be met by the modelling and sampling protocols. The sites can then be objectively scored and ranked, e.g. Bachu (2003). A ranking approach based on capacity and injectivity (e.g. Kaldi and Gibson-Poole, 2008) is beyond the scope of the workflow at this stage, although these metrics have pivotal roles elsewhere in the CASSEM project (Chapter 5). Risk strategies and parameterisation of input to a features, events and processes (FEP) register (e.g. Maul et al., 2004) is undertaken at this stage.

Criteria	Positive indicators	Cautionary indicators
Saline aquifer present	Salinity >100 gl -1	Salinity <10 gl -1
Aquifer depth	> 800 m <2500 m	<800 m >2500 m
Trap geometry exists		Accepted at start of workflow that no major trap structures exist
Caprock exists	>100 m thick	<20 m thick
Availability of geological data	3D seismic data, uniform coverage	Old 2D seismic data, variable coverage
Proximity to powerplant	<75 km	>100 km
Suitable porosity	>20%	<10%
Suitable permeability	>500 mD	<200 mD
Stratigraphy	Uniform	Complex lateral variation and complex connectivity
Aquifer volume	>100 m thick sandstone over 5.5 km^2 or for a 30m thick sandstone 10km^2	<20 m thick sandstone
Igneous rocks	An appreciation of their existence, geometry and effect on surrounding rock	Little knowledge of geometry and effect on surrounding rock
Containment	Knowledge of minimal routes to surface/high level from saline aquifer/ caprock – faults, boreholes, mineworkings etc.	Little knowledge of routes to surface, including faults and boreholes

Table 3.1 CASSEM initial area and site selection screening criteria

For CASSEM, saline aquifer targets were identified within a 75 km radius of two clusters of major CO_2 emitters: Drax/Ferrybridge (Lincolnshire) and Longannet/Cockenzie/Grangemouth (Firth of Forth) (Figure 3.2).

(a)



(b)

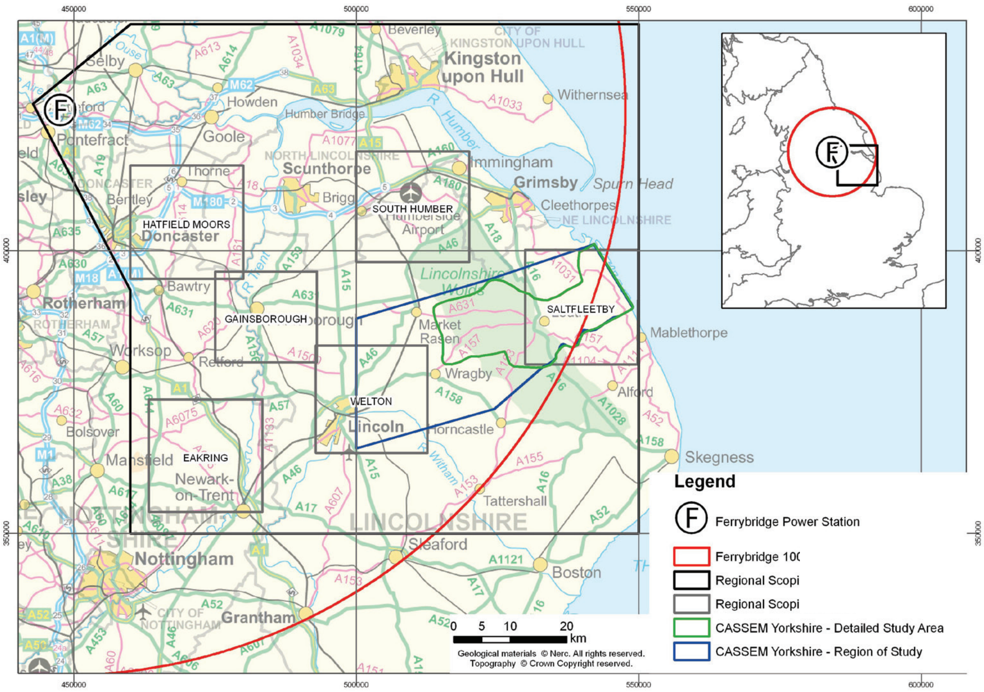


Figure 3.2 Location map for CASSEM target sites (a) Firth of Forth and (b) Lincolnshire

Firth of Forth – site screening

Targets within 75 km of the Longannet Power Station best matched to the CCS criteria extend around the Firth of Forth from West to East Fife and Edinburgh to East Lothian (Figure 3.2a). However, the area has relatively sparse, vintage 2D seismic data constrained by a single offshore well, and a complex stratigraphical sequence and structural pattern. The primary saline aquifer targets are the fluvial and aeolian sandstones of the Kinnesswood and Knox Pulpit formations of early Carboniferous to late Devonian age. The primary cap rock is the Ballagan Formation of Carboniferous age. Minor saline aquifers and seals occur throughout the overlying Carboniferous succession (Figure 3.3).

Whilst the primary target aquifer and cap rock meet some of the CCS criteria presented in Table 3.1, Cawley et al. (2005) concluded that the key stratigraphic targets for aquifer storage were less than ideal due to low to medium porosity (up to 20%), very low primary permeability and any secondary fracture permeability probably being too low at target depths for CCS storage. Nevertheless, in terms of aquifer volume and depth criteria, these rocks form the best saline aquifer target in the Midland Valley of Scotland and provide a potential test of Central and Northern North Sea scenarios for aquifers with complex structural traps and minimal hydrocarbon reserves.

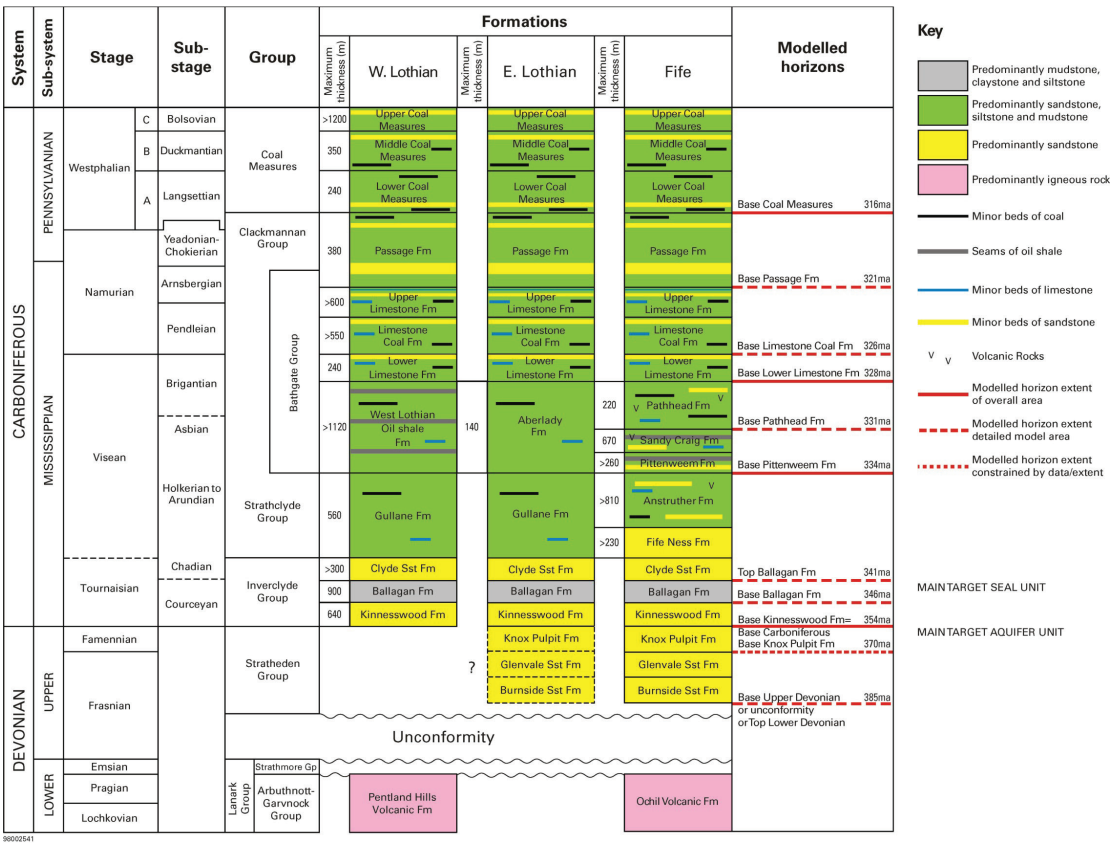


Figure 3.3 Simplified stratigraphy for the Firth of Forth site

Lincolnshire – site screening

The Lincolnshire area extends from Saltfleetby on the coast to Lincoln in the west (Figure 3.2b). In contrast to the Firth of Forth, this area has abundant modern, good quality data (2D and 3D seismics, wells and core samples) that describe a relatively simple and predictable eastward dipping geological succession with limited structural complexity. The primary target saline aquifer in this area is the Sherwood (or Bunter) Sandstone Group (SSG) and the corresponding cap rock is the Mercia Mudstone Group (MMG), both of Triassic age (Figure 3.4). A secondary target saline aquifer/ cap rock pair exists at greater depth, as represented by the sandstone-dominated Permian Rotliegendes Group sealed by the Marl Slate, Cadeby and succeeding evaporite rich cap rock formations.

Period	Geological Unit	Age (Ma)	Saline aquifer/ caprock/ overburden classification	Approximate depth below ground level at Saltfleetby
Cretaceous	Upper Cretaceous (Chalk Group)	90	Primary overburden	Base = 180 m (not modelled)
	Lower Cretaceous	100	Primary overburden	Base = 200 m (not modelled)
Jurassic	Upper Jurassic	151	Primary overburden	Base = 560 m (not modelled)
	Middle Jurassic (inc. Lincolnshire Limestone Fm)	164	Primary overburden	Base = 600 m (Top Lincolnshire Limestone modelled)
	Lower Jurassic (Lias Group)	179	Primary overburden	Base = 860 m (not modelled)
Triassic	Penarth Group	200	Primary overburden / caprock	Base = 870 m
	Mercia Mudstone Group	204	Primary caprock	Base = 1160 m
	Sherwood Sandstone Group	242	Primary saline aquifer	Base = 1490 m
Permian	Roxby Formation Equivalents	251	Primary bottom caprock	Base = 1560 m
	Brotherton Formation	253	Secondary overburden	Base = 1600 m (not modelled)
	Edlington Formation Equivalents	254	Secondary overburden / caprcock	Base = 1775 m
	Cadeby and Marl Slate formations (undifferenti-ated)	256	Secondary caprock (see details)	Base = 1780 m
	Rotliegendes Group	258	Secondary saline aquifer	Base = 1840 m
Carb.	Pennine Coal Measures Group	307	Underlies modelled succession	Base =2360 m (not modelled)

Figure 3.4 Simplified stratigraphy for the Lincolnshire site

These saline aquifer and seal pairs meet many of the selection criteria, with the major exception being that there are no significant structural traps. This site provides an opportunity to study dynamic trapping within a key target aquifer, the Sherwood Sandstone Group, with offshore equivalents in the southern North Sea that represent major oil and gas reservoirs with substantial saline aquifer potential (DTI 2006).

The Lincolnshire area is also important in that it includes the onshore continuation of a major offshore aquifer that is exploited for other human activities. As the geological succession is traced westwards and up-dip (Figure 3.5), the aquifer is utilised extensively for water abstraction. This presents an opportunity to examine the impact of CO_2 injection pressure effects on ground and surface water systems. At the outset, this was perceived as a significant risk. A hydrogeological model (Bricker et al., 2010) was produced (Case Study 2 below) and the results integrated with the dynamic flow simulation modelling (Chapter 4).

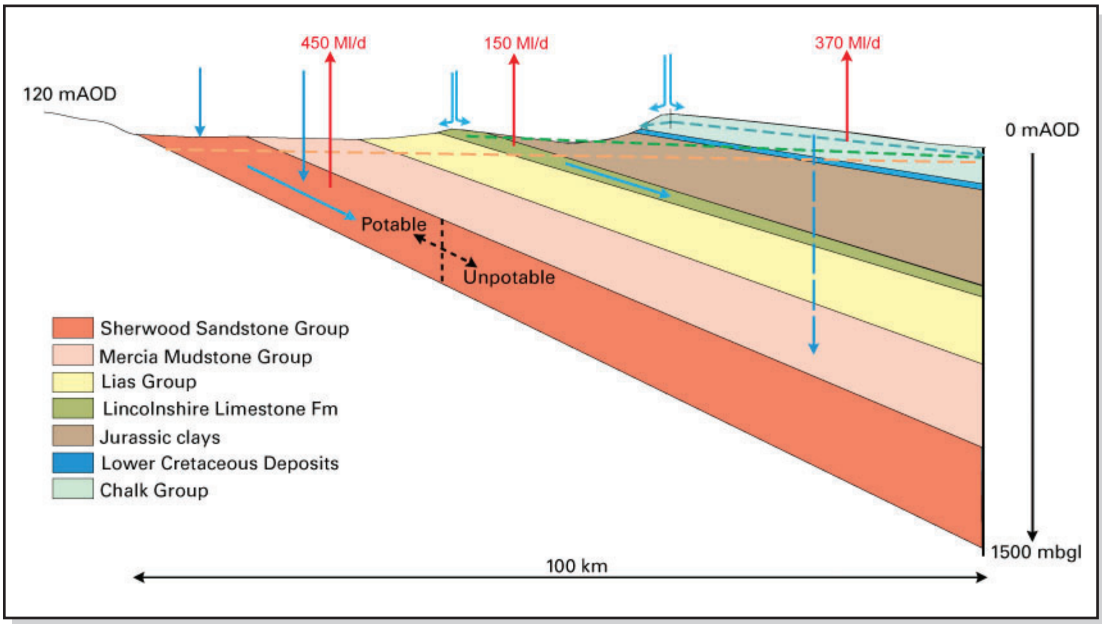


Figure 3.5 Schematic geological cross-section (west to east) of the Lincolnshire study area with regional groundwater flow and abstraction. Abstraction from the Sherwood Sandstone Group is approximately 85% unconfined, 15% confined. Blue arrows represent the flow of recharge, red arrows are abstraction in megalitres per day (Ml/d).

3.5 EVALUATION-DECISION GATE 1 (E/DG1)

At this gate an assessment and ranking of the target sites is carried out. This process should include an assessment of the uncertainty and potential challenges presented by the geology to inform data acquisition and best approach to modelling.

Geological knowledge, data availability and approximate depth to the saline aquifer/cap rock and presence of a structural trap (Firth of Forth only) are the key variables to enable an area to be selected for initial modelling. In summary, both CASSEM sites satisfy the basic geological criteria (Table 3.2) and provide sufficient data desirable for an initial characterisation exercise relevant to basin-scale assessments. They do, however, fall short on the requirements (e.g. 3D seismic data) for full site characterisation and prospective storage capacity, as described by Kaldi and Gibson-Poole (2008).

Criteria	Forth. Primary saline aquifer/cap rock (Knox Pulpit; Ballagan)	Forth. Minor aquifer/seal (e.g. sand bodies in Lower Carboniferous)	Lincs. Primary aquifer/seal (Sherwood Sstn./Mercia Mudstone)	Lincs. Secondary aquifer/seal (Rotliegendes/ Cadeby Marl Slate)
Saline aquifer present	Not known	Not known	Not known	Not known
Saline aquifer depth (elevation of top surface)	Ranges from -1300 to -3000 m OD in parts of the study area with anticlinal traps. Synclinal areas deeper. Comes to outcrop at margins of overall area.	Lower Carboniferous ranges from -400 to -2000 m OD in parts of the study area with anticlinal traps. Synclinal areas deeper. Comes to outcrop within overall area.	Ranges from 700 to -1555 m OD; < -800 m in 60% of the region of study	Ranges from -860 to -1955 m OD; i.e. all < -800 m in the region of study
Trap geometry exists	Several anticlinal trap structures identified	Several anticlinal trap structures identified	Not identified in region of study	Not identified in the region of study
Cap rock exists	Cap rock thought to be present in all areas south of Ochil Fault system, likely >100 m thick	Mudstone/siltstone 'seal' present throughout variable character overburden	Seal >200 m thick, locally transitional base	Cap rock>100 m thick over 40% of the region of study (CDFu + EDT)
Availability of geological data	Patchy, variable quality 2D seismic data with no well control at saline aquifer/ cap rock level	Patchy, variable quality 2D seismic data with limited well control	Good 3D seismic data in part	Good 3D seismic data in part
Suitable porosity	Up to 26% (Milodowski & Rushton, 2008)	Up to 17% (Passage Fm, Milodowski & Rushton, 2009) but very limited data	25% (approximate)	16% (approximate)
Suitable permeability	Mean 70-80 mD assumed, some up to 1000 mD, from previous work	Permeability not yet known	Limited knowledge assumed 500 mD	Permeability not known at time of E/DG1 (later HWU results gave permeability)
Stratigraphy	Likely lateral variability of aquifer rock types. Cap rock shows some lateral variability but moderately well known.	Likely lateral variability of aquifer rock types. Seals likely more continuous.	Uniform aquifer and seal	Fairly uniform saline aquifer, variable seal

Table 3.2a Summary of geological evaluation at E/DG1 for CASSEM sites

Saline aquifer volume	Assume >150 m thick sandstone for Knox Pulpit Fm over part of area and Kinnesswood Fm >100 m over whole area	Volumes of minor aquifers likely to be very small as maximum thicknesses of c.20 m and lateral extent not known.	>170 m thick sandstone throughout region of study	>40 m thick sandstone over approximately 200 km^2, >60 m thick sandstone over 150 km^2, >80 m thick sandstone over approximately 15 km^2,
Igneous rocks	Commonly cross-cutting in study area, geometry poorly defined	Commonly cross-cutting in study area, geometry poorly defined	Not identified in the region of study	Not identified in the region of study
Containment	Risks to containment include existing boreholes/wells, faults of unknown character, routes provided by igneous bodies	Risks to containment include existing boreholes/wells, faults of unknown character, routes provided by igneous bodies	Locali sed clusters of deep hydrocarbon wells	Localised clusters of deep hydrocarbon wells

Table 3.2b Summary of geological evaluation at E/DG1 for CASSEM sites

3.6 BUILDING THE GEOLOGICAL MODEL – LEVEL I

Construction of the Level I model is a key step in the workflow. It involves the compilation and assessment of the available data, followed by a series of iterative steps and feedback loops. These deliver a preliminary interpretation, test the validity and suitability of the geological data (Figure 3.1) and identify any shortcomings in data quality and sufficiency. The asset team will then make recommendations on dataset enhancement (e.g. is reprocessing of seismic data beneficial or necessary?) at the decision gate (E/DG2).

Data acquisition

For each selected site all publicly available geological data, including seismic data, underground mining, borehole, well data, isopach and sub-crop maps should be acquired, assessed and compiled in GIS format, and key datasets licensed and prepared for preliminary analysis using appropriate software (e.g. Geographix® Seisvision, WellBase and Landmark™). Combined with knowledge of the regional geological framework and local geological expertise, preliminary stratigraphic surfaces can be generated to honour geological reference points, e.g. wells, outcrop and seismic data. These geological surfaces are then assessed and gaps in seismic data and quality addressed by licensing and purchase of additional infill data.

Rock and fluid property data

All rock and fluid property data, including mineralogy, porosity, permeability, petrophysical metrics (e.g. Young's modulus, Poisson's ratio, etc.) and in situ metrics (e.g. fluid salinity, pressure and temperatures, and the historic and modern stress field) for key horizons, including target aquifer and cap rock, should be compiled and combined with a listing of rock sample availability from existing drill cores obtained during ground investigation (e.g. for coal, geothermal, oil and gas).

Where drill core material and/or well coverage is sparse, other regional drill core and surface outcrops may be a significant supplement providing (1) indications of vertical and lateral lithological heterogeneity in the geological model, (2) reservoir simulations and capacity estimates with information on stratigraphic architecture where heterogeneity is below the resolution of the main model, and (3) analogue samples for laboratory analysis.

Firth of Forth – data acquisition

In the example of the Firth of Forth, the geological framework and model is based on an interpretation of third-party 2D seismic data, limited downhole borehole/well data, subsurface mining data and BGS onshore mapping (Figure 3.6). At the depth of interest, the configuration of the proposed store is poorly constrained by the available data. Only the BGS Glenrothes borehole (Brereton et al., 1988), onshore in the north of the area, reached the target aquifer, the Knox Pulpit Formation. No boreholes penetrate the target aquifer or cap rock in the favoured sites, introducing considerable uncertainty in the geological interpretation. Five wells, shown in Figure 3.6, provide accessible time-depth information and were used in controlling the position of seismic picks; all of the wells terminate above the Ballagan Formation cap rock. Borehole core samples were collected from the Glenrothes borehole where the primary saline aquifer/cap rock are at depths >200 m, with additional primary saline aquifer/cap rock material from shallow depths (<70 m) and from outcrop.

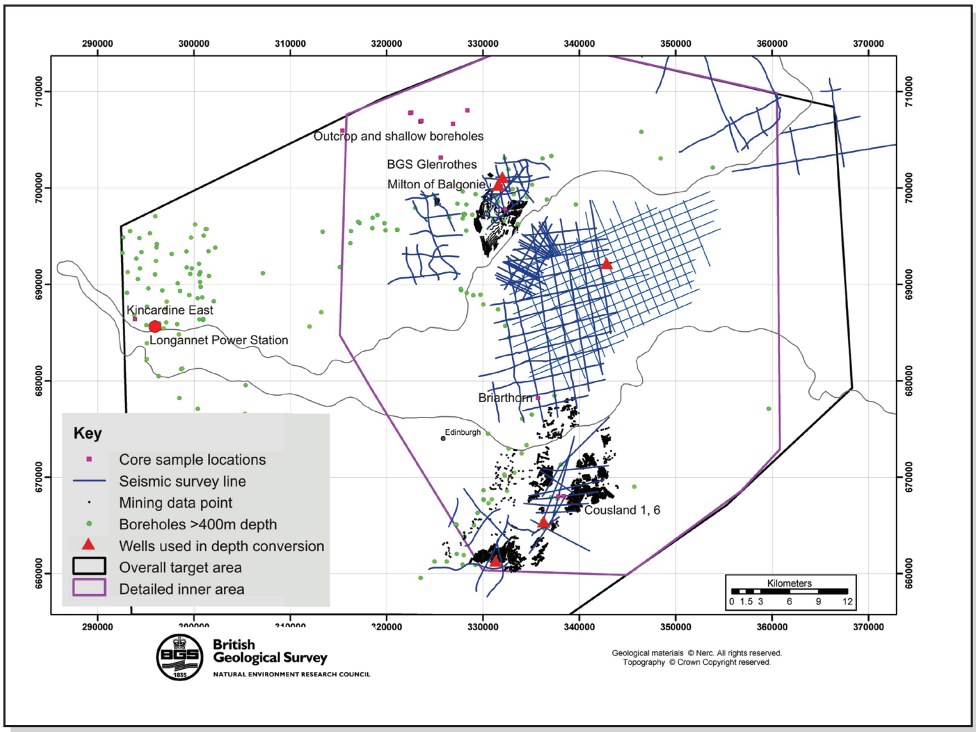


Figure 3.6 Data types and distribution in the Firth of Forth

Lincolnshire – data acquisition

In contrast, in the example of Lincolnshire, a data-rich site, the geological framework and model is based on an extensive interpretation of good-quality third-party 2D and 3D seismic data, geological borehole/well data and existing BGS geological mapping (Figure 3.7). The seismic picks were controlled using well data and mapped surface outcrop. Eighteen wells were used to depth-convert the geological horizons and faults.

In general, the wells penetrated through the entire Permo-Triassic succession to terminate in the underlying Carboniferous rocks. Borehole core samples were provided from the BGS Cleethorpes No.1 borehole (Downing et al., 1985) where the primary aquifer and secondary saline aquifer/cap rock were at depths from 1100–1190 m. Additional core material, including that from the primary cap rock, was available from boreholes of shallower depths to the west of the modelled area.

Asset team loop: data compilation, first response tools and initial model evaluation

After integration of known fixed points (e.g. well ties and, if near-shore, surface outcrop and mine maps), interpretation of seismic data allows preliminary surfaces and faults to be proposed and risk assessed (Chapter 6). These initial surfaces are built using a standard interpolation workflow in a package such as GOCAD (e.g. Ford et al., 2009b) or Petrel. For efficiency, seismic interpretation typically selects conspicuous surfaces that are then auto-picked into weaker signal portions with additional mimicking algorithms into deeper or shallower horizons. While still in the preliminary stage, some or all of the surfaces are tested using the first response tool set that was developed during the CASSEM project.

These tools address three key areas: (1) structural validity, (2) surface regions and pathways for CO_2 migration, and (3) depth critical regions for CO_2 phase behaviour:

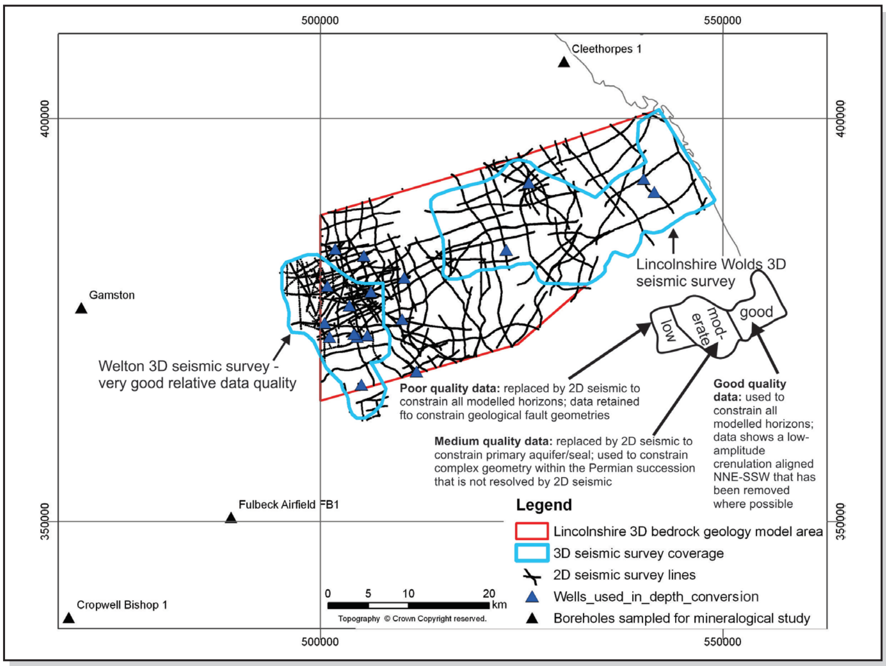


Figure 3.7 Data types and distribution in Lincolnshire

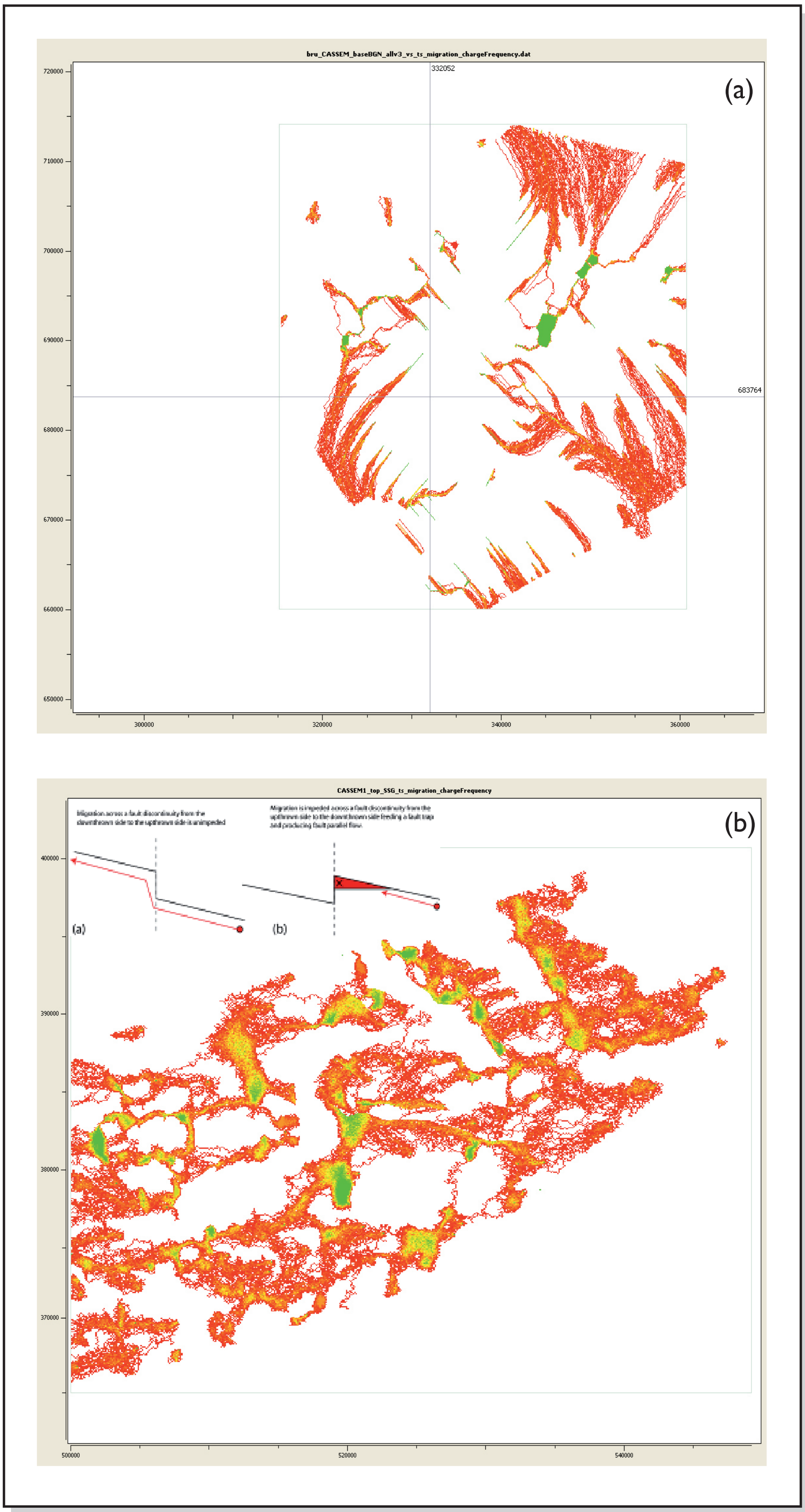


Figure 3.8 Mpath Single Map Migration output for saline aquifer/cap rock boundary based on 100 simulations with 20 iteration (±10 m uniform uncertainty) per well; wells represented as single dots: (a) Firth of Forth, base of Ballagan Formation showing structural traps (green polygons) and predicted CO_2 migration pathways (red polygons); (b) Lincolnshire, top of Sherwood Sandstone Group – green polygons identify structural highs and linear patterns identifying NW–SE trending faults.

(1) Structural validation used 2D-Move (Midland Valley Exploration Ltd) and provides a key early test where structural complexity is present. Indicators of structural complexity are: major faults (i.e. faulting with displacements >15% of the fault length at the slip-surface mid-point), folds with large amplitudes, or multiple fold sets with differing geometries. Precise structural validation is a lengthy iterative process (see Level II below); an initial quick test of whether preliminary surfaces are geometrically viable is the aim here. This validation is achieved through either reverse modelling ('restoration') techniques or forward modelling of a simple initial geometry (e.g. horizontal layers). Both invoke a suite of algorithms that describe deformation of rocks. Portions of the preliminary surfaces which are geometrically invalid or where there is large uncertainty, i.e. where minor differences in position or geometry would have a large impact, are highlighted.

(2) Pathways for migration of buoyant CO_2 below the seal of the target aquifer may be assessed using a single map migration technique such as Mpath (Permedia Research Group Inc). This geometric technique samples preferential migration directions for the surface investigated. Multiple (typically tens to hundreds) up-dip migration simulations, subjected to stochastic uncertainty, are run for a range of injection points to reveal likely migration pathways and traps. This provides an early opportunity to target further data collection activities in regions where CO_2 is likely to migrate, to integrate subsurface geometry and uncertainty, and identify likely target sites for injection wells.

Examples of the contrasting style in predicted migration directions of buoyant CO_2 between the two case study areas are shown in Figure 3.8. A relatively homogeneous dispersal pattern is predicted for Lincolnshire whilst the Firth of Forth displays a strong heterogeneity. The absence of an obvious structural (static) trap is a notable feature of the Lincolnshire saline aquifer site. Of interest in this study are the numerous (20–50) small structurally high areas ('traps') that are filled (up to 'spill') by the ongoing CO_2 flux that further enhances the 3D reservoir architecture dynamic trapping.

(3) Reservoir modelling and monitoring also requires an assumption or prediction of the density, viscosity and solubility of CO_2 under initial depth conditions. For example, does the adoption of the depth criteria (i.e. >800 m depth below mean sea level) for a uniform phase change guarantee that CO_2 remains in the dense phase as it migrates? Where geothermal and hydrostatic gradient data allow, using CO_2 Depth Profile (Dr. M. Naylor and University of Edinburgh) indicates where simple or complex multiphase behaviour is likely. For preliminary model surfaces with significant uncertainty that encompass critical depth regions, this tool will highlight regions where further work is required to improve data quality, confidence and interpretation.

This suite of initial tests allows the asset team to respond with a spatial re-evaluation and reinterpretation as a feedback loop around the Level I workflow. After a series of iterations, depending upon structural complexity and data quality, a Level I 3D model can be defined, comprising a series of interpolated digital surfaces (geological layers and some faults), or recommendations made for further database enhancement before a model can be built.

3.7 EVALUATION - DECISION GATE 2 (E/DG2)

At E/D2 the geological model is considered for an invest or hold decision and may be ranked against alternative storage sites identified by the client/operator. In the case of less favourable ranking, the asset team may make recommendations for database enhancement. Implementation of these recommendations forms a key part of a broader cost-risk-invest business decision.

At this stage, the preliminary Level I model may be released to inform planning and decisions on approaches to capacity modelling and monitorability. Similarly, a coarse static capacity estimate (see Jin et al. (2010) may be included to further advise the invest/hold decision.

Firth of Forth

From the initial work at the Firth of Forth site an assessment of the model results against basic geological criteria (Tables 3.1 and 3.2) indicates that over much of the investigated area, the saline aquifer/cap rock depth, trap geometry, distance from power plant, and porosity, all positively meet the geological criteria with relatively high confidence. Known complexity of stratigraphy, presence of igneous rocks, existing permeability measurements and containment issues negatively meet the geological criteria. Critically, the existence, thickness and volume of the saline aquifer/cap rock and salinity are unknown due to the lack of well data at appropriate locations. On this basis, the Firth of Forth site would be negatively ranked and held at E/D Gate 2. However, in order to further test the workflow, this site was progressed through to the Level II intermediate model with the Forth Anticline as the target recommended for further study.

Lincolnshire

In contrast, the Lincolnshire area has relatively simple and predictable geology and good data coverage (Table 3.2). The modelled horizons for the Lincolnshire site could be built with a greater degree of confidence and show a simple easterly dipping succession of layered strata cut by a series of relatively minor faults. Recognised issues with minor fault displacements and differing permissible options for fault continuity were considered to have only minor effects (Ford et al., 2009). Lincolnshire was cleared for advancement at E/D Gate 2 by all of the first response tools, with no major recommendations for data enhancement.

CASE STUDY 2: DATABASE ENHANCEMENT, FIRTH OF FORTH

Many of the potential offshore storage targets for UK CCS are covered by relatively old seismic data acquired during the early days (1970s and 80s) of hydrocarbon exploration and licensing. Modern reprocessing techniques now offer the opportunity to improve poor quality data, and confidence in data interpretation and the geological model. As part of the CASSEM methodology, a reprocessing test was performed on a grid of original offshore 2D seismic data with modern industry-standard (Schlumberger) processing techniques.

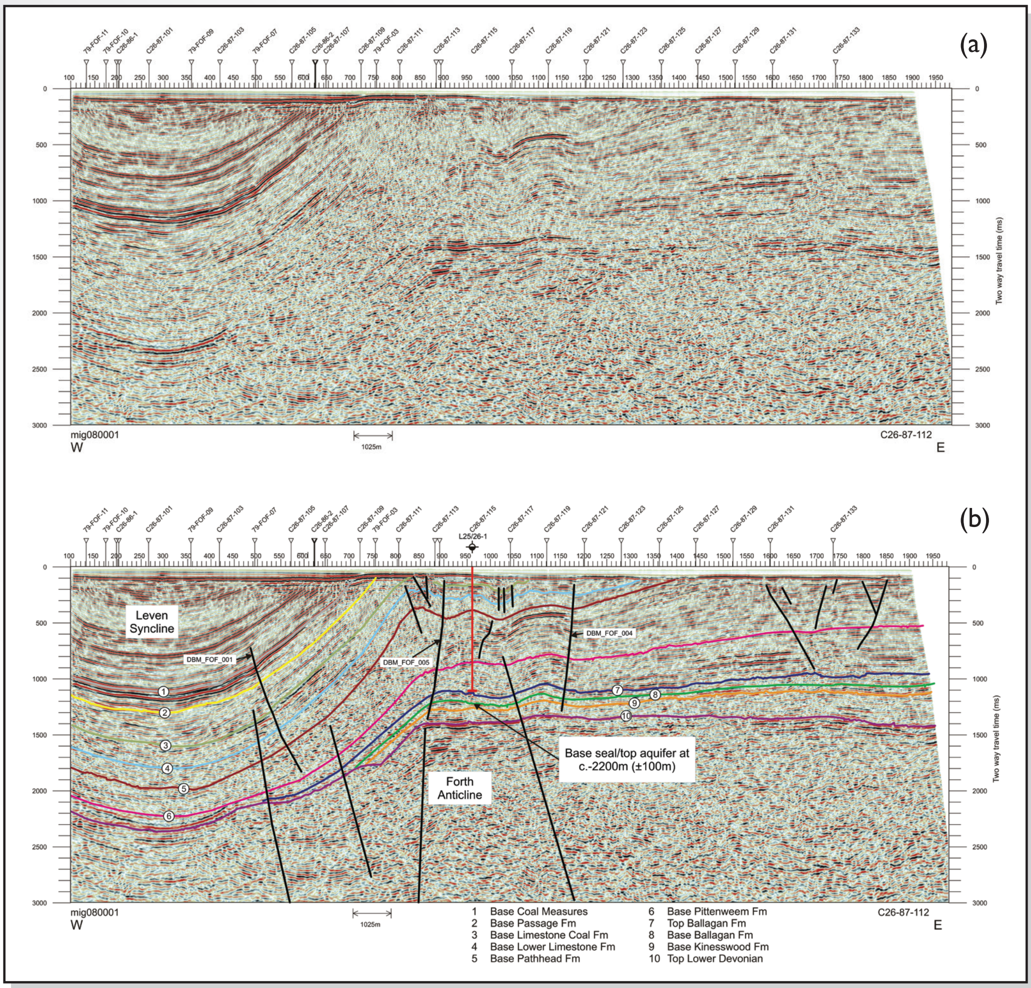


Figure 3.9 Example of the best seismic data from the Firth of Forth area. Line C26_87_112 oriented SW–NE through the Forth of Forth-1 (25/26-1) tied well. Shown with permission of Phoenix Data Solutions: (a) primary data and (b) interpreted geology and regional structure. Only the labelled faults were included in the 3D geological model.

In the Firth of Forth, the geological succession is folded into a series of NNE- trending anticlines and synclines and cut by steep to vertical faults of varying orientation (e.g. Figure 3.9). First response tool analysis highlighted an unsatisfactory compromise in the interpretation of the seismic data, most critically in the Leven Syncline with a 'downlap' scenario with multiple pinching out of units at the saline aquifer/cap rock level. This is important as the catchment area within the trap is interpreted to be limited. Up-dip single map migration runs (assuming buoyant CO_2 behaviour) for a range of stochastic uncertainties and wells showed dramatic tendency for migration away from the target antiformal structural trap (see Figure 3.8a). In addition, the irregular discontinuous nature of some of the key stratigraphic horizons was initially interpreted as due to faulting. Much of this faulted data is located around the Forth Anticline on the eastern side of the Leven Syncline, which was predicted to host the target aquifer within the critical depth interval.

Database enhancement was recommended. Reprocessing of the 2D seismic data set comprised 30 lines totalling approximately 500 km. The technical details, described in Sansom (2009), involved pre-stack noise attenuation, pre-stack demultiple, offset migration and post-stack processing.

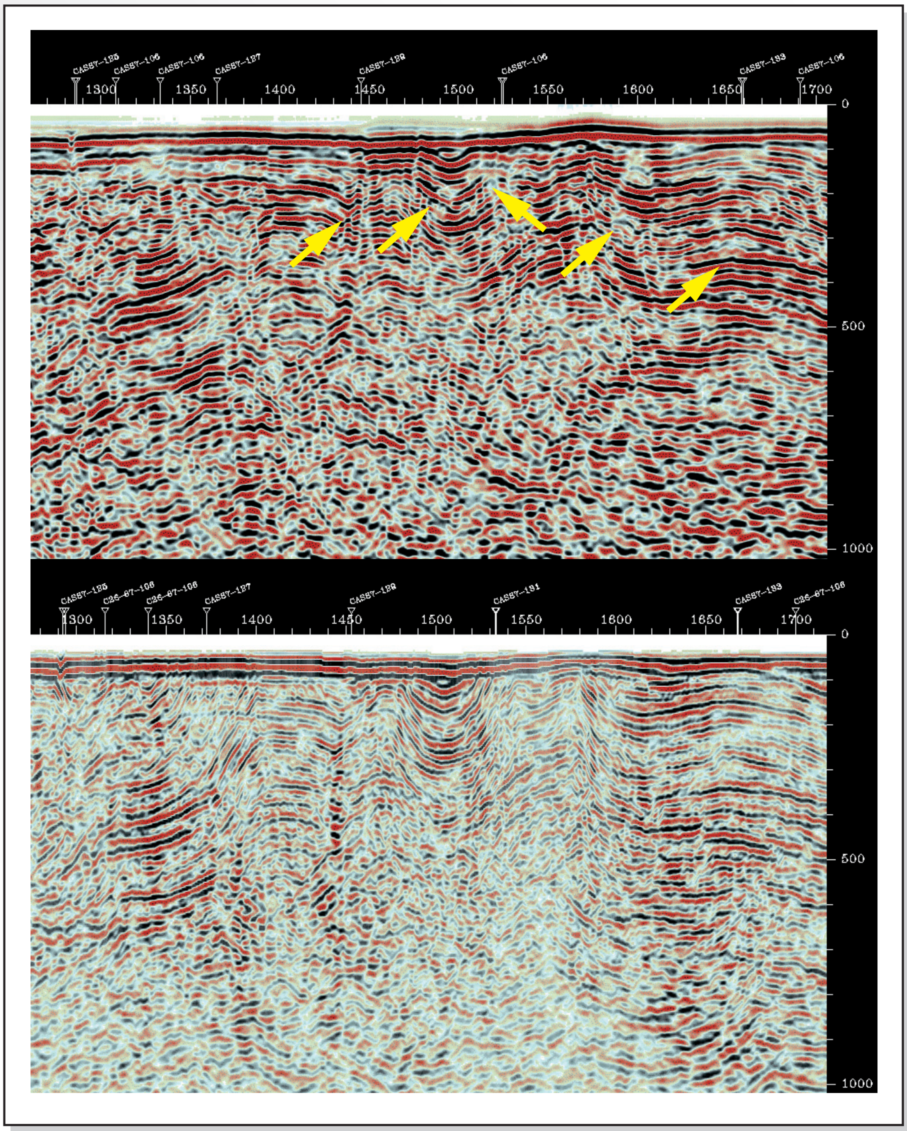


Figure 3.10 Example of original seismic data (top) compared to reprocessed data (below) for part of Conoco 87 Line 106, showing the improvement in the imaging of a series of near-surface folds. The poorly imaged folds in the original data were previously, and incorrectly, interpreted to be a series of faults (highlighted by yellow arrows). Vertical scale is TWTT (Two Way Travel Time) in milliseconds.

Interpretation of the reprocessed data (McInroy and Hulbert, 2010) revealed the following:

- Areas with incoherent reflectors in the original dataset, often interpreted to be faults, now revealed as coherent steeply dipping and tightly folded reflectors. Several faults were removed from the original interpretation (Figure 3.10).
- Better imaging in the trough of the Leven Syncline led to reinterpretation of seismic picks and corrected geological interpretation from lateral pinch-outs to through-going (sub)parallel synformally folded layers.
- Change in depth of key picks over the Forth Anticline (up to 200 m upwards) and the Leven Syncline (up to 1000 m downwards) (Figure 3.11).
- Removal of many of the deep reflections (artifacts?).

This work clearly illustrates the added value and cost benefit that early reprocessing brings to confidence in geological interpretation.

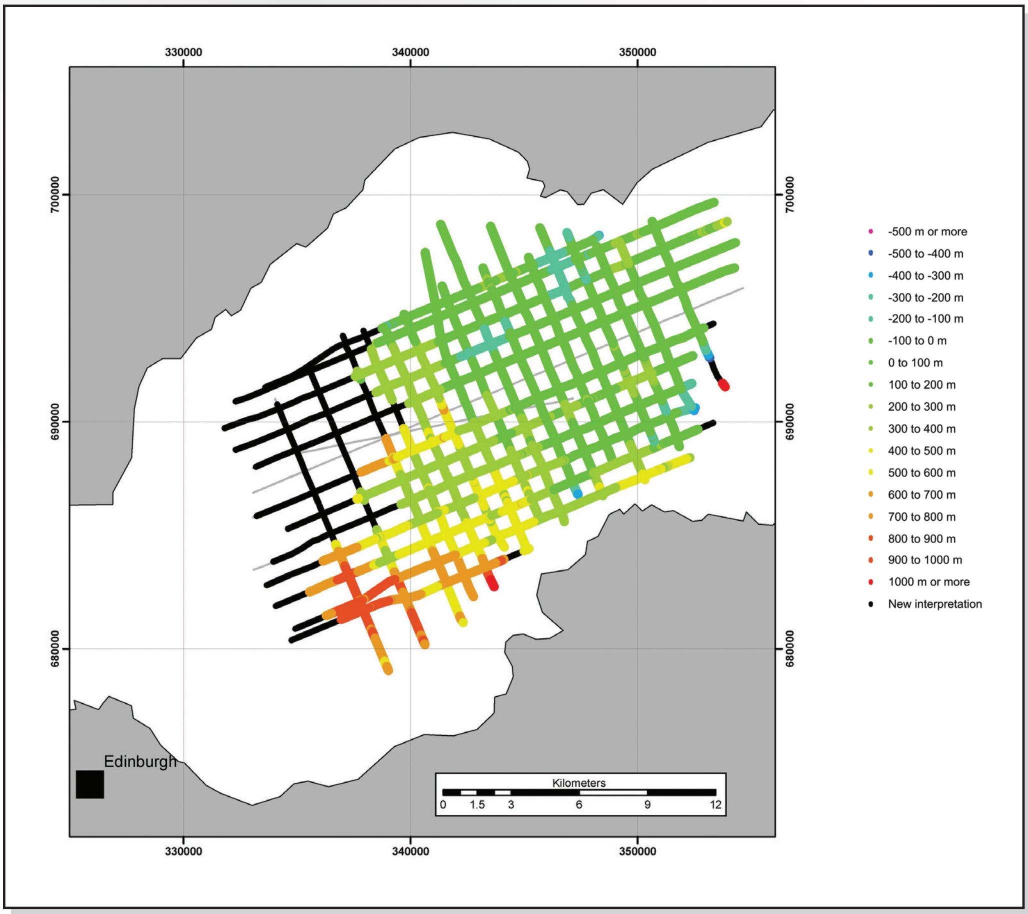


Figure 3.11 Example of difference between original and reprocessed interpretations of depth difference to base of the Ballagan Formation (cap rock).

3.8 BUILDING THE GEOLOGICAL MODEL - LEVEL II

Level II Model

At this stage a full geological model is constructed comprising key stratigraphical surfaces and faults of the target saline aquifer and cap rock and surrounding stratigraphies. Model conditioning includes further application of structural restoration techniques and geometric tests on the surfaces.

Depending upon the degree of structural complexity, there may still be significant changes to local elements. For example, where faults are associated with large displacements and/or more intense surface curvature, then limiting their position at depth is problematic. This requires best estimates of thickness, dip and fault geometry. Confidence in surface curvature is also the starting point for strain analyses and modelling of discrete fracture networks. MPath may also be redeployed at this stage for locating injection wells in the reservoir simulations (Chapter 5).

The two CASSEM project sites provide contrasting illustrations of this workflow stage.

Firth of Forth Level II model

The data, construction methods and limitations of the full 3D geological model are described in Monaghan et al. (2008b). Representative images are shown in Figure 3.12.

Model limitations include:

- Scale of use 1:250,000 to 1:50,000, locally higher in certain areas.
- Igneous intrusions and vents not modelled.
- In target storage area, no wells reach suitable depths and saline aquifer/cap rock location is highly uncertain: constrained by geologists' interpretation only.
- Faults are generalised as discrete planes of movement; in reality, they typically occur as complex zones of deformation and brecciation, including multiple fracture surfaces, and may act as a barrier (if sealed) or a pathway (if open) for fluid migration.
- Complex sub-seismic stratigraphy (e.g. alternating, interleaving mud and shale layers) in reservoir and cap rock are indicated in neighbouring area well logs.

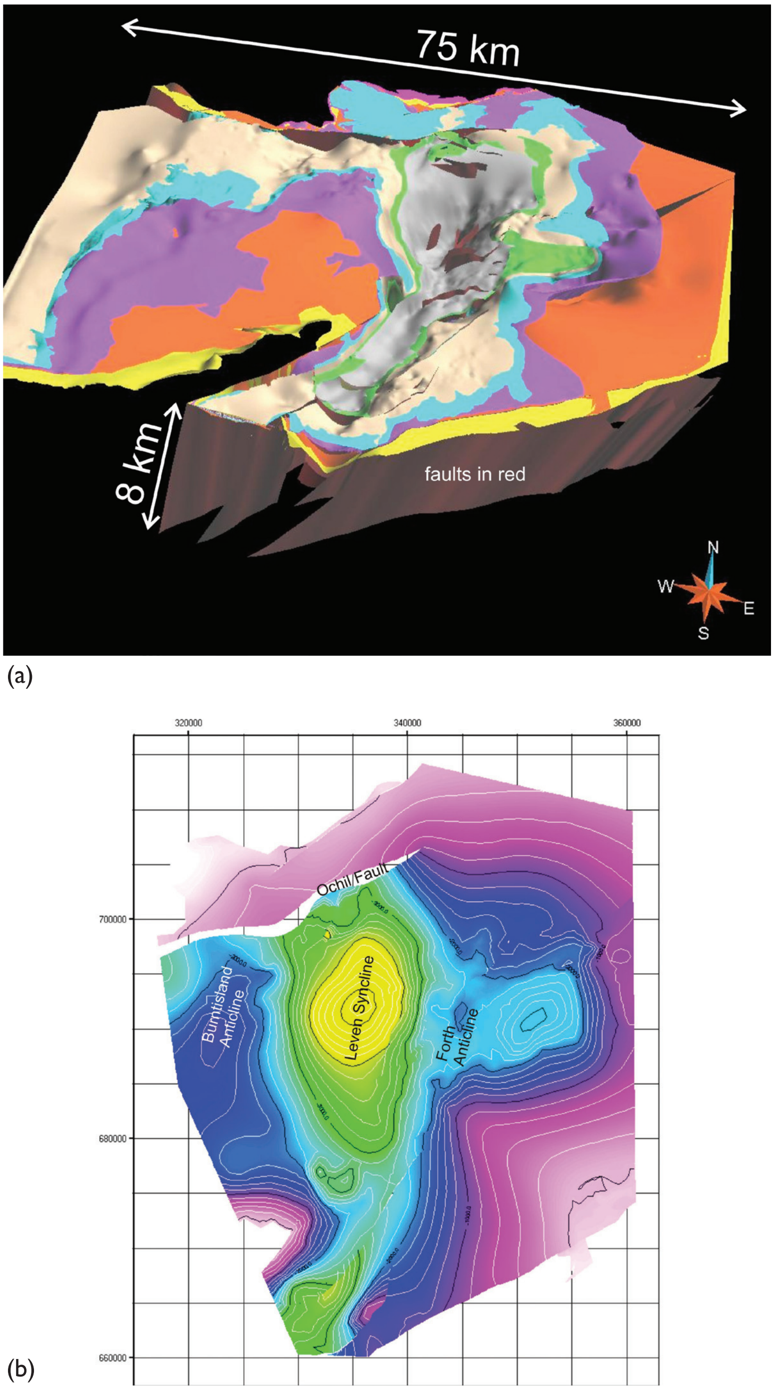


Figure 3.12 (a) Level II 3D geological framework model for Firth of Forth; (b) Contour map plot of the base Ballagan Formation (base cap rock/top saline aquifer).

Figure 3.12 illustrates the Midlothian-Leven Syncline structure (black contours every 1000 m, so deepest part of syncline: 5200 m) and the Forth and Burntisland anticlines.

The Firth of Forth level II model was significantly revised following the reprocessing of legacy seismic data (Case Study 2 above). Conditioning and validation of the complexity present in the new model included revising surface curvature and reducing uncertainty in the depth and position of surfaces by applying unfolding and backstripping techniques.

Unfolding

As the Firth of Forth folds are modelled as concentric structures affecting the complete geological succession, then a flexural slip unfolding algorithm can be applied to validate the model. The algorithm works on the limbs of a fold by de-rotating them back to a horizontal datum (reference line in 2D, a surface in 3D) or an assumed regional reference line/surface and then removes the displacements between the separate rock layers.

Backstripping

Backstripping is a commonly applied reverse modelling technique that tests the relationship between variations in sediment thickness and timing of movements on individual faults within a geological section. It effectively steps backwards in time, sequentially removing the current uppermost rock layer for the given period, migrating the corresponding lower layers upwards and applying various corrections (for decompaction and isostasy). In the Firth of Forth model where these surfaces no longer exist (i.e. eroded away), they were reinstated above the present day surface, honouring the geometry of the geological structure preserved at depth (see difference in Figure 3.13a, b and c). This tested for and excluded the complication that the folding which formed the Leven Syncline occurred during the main sedimentation (Carboniferous).

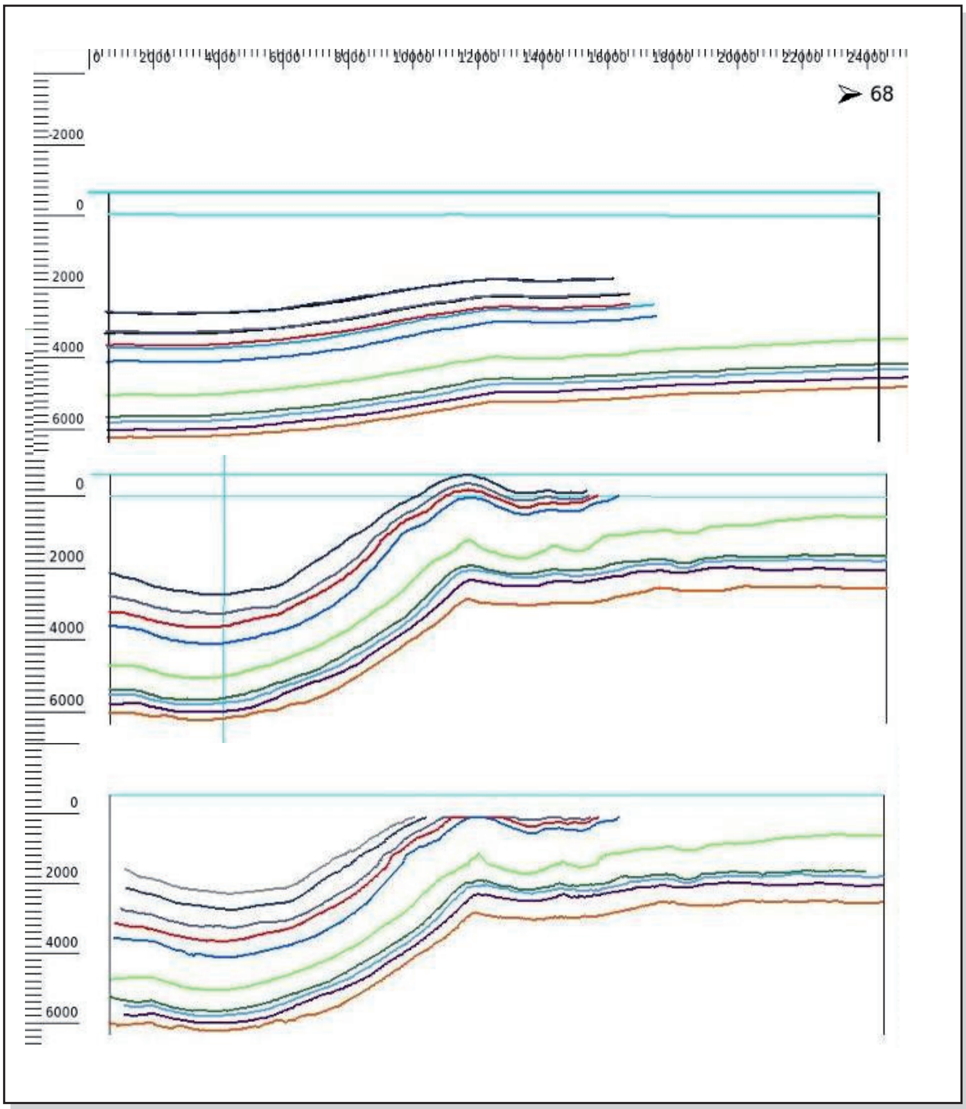


Figure 3.13 Example from bottom to top of (a) smoothing, (b) eroded surface rebuilding and (c) 80% flexural slip unfolding to -6000 m datum about a 05 degree SW pin line in the Leven Syncline, as applied to Firth of Forth modelled surfaces. Backstripping model validation not shown.

Lincolnshire level II model

The data, construction methods and limitations of the 3D geological modelling are described in Ford et al. (2009b). Maximum error on depth of modelled surfaces is interpreted as ±30 m, with ±15 m for the aquifer top surface as illustrated in Figure 3.14. The faults shown are those identified from the seismic reflection data and where an offset or disturbance is observed. Faults with a vertical displacement of >10 m are resolvable, many cross the interpreted horizons and potentially provide vertical high permeability pathways.

The models confirm a high level of data-fitting, with a GOCAD model confidence showing 95% of the seismic data points are honoured by the initial surfaces to a tolerance of less than 20 m. Such confidence permits the construction of uncertainty maps and reliable surface elevation maps for each horizon (Figure 3.15). Thus, further structural analysis of the relatively simple structure of the Lincolnshire model is unlikely to significantly refine the depth and thickness errors.

As the target aquifer is also utilised for up-dip groundwater abstraction (Case Study 3 below) then an assessment of the potential CO_2 migration pathways is important at this stage.

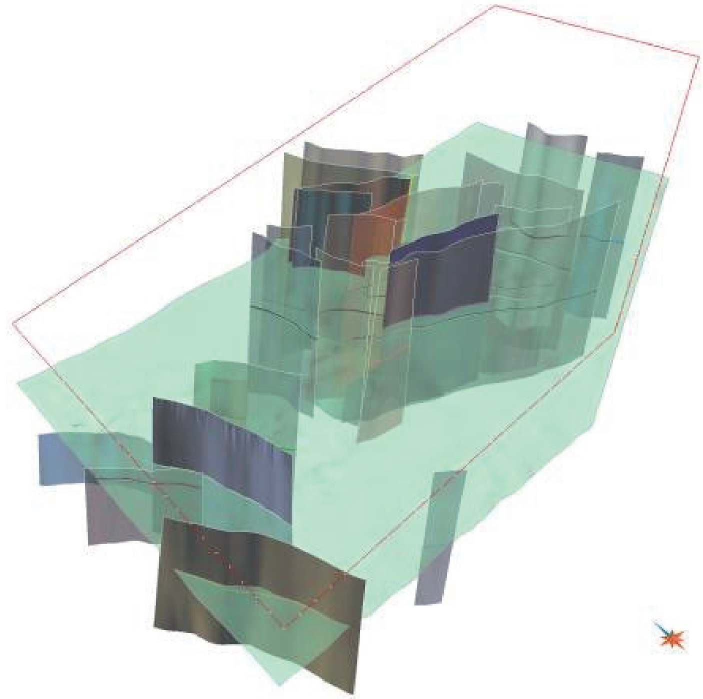


Figure 3.14 3D geological framework model for Lincolnshire faults intersecting top Sherwood Sandstone Group – view to NE.

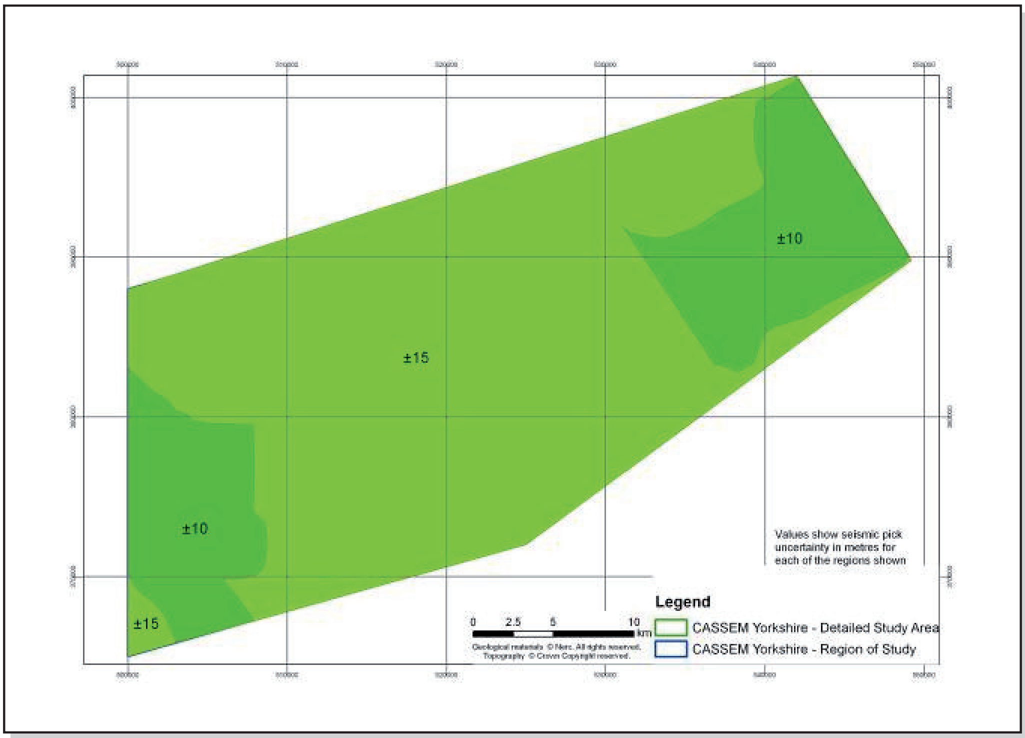


Figure 3.15 Seismic pick uncertainty map for the top Sherwood Sandstone Group.

The simple pattern of lineation in migration pathways due to flow that is parallel to faults on the up-dip side (Figure 3.8) results in the distribution of fetch areas and structural closures shown in Figure 3.16. The interpreted faults in the model may act as conduits and facilitate the rise of CO_2 to stratigraphically higher lithologies, or act as impermeable barriers and compartmentalise any westward migration (thereby limiting storage capacity). Further database enhancement is recommended to mitigate this uncertainty.

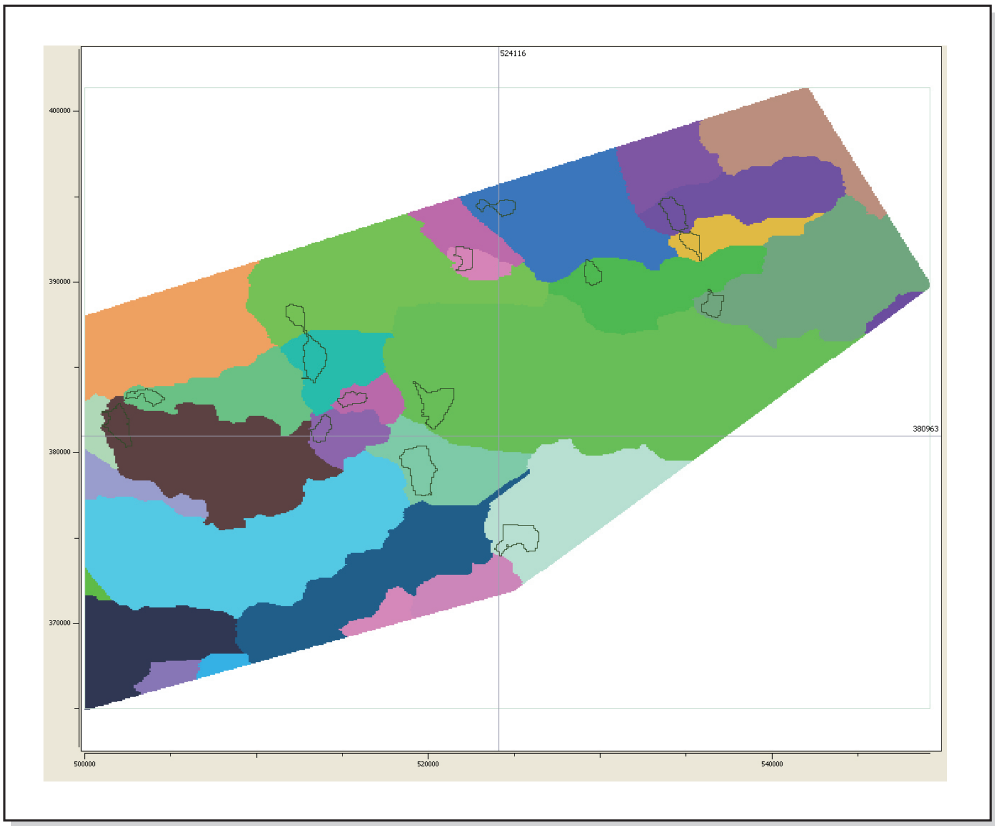


Figure 3.16 Mpath Fetch and Closure Analysis on the Lincolnshire Sherwood Sandstone Group. Note 15 principal structural closures (black outlines). Colours to differentiate fetch areas ('catchments') are arbitrary. Area is likely to be scalable and be well suited for dynamic trapping (see Chapter 4).

CASE STUDY 3: A HYDROGEOLOGICAL ASSESSMENT OF CO_2 INJECTION IN EAST LINCOLNSHIRE

The impact of CO_2 injection on shallow groundwater systems is a key issue for onshore storage options (e.g. Nicot, 2008; Birkholzer et al., 2009 and Yamamoto et al., 2009). Injection of CO_2 has the potential impact of raising groundwater pressures and changing groundwater flow in aquifers many tens of kilometres distant from the injection site. In the eastern part of the Lincolnshire model, saline fluids within the Sherwood Sandstone aquifer (SSG) pass up-dip into fresh groundwater, which is extensively extracted for public supply. The chalk aquifer which overlies the SSG at the injection site is also used extensively for public water supply (Figure 3.5). Thus, an examination of the hydrogeological implications of deep CO_2 storage on shallow groundwater systems has relevance to any wider environmental and impact assessments.

The potential impact of onshore to near-shore injection of CO_2 on the hydrogeology of the SSG freshwater aquifer has been modelled by Bricker et al. (2010). This work evaluates the hydrogeological properties of the geological formations which form the aquifer, the cap rock and the overburden, and numerically simulates the injection of CO_2 and its potential impact on the shallow (up-dip) groundwater systems.

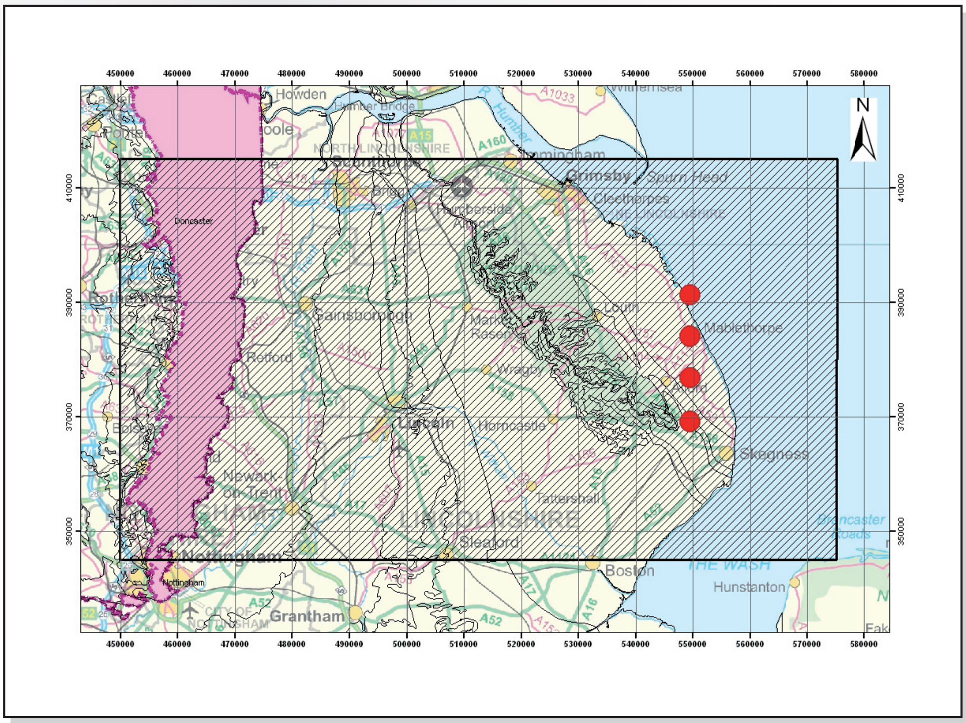


Figure 3.17 Area covered by the CASSEM numerical groundwater model. The SSG outcrop area is shown in pink, and injection sites in red.

A dual approach was adopted. Firstly, to create a hydrogeological conceptualisation of the system and, secondly, to perform a groundwater modelling exercise. The hydrogeological task, using shallow aquifer property data derived from the BGS aquifer properties database and the Environment Agency, sought to characterise the hydrogeological system at depth and to identify the potential leakage routes that might occur due to increased pressure caused by CO_2 injection. Drawing on this, a groundwater model was then developed to evaluate groundwater heads pre- and post- injection, leakage through the seal formation, water balance calculations and potential impacts on groundwater abstraction and river flows.

Key findings from the hydrogeological study are listed below:

- Three major aquifer units are present in the area, supporting licensed abstraction ranging from 150 to 450 Ml/d.
- Four key transport routes identified: laterally up-dip along the Sherwood Sandstone, through the cap rock (Mercia Mudstone Group), through deep boreholes, and through faults.
- Groundwater at an injection zone some 80 km into the confined aquifer is expected to be brine with values typically between 35–80 g/l.
- The main Sherwood Sandstone aquifer becomes less permeable and less productive with depth as fracture flow decreases.
- Transmissivity at depth is estimated to be 40–135 m^2/d (28–95 Dm) but permeability may be reduced by less dissolution of cements and presence of fibrous clays.
- Based on regional analyses, the intrinsic permeability of the SSG may vary over four orders of magnitude.
- The cap rock is lithologically heterogeneous and subject to geochemical weathering at depths <400 m below ground level.

The dynamic effects of CO_2 injection were then approximated using a 3-layer ZOOMQ3D numerical groundwater model which represented the spatial variation of the geological and hydrological properties of the Sherwood Sandstone. CO_2 injection was simulated at a rate of 15 Mt/yr distributed across eight injection wells.

Regionally, the Mercia Mudstone Group (MMG) is heterogeneous with varying proportions of mud to sand, and, therefore, and the model assumes that the cap rock does not have a perfect seal. A vertical hydraulic conductivity of 10^{-6} m/day for the MMG was applied within the groundwater model. Under this leakage scenario, groundwater heads in the shallow confined SSG aquifer, where it is used for potable water supply, increase by between 0.01–10 m. Groundwater levels within the unconfined aquifer increase by <0.01 m to 1 m, with a corresponding increase in river flows of approximately 1.7%.

Results from the model highlight two important points. Firstly, that the degree of impact on shallow groundwater systems is highly sensitive to the vertical leakage assigned to the cap rock. Reducing the vertical hydraulic conductivity of the MMG by one order of magnitude to 10^{-7} m/day has the effect of increasing groundwater heads in the shallow confined aquifer by 0.1–50 m and increasing river flows on the unconfined aquifer by approximately 9%.

Secondly, the response of groundwater heads in the deep confined part of the aquifer to injection, is rapid, with groundwater heads approaching their maximum limit within the first five years of injection (Figure 3.18). Recovery of groundwater heads to baseline conditions post-injection is equally rapid within the deep saline aquifer, with near complete recovery occurring within the first five years. Recession of groundwater heads in the shallow confined aquifer occurs less quickly, with groundwater heads still elevated by up to 1 m ten years after injection ceases.

The approach adopted in this study provides a preliminary assessment of CO_2 impacts. To improve the model requires a better understanding of facies variation in the SSG and geomechanical modelling of faults, such that preferential flow paths within the storage formation can be accounted for.

At the interface between the deep and shallow confined aquifer, particle tracking shows on a small movement (c.6 m) of water over a 20-year injection period. Lateral movements of water interface are more strongly influenced by ongoing surface abstraction, rather than CO_2 injection and migration, assuming intergranular flow.

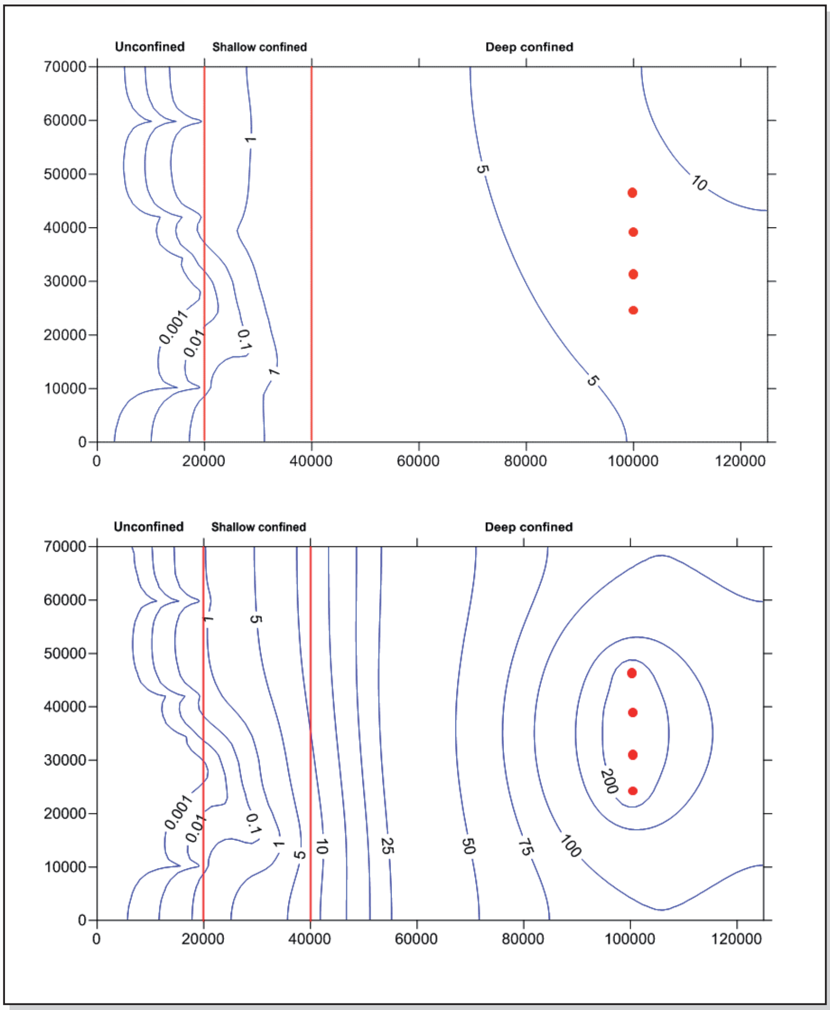


Figure 3.18 (a) Difference in groundwater pressure heads between the baseline and injection scenarios. Continuous CO_2 injection for 20 years was modelled using a vertical hydraulic conductivity of 10-6 m/day for the MMG cap rock. (b) Recovery of groundwater pressure heads. The difference between baseline and five years after injection has stopped is illustrated. Continuous CO_2 injection for 20 years was modelled using a vertical hydraulic conductivity of 10-6 m/day for the MMG cap rock.

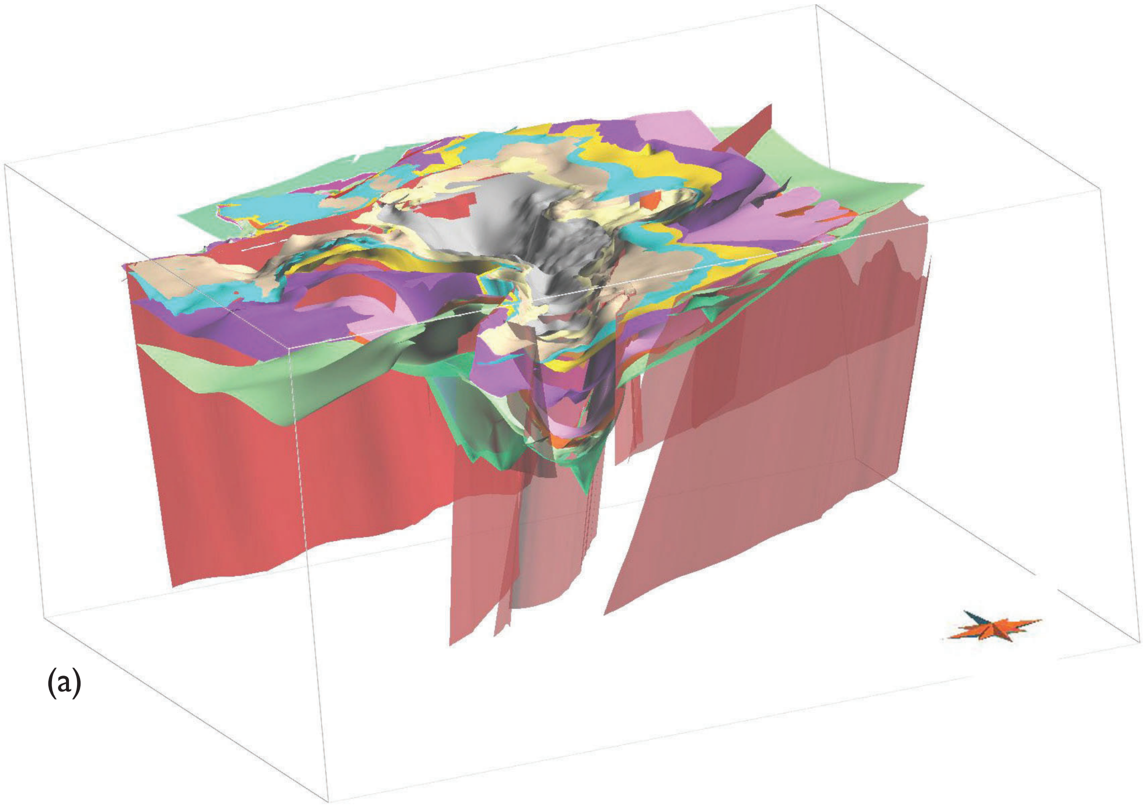
3.9 EVALUATION-DECISION GATE 3 (E/DG3)

At this gate all of the previous model iterations and data refinements are combined and compared to determine the best model version that will progress to Level III and ultimately provide the framework for storage capacity modelling.

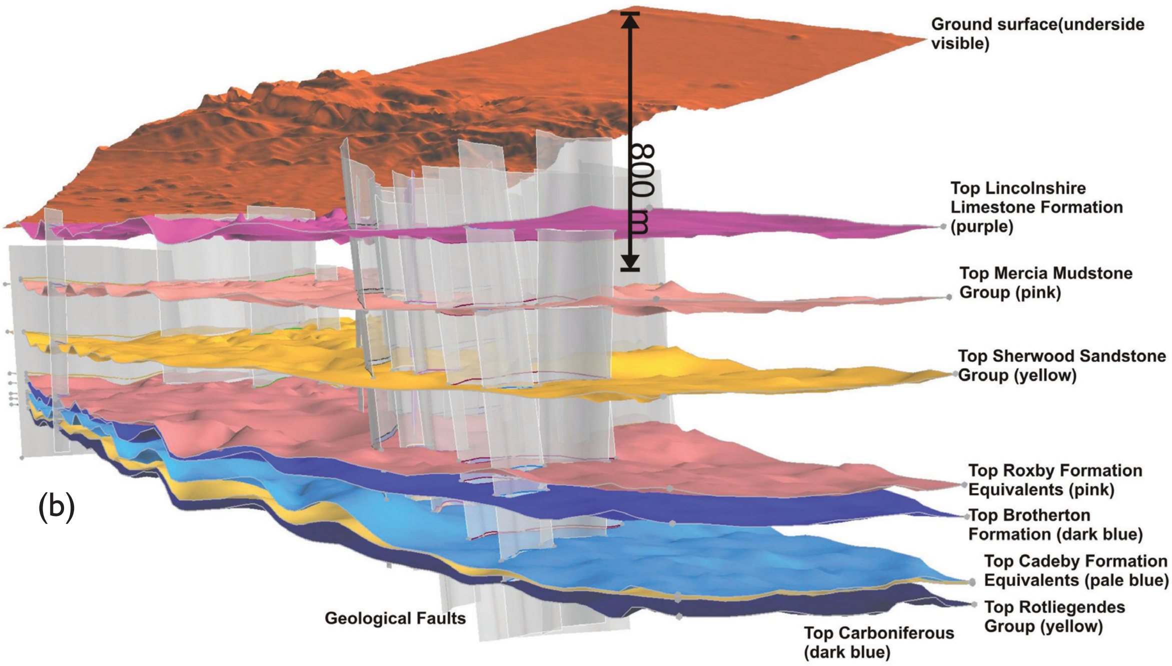
An assessment of the model uncertainties is required to inform the decision-making process and to make recommendations to hold for further analysis or invest and progress to the final delivery stage.

3.10 BUILDING THE GEOLOGICAL MODEL - LEVEL III

The chosen Level III geological model is now refined and the data sets quality-assured. The surfaces are exported from the modelling package in suitable formats (e.g. ASCII grids) for wider use. It is important to confirm maximum and minimum scales of use so that the models are utilised appropriately in a range of reservoir simulations. The final released geological framework models for the Firth of Forth and Lincolnshire are shown in Figures 3.19a and 19b.



(a)



(b)

Figure 3.19 Final geological framework models for CASSEM sites: (a) Firth of Forth (3x vertical exaggeration) and (b) Lincolnshire (10x vertical exaggeration).

3.11 SUMMARY

The quality of available data and range of geological histories creates an inherent variability of natural CO_2 stores. The geological interpretation and modelling workflow derived through the CASSEM project work is an attempt to address this natural variability. The workflow is flexible and will derive validated geological frameworks. Large uncertainties and biases are inevitable, but can be mitigated by targeted data collection and critical path analysis of data interpretation. It is anticipated that this workflow will, through application, evolve and become better fitted to CCS exploration targets.
Key findings:

- Establishment of an asset team, with frequent interaction and communication of data limitations and uncertainty issues with others parts of the storage methodology, is fundamental to the timely identification of major hurdles and difficulties.
- Use of structural restoration techniques (first response tools) will provide early assessment of site suitability and highlight inconsistencies in the geological interpretations that require further detailed modelling and risking for capacity estimates.
- Early reprocessing and reinterpretation of data (e.g. seismic) will reduce uncertainty in the geological model, with improved resolution of fault structures and constraining depths of key surfaces.
- For a relatively simple geological site with good data quality (e.g. Lincolnshire), the model is easily understood and utilised by other partners and a definition of initial conditions in the saline aquifer reservoir can be estimated with confidence.
- For a geological site with complicated geometries and structural features (e.g. Firth of Forth), communication of the geological uncertainty and estimates of reservoir conditions is consequently more challenging.