

GHGT-12

Subsurface Characterisation of a Saline Aquifer Cited for Commercial Scale CO₂ Disposal

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Abstract

The Yorkshire & Humber area contains some of the biggest CO₂ emitters in the UK. The UK Southern North Sea (SNS) contains a number of gas fields and saline aquifers which could provide storage for some of that CO₂. National Grid Carbon (NGC) has plans to connect these sources and sinks via a shared 24" pipeline in a hub & spoke arrangement called "The Humber Cluster Project". After several years of high level study using multi-client seismic surveys and a database of released well data, an anticlinal structure of around 25 km length and 8 km width with a 275 m thick Bunter sandstone formation (saline aquifer) was selected for detailed analysis. Two crestal wells in the structure called 5/42 were drilled in 1970 and 1990 looking for hydrocarbons but only brine was found. Basic formation evaluation logs were acquired in both wells. Limited core and pressure data were acquired in the 1990 well. No record of any water analysis is available and the core and log coverage was limited. As of mid-2012 some uncertainties remained with respect to the suitability of 5/42 for CO₂ disposal. Little was known about the strength & permeability of the cap rock which consists of 10-12 m of shale overlain by about 80 m of halites and mudstones. Although the structure seems well defined and no major faulting was seen in the Bunter sandstone there was little reservoir permeability data, especially vertical permeability. In addition no flow test, production or injection, had been undertaken in 5/42. To address these issues, the company applied for and was awarded the UK's first Carbon Storage licence from the UK Government in November 2012 which permitted the drilling of appraisal well 42/25d-3 in the summer of 2013 with generous financial support from the European Commission (through their EEPR scheme) and the UK Energy Technologies Institute (ETI).

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15-25% and permeabilities of 10-1000 mD. Several generic studies looking at the potential of the Bunter sandstone for CO₂ storage can be found within the CCS literature, i.e. [2, 3, 4].

Using these generic studies along with specific site analyses undertaken by NGC, a structure called 5/42 was selected for detailed review. 5/42 is a massive anticline structure at around 25 km long, 8 km wide with a reservoir section in excess of 200 m thick.

Two seismic surveys were available over at least part of the 5/42 structure. The Ravenspurn Ocean Bottom Cable (OBC) survey shot by Western Geophysical in 1997 covers the whole 5/42 structure. The PGS Mega Merge multi-client survey consists of various vintages of towed streamer data and covers the western half of the structure. Note that a new speculative survey has been shot over quadrants 42 & 43 of the UK SNS by Polarcus in 2013, [6].

Two hydrocarbon exploration wells were drilled on the crest of the structure in 1970 and 1990. Formation evaluation logs were acquired in both wells with some core and a Repeat Formation Tester (RFT) acquired in the later well. No water samples were taken that could be analysed and the core coverage was found to be limited. A number of other wells have been drilled around the 5/42 structure targeting deeper stratigraphic intervals. The amount of log data acquired over the Bunter interval in these wells was limited but has proved useful in constraining the structure whose Bunter Top Surface map is shown in Figure 2. Note the well symbol colored red corresponding to location of the new appraisal well; the logic behind the choice of this location is discussed in Section 3.1.

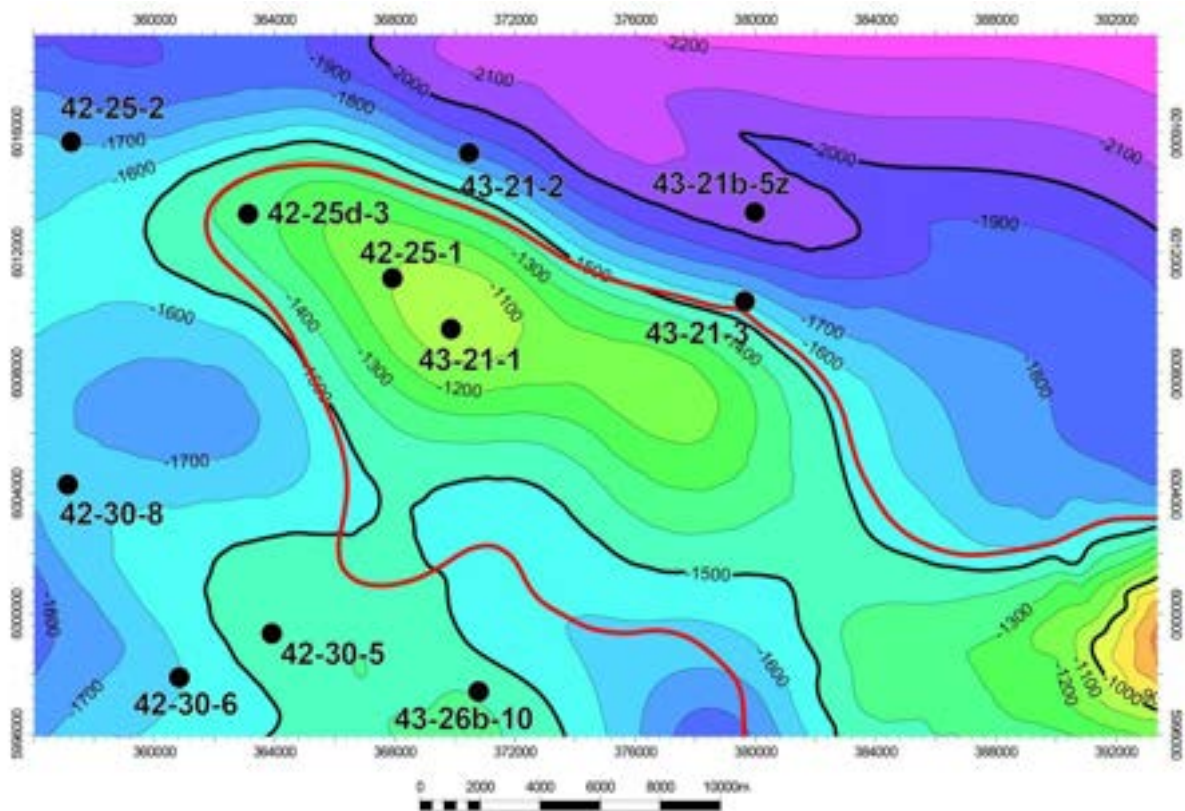


Figure 2: Bunter Top Depth Surface (m below mean sea level), Appraisal Well Location and Seismic Phase Reversal Contour

As of mid-2012 some uncertainties remained with respect to the suitability of 5/42 for CO₂ disposal. In particular little was known about the strength & permeability of the cap rock which consists of 10-12 m of shale, known as the Röt Clay, overlain by about 80 m of halites and thin inter-bedded mudstones, known as the Röt Halite. Both layers display uniform thickness in all the wells surrounding the structure. Heinemann et al [3] discuss the extent of this regional seal and note how it becomes a proven seal in the Bunter hydrocarbon gas fields which lie about 50 km north of 5/42.

Although the target structure was well defined, there was little reservoir permeability data, especially vertical permeability and no flow test, production or injection, had been undertaken in 5/42.

To address these issues, the company applied for and was awarded the UK's first Carbon Storage licence from the UK Government in November 2012 which permitted the drilling of appraisal well 42/25d-3 in the summer of 2013. The bulk of the funding for the well came from the European Energy Programme for Recovery (EEPR) along with some funding from the Energy Technologies Institute (ETI) as well as NGC. The ETI is using the NGC experience in designing and delivering the appraisal well to develop its generic understanding of the requirements for appraising aquifers, following on from its UK Storage Appraisal Project, the results of which are now available through the CO₂ Stored database, [5]. The ETI are also promoting the idea of hub & spoke developments, like that shown in Figure 1, connecting a number of potential geographically collocated onshore CO₂ sources like those in Yorkshire & Humberside to a set of collocated offshore storage sites like those in the UK SNS, [7].

3. Appraisal Programme

A number of objectives were set for the appraisal programme. These included:

- Retrieve core, especially from the cap rock
- Brine samples, ideally from more than one depth to identify any compositional effects, i.e. salinity versus depth
- Production and injection tests
- Conventional logging, i.e. Gamma Ray, Resistivity, Neutron and Density
- Special logging, i.e. Dipole Sonic for geomechanical modelling, Ultrasonic Borehole Imager (UBI) & Oil-Based Micro-Imager (OBMI) to look for fractures & faults, Nuclear Magnetic Resonance (NMR) to allow for permeability prediction and Electron Capture Spectroscopy (ECS) to identify mineral assemblages.
- Pressure measurements
- Mini-Frac and Vertical Interference Test (VIT)
- Flow and injection tests to assess dynamic reservoir performance

Some of these objectives, in particular the core acquisition, require a substantial set of follow-up laboratory analysis relating to Conventional Core Analysis (CCA), Special Core Analysis (SCAL) , geomechanical testing, formation damage testing, sedimentology and petrophysics.

3.1. Well Location

The first major decision concerned the location of the appraisal well. With such a big structure, see Figure 2, there were a number of possible locations under consideration. With two penetrations in the crest, albeit with limited poor quality core acquisition and a set of logs from the 42/25-1 well over only part of the reservoir, it was decided to focus down-dip toward the spill point of the structure. This was done to investigate a feature seen on the seismic coverage of 5/42 and the surrounding area known as the “seismic phase reversal”. The phase reversal is the red contour that surrounds 5/42 as seen in Figure 2. This feature opens out at the eastern and southern end of 5/42 where it extends for 10's of kilometers on a regional basis.

Inside the contour, all wells drilled to date show good quality reservoir through the whole of the Bunter sandstone interval with the upper part of the formation having porosity of 25% or more. Outside the phase reversal, the top of

the Bunter sandstone is of poor quality with porosity less than 10%. Diagenetic cementation is believed to be the cause of the reduction in reservoir quality.

The nature of the phase reversal can be seen on seismic data and is illustrated on a N_S line running across the crest of the structure in Figure 3

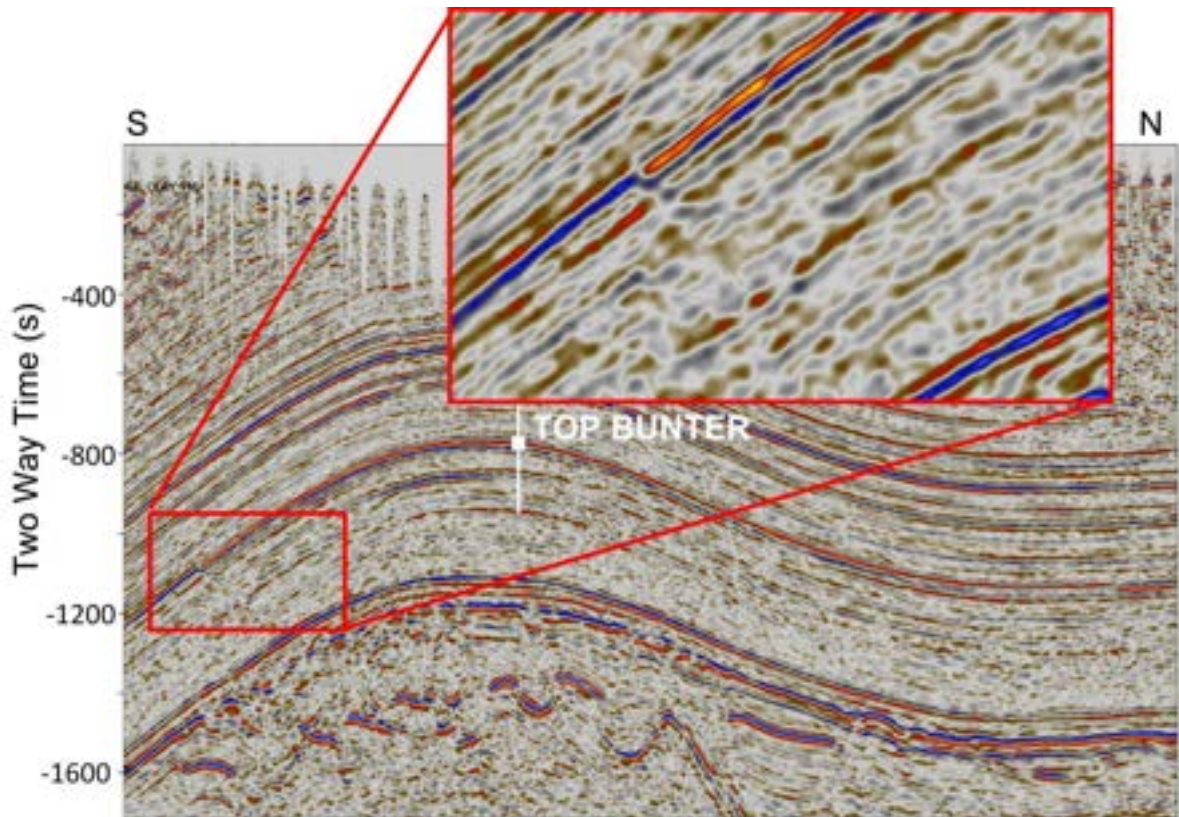


Figure 3: South-North Seismic Cross-Section Showing Phase Reversal

3.2. Operational Phase

42/25d-3, NGC's first ever well, was drilled and tested in June & July of 2013 with no harm to people or the environment and within the allotted budget. After starting the well using water based mud, a switch was made to use oil based mud through the bulk of the drilling program. This decision was made to minimize the effect of the drilling fluid on the cap rock and Bunter sandstone where salt plays a major role. A schematic showing the whole drilling & testing program of the near vertical well is shown in Figure 4. Formation Integrity Tests (FIT) were made after setting the casing in the 17½ inch [0.445 m] hole at 2246 ft [684.6 m] Measured Depth (MD) in the Lias and after setting the next casing in the 12¼ inch [0.318 m] hole at 4494 ft [1369.8 m] MD in the Röt Halite formation. In neither case could a fracture be generated with the maximum permissible pressure allowed by safe drilling practices, indicative therefore of the high geomechanical strength of these overlying layers.

Obtaining core from the cap rock had been given the highest priority of the data acquisition programme and the 27.43 m [90 ft] core section planned to be taken through the Röt Halite, Röt Clay and top 1 m of the Bunter sandstone was successfully achieved. It was then planned to take a second consecutive 54.86 m [180 ft] core

through the Upper Bunter sandstone, switch to the drill bit before taking a third and final 54.86 m section across the Middle/Lower Bunter. In practice the coring program progressed so well that three consecutive 54.86 m cores were taken across the Upper & Middle Bunter and on into the top of the Lower Bunter.

Having achieved the required Total Depth (TD) for the well, some 30 m into the underlying Bunter shale to allow a sump for the subsequent suite of logging, the next phase then commenced. The first logging run contained the conventional tools which included the porosity logs. These logs allowed the sub-surface team to select depths at which pressure measurements and brine samples would be taken during the suite of Multiple Dynamic Testing (MDT) runs. The porosity log was also used to estimate permeability using a porosity-permeability transform that had been generated using the available regional Bunter core data. Since most of these available data are from the few Bunter hydrocarbon gas fields which are up to 60 km distant from 5/42, it was felt that this transform was unlikely to be particularly effective. Sections of the Computer Processed Interpretation (CPI) log are shown in Figure 5.

Next to be run were the set of specialized logging runs. The UBI and OBMI tools were used to look for signs of fractures and faulting; note that nothing of any significance was seen from the subsequent analysis of these logs. The dipole sonic tool was run to gather data used to populate the geomechanical model. Whilst not strictly needed for this well, the NMR tool was run to gather data that can be used later to calibrate the permeability model for any future appraisal or development wells since this log will be calibrated against core measurements.

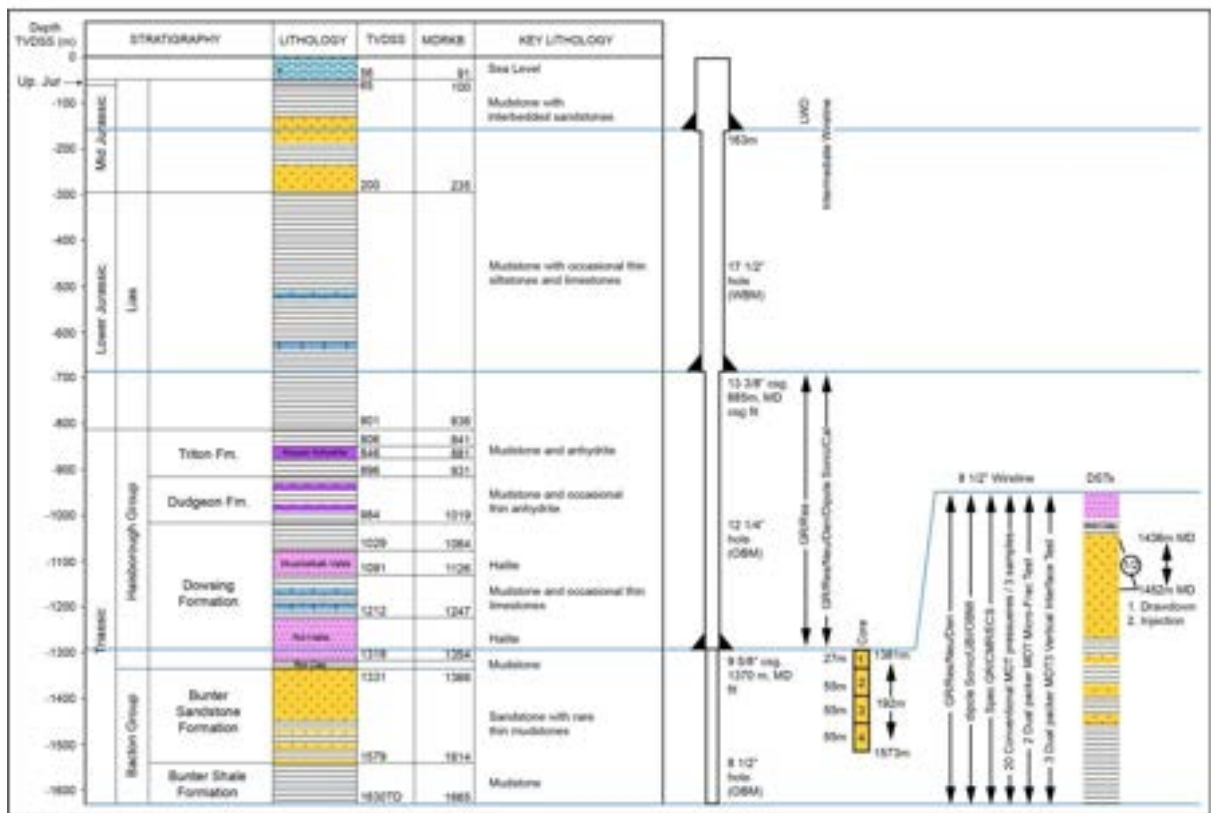


Figure 4: Complete drilling & appraisal programme

Two MDT runs were made. On the first run pressure data were taken at twenty depths, roughly every 10 m or so. To measure pressure the tool draws some fluid from the formation and in doing so it measures the fluid mobility $\lambda = K/\mu$ where K is the permeability and μ is the viscosity. Since the fluid here is single phase brine whose viscosity can be predicted accurately knowing the pressure, temperature and salinity, measuring mobility gives a direct prediction of permeability. These permeability estimates are compared with the regional porosity/permeability in the right hand column of Figure 5; the curve is the regional predictor and the purple dots are the values derived from the pressure measurements. The match between the regional predictor and these measurements is considered very good. This MDT run also took three brine samples, one each from the Upper, Middle and Lower Bunter; ionic analysis of these samples show a salinity versus depth trend.

The second MDT run was made to test the strength of the Röt Clay cap rock and the Lower Bunter sandstone using mini-frac tests followed by three VIT tests. The mini-frac test in the Röt Clay and that in the Lower Bunter showed that both formations are extremely strong. The fracture closure pressure in the Röt Clay and Lower Bunter were measured to be 264 bar and 262 bar, respectively.

Three VIT tests were made one each in the Lower, Middle and Upper Bunter. The VIT tool has a pair of packers which can be inflated to seal off a short length of the borehole at the required depths. A reciprocating pump then generates a pressure drawdown to cause fluid flow into the tool with a pressure probe between the packers and two more pressure probes at offsets of 2 m and 10 m above the packers. This assembly has been designed to measure not just horizontal permeability K_H but also vertical permeability K_V ; the K_V/K_H ratio is considered extremely important for characterising CO₂ plume development in a saline aquifer.

The first VIT measurement in the Lower Bunter was considered a great success. The subsequent VIT measurements in the Middle and Upper Bunter were less successful because of problems with the tool. The third test had to be abandoned before its completion because of a data transmission failure. Nevertheless, valuable data were gathered to help develop the K_V/K_H ratio which is estimated to be in the range 0.08 to 0.15.

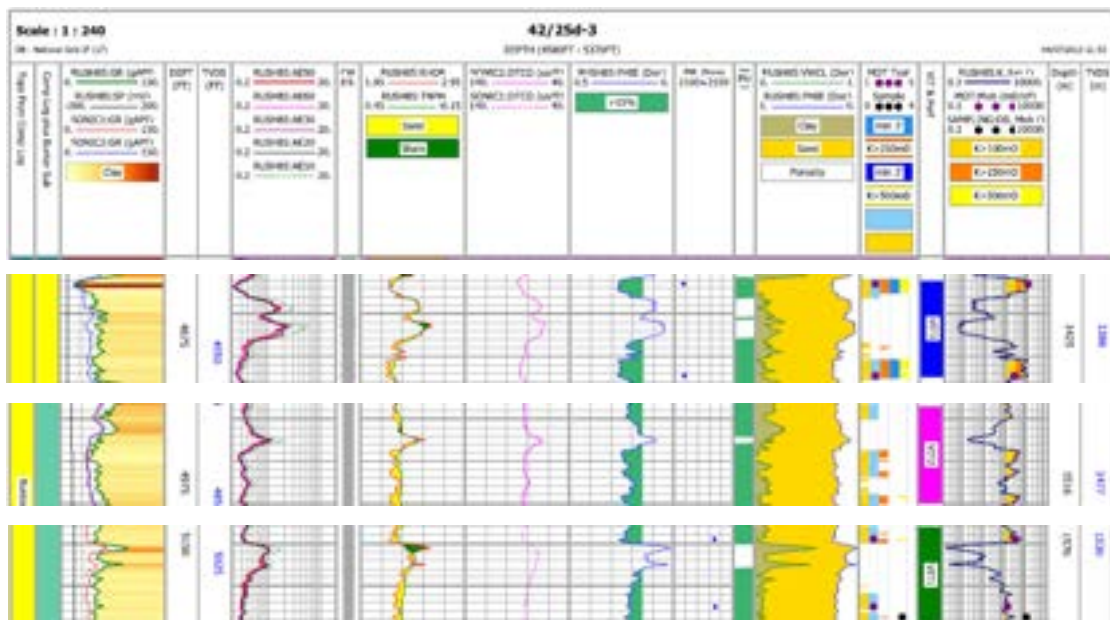


Figure 5: Excerpts from the CPI log at the VIT stations

With the logging and MDT programme complete, the well was prepared for the Drill String Test (DST) of production and injection. The well was cased through the Bunter and the DST string run into the well. The string contained an Electric Submersible Pump (ESP) as it was known that the reservoir pressure was too low to allow the dense brine to flow to surface without assistance. An 18 m interval near the top of the Bunter was perforated.

The first phase of the DST was to flow the well at 795 m³/d [5000 stb/d] for approximately 24 hours. During this phase, further brine samples were taken. An electrical problem with the ESP meant that near the end of the flowing period there was a temporary short duration shut-in, otherwise there were no issues of note. At the end of the flowing period, a 48 hour shut-in was conducted; modelling of the test before the well was drilled had shown the 24 hour flow and 48 hour shut-in should allow the maximum opportunity to gather data about any potential barriers or baffles within the reservoir. Analysis of this test indicates that the average reservoir permeability is 270 mD and that no barriers or baffles to flow were seen within 1.3 km radius of the well.

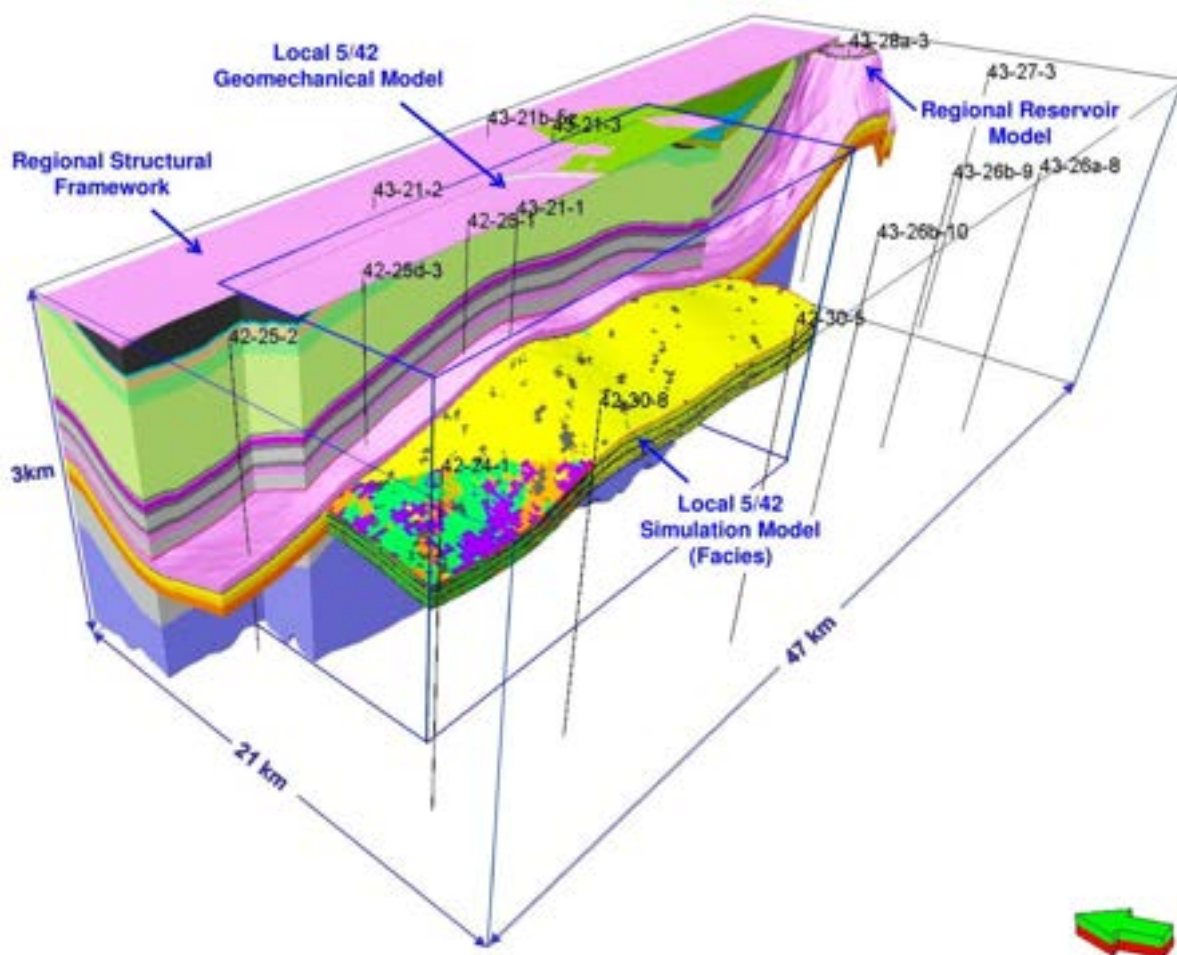


Figure 6: Regional & Local Geological, Simulation & Geomechanical Models

At the end of the shut-in, a three-rate injection test was undertaken. Ideally the injection test would have used CO₂ as the injectant. However acquisition of an offshore deliverable source of adequately pressurised super-critical CO₂ of sufficient volume for injection testing was not considered realistic.. Therefore the next best fluid was

filtered and treated sea-water as its density of 1030 kg/m^3 compared reasonably well with that of cold (sea-bed temperature $\sim 5^\circ\text{C}$) CO_2 at $800\text{--}900 \text{ kg/m}^3$. The three injection rates selected were 795, 1590 and $2385 \text{ m}^3/\text{d}$ [5000, 10000 and 15000 stb/d], each of three hours duration with a 12 hour shut-in to conclude.

Following the completion of the injection test, the well was plugged and abandoned thus concluding the offshore operations phase of the programme.

4. Next Steps

The main objective of the appraisal well was to gather additional data to refine existing models, i.e. static geological model & dynamic reservoir simulation model as well as building a new geomechanical model. Figure 6 is the most recent build of these three models in a cut-away format to show the over-lapping volumes of interest.

Much of the data has now been analysed such as the petrophysics, image logs, brine composition, conventional core analysis and chemostratigraphy. Awaiting completion is the special core analysis, long duration formation damage and sanding assessment, sedimentology & petrography; most of this will be available in the coming months.

The current development plan envisages a platform at the western end of the field from which up to three deviated wells will be drilled and completed in the lower half of the Bunter to handle a phase-I maximum injection rate of 2.65 Mt/yr . The predicted plume evolution is shown in Figure 7 which shows a cross-sectional view of the Bunter from the west to the crest of the aquifer.

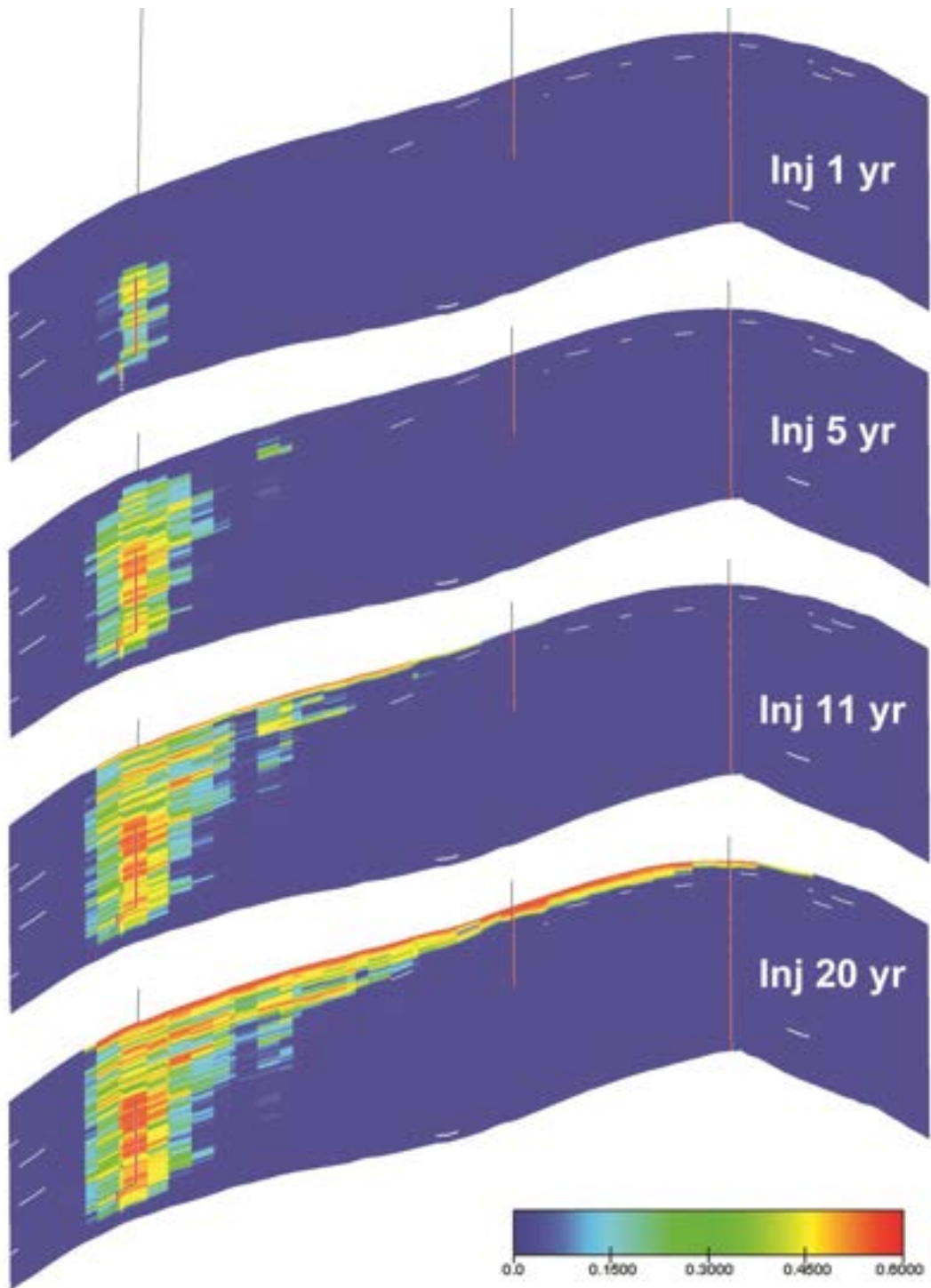
Because of the density difference between the native brine, $\rho_B \approx 1200 \text{ kg/m}^3$ and the CO_2 density ρ_{CO_2} , which will vary between $600 < \rho_{\text{CO}_2} < 800 \text{ kg/m}^3$ at the prevailing pressure and temperature, after exiting the perforations and flowing near-horizontally for a few 100's m, the CO_2 migrates upwards. Based on the current model parameters, the CO_2 reaches the cap rock above the perforations after five years and reaches the crest of the structure after 11 years. In this scenario, the phase-I injection scheme is planned to inject for 20 years.

The technical basis of a Measurement, Monitoring and Verification (MMV) plan is currently being prepared as part of the subsurface Field Development Plan (FDP). One of the main monitoring tools being investigated is 4D seismic to image the plume development and allow validation of the static & dynamic models and if necessary, history matching of the predictions shown in Figure 7. Synthetic 4D seismic responses based on these model predictions have already been generated to show the usefulness of this approach.

Acknowledgements

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The delivery of the drilling and appraisal programme safely, on time and with no harm to people or the environment was due to the skills of the drilling manager Martin Booth and his colleagues at Zenith Energy and the team at Applied Drilling Technology International Limited (ADTI), both of Aberdeen, UK.

Figure 7: Predicted CO₂ Plume Evolution

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