The Endurance CO_2 Storage Site, Blocks 42/25 and 43/21, UK North Sea

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Abstract

The Endurance, 4-way, dip-closed, structure in UK Blocks 42/25 and 43/21 occurs over a salt diapir and within Triassic and younger strata. The Lower Triassic Bunter Sandstone Fm. reservoir within the structure was tested twice for natural gas (in 1970 and 1990) but both wells were dry. The reservoir is both thick and high quality and as such an excellent candidate site for sub-surface carbon dioxide storage.

In 2013 a consortium led by National Grid Carbon drilled an appraisal well on the structure and undertook an injection test ahead of a planned development of Endurance as the first bespoke CO_2 storage site on the UK continental shelf with an expected injection rate of 2.68 million tonnes of dense phase CO_2 each year for 20 years. The site was not developed following the UK government's removal of financial support for carbon capture and storage demonstration projects.

Key Words

Carbon capture and storage, CCS, Triassic Bunter Sandstone

Capture of carbon dioxide produced from fossil fuel power plants and other industrial processes followed by its burial as a dense phase fluid deep underground (carbon capture and storage or CCS) is a proven technology for reducing the emissions of greenhouse gases to the atmosphere (Gluyas and Mathias, 2013). It is considered to be a transition technology that would allow industry reliant upon combustion of fossil fuels to decarbonise ahead of switching energy sources to use renewable and low-carbon energy. The quantity of CO_2 currently captured and injected into geological storage sites is about 40 million tonnes per annum (Global CCS Institute, 2018) a miniscule amount when compared with the quantity of greenhouse gases emitted by human at 53.5 billion tonnes of CO_2 equivalent in 2017 (UN Environment, 2018).

The depleted petroleum reservoirs in the UK North Sea and their laterally equivalent saline aquifers are an enormous resource for the UK in terms of pore volume within which carbon dioxide could be stored. The theoretical CO_2 storage potential in 500 sites in the UK sector of the North Sea is 78 billion tonnes at 50% confidence levels (Bentham et al, 2014); this compares with emissions from the UK which stood at 364.1 million tonnes in 2018 (BEIS, 2019).

The Endurance site was appraised in 2103 with a single well (42/25d-3) drilled to test a large potential storage structure in the Southern North Sea. The structure had been identified in a number of earlier reports as prospective, including in Holloway et al (2006). The structure, although appraised, has not been developed as a storage site due to the withdrawal of UK government support in November 2015. It remains as the only well ever drilled in the UK sector with the intent of using it for carbon dioxide geostorage.

History of exploration and appraisal

The Endurance structure was initially identified as a gas prospect in the late 1960s and tested by two wells 42/25-1 (BP, 1990) and 43/21-1 (Mobil, 1970). Both were assessed to be water bearing at the Triassic Bunter Sandstone Formation level (Figure 1). A further well was drilled within what we now know to be Endurance closure at top Bunter level, 43/21-3 (Agip, 1992). It targeted the Carboniferous reservoir section and was dry. National Grid Carbon and partners Capture Power drilled 42/25d-3 in 2013 to appraise Endurance for geostorage of carbon dioxide (Figure 2).

The Blocks containing the Endurance structure (42/25 and 43/21) lie at the western edge of what could be termed the Bunter province within the Southern North Sea. Immediately to the east of Endurance are a cluster of abandoned gas fields and tested structures with Triassic Bunter sandstones as the target reservoir interval. The Esmond, Forbes and Gordon fields were discovered in late 1960s and early 1970s; production began in 1985 (Ketter, 1991) and the fields were abandoned by the turn of the millennium. In between the former fields are a suite of tested structures with Triassic Bunter sandstone reservoirs that were found to be water bearing or with minor gas shows. The Endurance structure was one such 'dry' prospect (Underhill et al, 2009; Yielding et al, 2011). Migration of gas to the Bunter Sandstone Formation has been attributed to the local presence of Tertiary dykes (Bifani, 1986; Brown et al, 1994).

Carboniferous age reservoirs have also been targeted in the area and have proved productive in Quad 43 including the Trent, Cavendish, Kepler and Kilmar fields all with lowermost Upper Carboniferous (Namurian) reservoir intervals (O'Mara et al, 1999; O'Mara et al, 2003; Wasielka et al, 2020). The Garrow gas field (Parkmead, 2016) has both Carboniferous and Permian (Rotliegend) sandstone reservoirs and lies partially beneath the northern flank of Endurance. To the north west both the Breagh and Crosgan fields have Lower Carboniferous sandstone reservoirs (Nwachukwu et al, 2020 ; Axis, 2015).

Regional Context

Blocks 42/25 and 43/21 occur within the northern half of the Southern North Sea gas basin. The oldest sedimentary rocks penetrated in Quads 42 and 43 are Lower Carboniferous sandstones, limestone and mudstones beneath the Base Permian Unconformity (BPU) in the west of Quad 42. Progressively younger Carboniferous age rocks occur beneath the BPU towards the south east of the area. In the east of Quad 43 Westphalian D age red beds subcrop the BPU. Overall the whole Carboniferous section occupies a large south eastward plunging syncline (Underhill, 2003). During the Lower Carboniferous (Visean), sedimentation occurred in a series of syn-rift basins broadly defined by pre-existing Caledonian structures. The later Namurian and Westphalian intervals vary in thickness on a regional scale in the offshore area implying that sedimentation was not controlled by the block/basin geology as was the case onshore UK. The Carboniferous closed with the Hercynian Orogeny caused by continental collision during the formation of Pangea. The basins formed during the Carboniferous were inverted, uplifted and eroded (Underhill, 2003).

Early Permian subsidence occurred across the whole of the Southern North Sea and east to Poland (the Southern Permian Basin) with the Endurance area near the centre of the basin. The Lower Permian here is dominated by thick lacustrine mudstones deposited in an ephemeral lake (Silverpit Fm. mudstones) overlying the eroded Carboniferous rocks and having some residual topography. There are a few basal sandstones (so called ‘lower Leman Sandstone Fm.’) scattered across the basin including at Garrow and Cygnus fields (Catto et al, 2017) where they form a secondary reservoir to the underlying Carboniferous sandstone reservoirs. Late Permian, Zechstein Group limestones, dolomite and evaporites overlie The Silverpit Mudstones.

At Endurance the Triassic is divisible into three stratigraphic units. The Early Triassic saw deposition of a mudstone dominated Bunter Shale Formation overlain by the Bunter Sandstone Formation reservoir interval. The remaining Mid-Triassic and Late Triassic strata are mudstone dominated with subordinate evaporites (Figure 3). The Triassic interval comprises entirely non-marine sedimentary rocks. The Bunter Sandstone Formation was deposited in a combination of braided, ephemeral fluvial channels and braid plains with subordinate aeolian dunes (Figure 4). The sediments were derived from the London Brabant Massif to the south and Mid-North Sea High to the north. The Triassic strata are overlain by Lower Jurassic marine mudstones that also subcrop the sea bed.

Post-Carboniferous structuration occurred in several phases. The Lower Permian interval is affected by normal faulting similar to that seen elsewhere in the Southern North Sea, whilst the Triassic and younger sections are heavily structured due to halokinesis and inversion during the Tertiary. The impact of Zechstein salt movement is dramatic with a diapir subcropping the sea bed 25 km to the south east of Endurance (Figure 5).

Database

Three suites of seismic data were available for interpretation (Figure 6). These include a vintage 2D seismic data set (not shown on Figure 6), an ocean bottom seismic survey and a Polarcus (2012) high resolution survey shot specifically for Endurance.

There are three wells that penetrate the Endurance structure including the most recent drilled by Nationalgrid Carbon (42/25d-3). A further 13 wells surrounding Endurance have been used to constrain the stratigraphic correlation for the reservoir interval and all but three of the total sixteen wells have full log suits enabling petrophysical analysis and interpretation (Figure 6).

Sixteen meters of core were available from historical well 42/25-1 while the entire Bunter Sandstone Formation and a section of the overlying ‘Röt Clay’ caprock were cored in 42/25d-3 (4 cores).

Trap

The trap for Endurance is a well-defined elliptical, four-way dip closed pericline oriented northwest-southeast and overlying a salt swell (Figures 2 and 7a, 7b). Primary seal is provided by the Röt Clay unit. This is overlain by 90 m of Röt Halite unit and then 900 m of the mudstone dominated Haisborough Group.

A key consideration for storage of carbon dioxide is the integrity of the trap and significant effort was put into mapping faults that occur in the Endurance structure. Discontinuities occur in the Top Triassic reflector and these were used to map fault traces. Fortunately, all of the identified faults at Top Triassic sole out within the Upper Triassic mudstone interval and none penetrate the Röt Halite unit. Similarly, a few minor discontinuities occur in the Top Bunter Sandstone reflector across the crest of Endurance. These faults are also of very limited vertical extent and the Endurance structure is considered to be well sealed. Moreover, no evidence was found in the original exploration wells or the recently drilled appraisal well 42/25d-3 that petroleum gas had ever been present in the Endurance structure.

Reservoir and petrophysics

The reservoir within the Endurance structure is entirely within the Lower Triassic, Bunter Sandstone Formation, a regionally extensive and laterally continuous interval that can be traced for tens of kilometres in all directions. The Bunter Sandstone Fm. is approximately 275 m thick throughout and beyond the Endurance structure and made up of fluvial and aeolian sandstones commonly with very fine to fine grain size. Individual sandstones are arranged into large-scale fining upwards units with fluvial and aeolian sandstones at the base with siltstone and playa lake claystone alternations towards the top. The finer grained lithologies occur predominantly in the lower part of the Bunter Sandstone Formation while the coarser-grained deposits are more common in the middle and upper parts of the Bunter Sandstone Formation.

Determination of net:gross ratio (NTG) and net cut-off for CO_2 storage systems is difficult because of the short period of CO_2 injection compared with natural, petroleum charging. The uncertainly in NTG was captured by using a cross plot of porosity versus permeability to define porosity equivalents to the permeability for production of petroleum gas (0.1 mD = 4.56% porosity), light oil (1 mD = 7% porosity) and the threshold above which the reservoir volume is insensitive to change in permeability cut-off (17.9 mD = 12% porosity). The three porosity cut-off values of 12%, 7% and 4.56% were used as low, mid and high cases yielding NTG of 0.752, 0.927 and 0.993 respectively. Uncertainty in the NTG has only a modest impact on the calculated net pore volume (-5.3% to +0.7%).

The porosity range for the reservoir is from 10% to 34% with an average value of 19.2% while the permeability ranges from 0.1 mD to 10,000 mD with an average of 271 mD (Figure 8). The ratio of vertical to horizontal permeability (kv/kh) was measured at 0.1 to 0.15.

The reservoir pressure in 42/25d-3 was measured at 0.07 MPa (10 psi) below that of 42/25-1 drilled 23 years earlier. This pressure drop was probably caused by production of gas from the Esmond Field (50 km to the north east) and consequential expansion of the aquifer as voidage replacement. Thus, the connected aquifer, within the Bunter Sandstone Formation, is calculated to be between 20,000 km^2 and 23,000 km^2 in area, bounded by the Dowsing Fault Zone to the west and thinning eastwards beneath the Base Cretaceous Unconformity onto the Cleaver Bank High in the Dutch sector of the Southern North Sea.

Ahead of drilling the Endurance appraisal well, 42/25d-3, a major concern for the operator was the potential for all of the porosity in the reservoir to be plugged with halite. Porosity completely and partially obliterated by halite is a common occurrence within the Bunter Sandstone Fm. of the Southern North Sea. Such halite had not been reported in either of the two exploration wells drilled on Endurance (42/25-1 and 43/21-1) but both wells were drilled with water-based mud which could have led to dissolution of any salt during drilling. A detailed analysis of the 3D seismic data at top reservoir level showed the presence of a seismic phase reversal boundary broadly coincident with the Endurance closure in the north west but opening out towards the north east (Figure 9). Based on comparison with data from synthetic seismograms, the Endurance structure was interpreted to contain high quality, porous sandstones whilst much of the surrounding area to the north, west and south was deemed to be non-porous due to salt plugging. The reservoir at 42/25d-3 was forecast to be high quality and proved to be so on drilling.

Carbon dioxide storage capacity, injectivity and monitoring

The net pore volume calculated for the Endurance structure is 4.6×10^9 m^3 (28 billion barrels).The development plan called for the injection of 2.68 million tonnes of dense phase carbon dioxide over a 20 year period yielding a total injected mass of 53.6 million tonnes or about 2% of the net pore volume.

Well 42/25d-3 was tested for injectivity over an 18 m interval at the top of the reservoir section. Filtered sea water was used for the injection test due to the difficulties of handling dense phase carbon dioxide as well as the difficulty of obtaining it. An initial 24 hour test injected sea water at 795 m^3 day^{-1} ((5000 bbl/day) and this was followed by a multi-rate test at 795, 1590 and 2385 m^3 day^{-1} (5000, 10,000 and 15,000 bbl/day). A shut-in pressure build-up of 48 hours followed the multi-rate test.

The protocols which have been developed for the storage of carbon dioxide in the subsurface include the definition of three volumes: the storage site refers to the reservoir interval into which the carbon dioxide will be injected; the storage complex which includes the overburden and underburden (top seals and where present base seals) and the monitoring area (Ringrose et al, 2013). For Endurance the reservoir is of course the Bunter sandstones. The complex includes the overburden up to and including the Liassic mudstones and the underburden down to the base of the Zechstein Group (evaporites). The monitoring area is of course larger still (Figures 10a, 10b and 10c).

The expectation was that with government support the Endurance structure was likely to be one of two carbon geostorage test sites on the UK continental shelf; the other being reuse of the depleted Goldeneye condensate field (Stewart and Marshall, 2020). However, in November 2015 as part of the comprehensive spending review the incumbent government in the UK broke its manifesto promise to support carbon capture and storage demonstration projects and without consultation cancelled the £1 billion of committed support. Overnight the embryonic UK carbon capture and storage industry's global leadership evaporated and four years on the UK is still without a carbon dioxide storage project while other nations have developed projects.

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References

Axis Well Technology. 2015. Cluff Natural Resources, Competent Person's Report of the Hydrocarbon Interests of Cluff Natural Resources in the Southern North Sea, UK https://www.cluffnaturalresources.com/wp-content/uploads/2016/01/5-Axis-CPR-on-Southern-North-Sea-Assets-02-December-2015_Optzd.pdf accessed on 5th December 2019

BEIS. 2019. 2018 UK greenhouse gas emissions, provisional figures, Statistical release: national statistics

Bentham, M., Mallows, T., Lowndes, J. and Green, A. 2014. CO_2 STORage evaluation database (CO_2 Stored). The UK's online storage atlas, Energy Procedia, **63,** 5103-5113

Bifani, R. 1986. Esmond gas complex. In: BROOKS, J., GOFF, J. C. & VAN HOORN, B. (eds) Habitat of Palaeozoic Gas in NW Europe. Geological Society, London, Special Publications, 23, 209–221

Brown, G., Platt, N.H. and McGrandle, A., 1994. The geophysical expression of Tertiary dykes in the southern North Sea. First Break, 12 (3), pp. 137-46I

Catto, R., Taggart, S and Poole, G. 2017. Petroleum geology of the Cygnus gas field, UK North Sea: from discovery to development. Geological Society, London, Petroleum Geology Conference series, **8**, 307-318, 23 March 2017, https://doi.org/10.1144/PGC8.39

Global CCS Institute. 2018 The Global Status of CCS, https://indd.adobe.com/view/2dab1be7-edd0-447d-b020-06242ea2cf3b accessed on 5th December 2019

Gluyas, J.G. and Mathias, S.A. 2013. Geological Storage of carbon dioxide (CO_2), Geoscience, technologies, environmental aspects and legal frameworks, Woodland Publishing, 340pp

Holloway, S., Vincent, C.J. and Kirk, K.L. 2006. Industrial carbon dioxide emissions and carbon dioxide storage potential in the UK, British Geological Survey, Sustainable and renewable energy programme, commercial report CR/06/185N http://nora.nerc.ac.uk/id/eprint/4837/1/CR06185N.pdf accessed on 14th December 2019

Johnson, H., Warrington, G. and Stoker, S.J. 1994. Lithostratigraphic nomenclature of the UK North Sea, 6 Permian and Triassic of the Southern North Sea, British Geological Survey

Ketter, F.J. 1991 The Esmond, Forbes and Gordon Fields, Blocks 43/8a, 43/13a, 43/15a, 43/20a, UK North Sea, In Abbots, I.L. (ed) United Kingdom Oil and Gas Fields, *25 Years Commemorative Volume*, Geological Society Memoir, **14**, 425-432

Nwachukwu, C.M., Z. Barnett, Z. and Gluyas, J.G. 2020. The Breagh Field, Block 42/12a, 42/13a and 42/8a, UK North Sea, *this volume*

O'Mara, P.T., Merryweather, M., Stockwell, M. & Bowler, M.M. 1999. The Trent Gas Field; correlation and reservoir quality within a complex Carboniferous stratigraphy. In: Fleet, A.J. & Boldy, S.A.R. (eds) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. Geological Society, London, 809–821.

O'Mara, P. T., Merryweather, M., Stockwell, M. & Bowler, M.M., 2003. The Trent Gas Field, Block 43/24a, UK North Sea. In: Gluyas, J.G. & Hichens, H.M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*. Geological Society, London, Memoir, 20, 835–849.

Parkmead. 2016 Relinquishment report, Licence P.2107 UKCS Blocks 42/20A, 42/25B, 43/16 & 43/21C, Parkmead Group, May 2016 https://itportal.ogauthority.co.uk/web_files/relinqs/P2107.pdf accessed 5th December 2019

Ringrose, P.S., Mathieson, A.S., Wright, I.W., Selama, F., Hanssen, O., Bissel, R., Saoula, N. and Midgley, J. 2013. The In Salah CO_2 storage project: lessons learned and knowledge transfer, Energy Procedia, **37,** 6226-6236

Stewart, N. and Marshall, J.D. 2020 The Goldeneye Field, Blocks 14/19a and 20/4b UK North Sea, *this volume*

Underhill, J.R. (2003) The tectonic and stratigraphic framework of the United Kingdom's oil and gas fields, *In* United Kingdom Oil and Gas Fields – Commemorative Millennium Volume (eds J.Gluyas & H.M.Hichens), Geological Society of London Memoir No. **20**, 17-59

Underhill, J.R., Lykakis, N. and Shafique, S. 2009. Turning exploration risk into a carbon storage opportunity in the UK Southern North Sea. Petroleum Geoscience, Vol. 15 2009, pp. 291–304

UN Environment. 2018. Emissions Gap Report 2018, Intergovernmental Panel on Climate Change Side Event, COP 24, December 2018, https://www.ipcc.ch/site/assets/uploads/2018/12/UNEP-1.pdf accessed 5th December 2019

Wasielka, N, Gluyas, J.G., Breese, H. and Symonds, R. 2020. The Cavendish gas field, Block 43/19, UK North Sea, *this volume*

Yielding, G., Lykakis, N. and Underhill, J.R. 2011. The role of stratigraphic juxtaposition for seal integrity in proven CO2 bound traps of the Southern North Sea. Petroleum Geoscience, 17, pp. 193-203.

Figure Captions

Figure 1 Regional map showing the location of the Endurance carbon dioxide storage structure in relation to surrounding gas fields (basemap modified from Parkmead, 2016. Parkmead acreage shown in yellow).

Figure 2 Depth structure and closure map for the Endurance structure on top Bunter Sandstone Formation.

Figure 3 Lithostratigraphy of the Triassic interval within the Endurance area (based on Johnson et al, 1994).

Figure 4 Sketch of Bunter Sandstone Formation depositional environments in the Endurance area.

Figure 5 Structural configuration of Endurance and adjacent areas caused by salt diapirism. The reservoir subdivisions (L1a to L3b) are annotated for Bunter Sandstone.

Figure 6 Seismic and well database. The ocean bottom seismic survey area is shown by the yellow shaded area and the Polarcus survey by the densely lined area. The blue line shows closure of the structure and the pink line the extent of the seismic polarity reversal within the Bunter Sandstone (equivalent to porous sandstone without halite cement).

Figure 7a Southwest-northeast arbitrary seismic line showing dip closure and fault distribution within the overburden, 7b northwest-southeast arbitrary seismic line showing dip closure and faults in the overburden.

Figure 8 Crossplot of core porosity and core horizontal permeability from well 42/25d-3.

Figure 9 Well correlation panel showing salt plugged reservoir (Facies 5, blue fill) occurs outside the seismic phase reversal boundary (42/25-2, 43/21-3 and 43/26b-9) while porous reservoir occurs within the seismic phase reversal boundary (wells 42/25d-3 and 43/21-1). Logs shown are, from L to R: gamma ray and computed effective porosity.

Figure 10a Vertical section through Endurance showing the storage site, storage complex and monitoring area; b stratigraphic definition of the storage site and storage complex; c map showing the limit of the storage site, complex and monitoring area. The spill point of the storage structure is at its SE corner and hence an additional monitoring area has been identified to the SE of Endurance; it being a 4-way, dip-closed structure adjacent to the spill point.