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Gestco case study 2a-1: Storage Potential of the Bunter Sandstone in the UK sector of the southern North Sea and the adjacent onshore area of Eastern England

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Gestco case study 2a-1: Storage Potential of the Bunter Sandstone in the UK sector of the southern North Sea and the adjacent onshore area of Eastern England

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Foreword

This case study, is the published product of the GESTCO project - a study by the British Geological Survey (BGS) and eight other organisations; BGR, BRGM, GEUS, GSB, IGME, NITG-TNO, NGU and Ecofys. GESTCO is an acronym for European Potential for Geological Storage of CO_2 from fossil fuel combustion. The goal of this project is to determine whether geological storage of CO_2 is a viable method of reducing greenhouse gas emissions from fossil fuel combustion, capable of widespread application.

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In addition to the organisations acknowledged in the Foreword, the authors would like to thank to WesternGeco for allowing the use of one of the seismic reflection lines (figure 2a1.12), from the southern North Sea data, in this report.

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Location of the Bunter Sandstone Formation

A major sandstone rock unit, known onshore as the Sherwood Sandstone Group and offshore as the Bunter Sandstone Formation crops out between Nottinhgam and Teeside (Figure 2a1.1). East of the outcrop it is present in the subsurface beneath much of eastern England. It continues eastward beneath the UK sector of the Southern North Sea and across into the Dutch Sector, the Netherlands, Germany and Poland where it is known as the Buntsandstein Formation. In this report the combined onshore Sherwood Sandstone Group in eastern England and Bunter Sandstone Formation offshore in the southern North Sea is described for convenience as the Bunter Sandstone.

The Bunter Sandstone has many of the characteristics required for CO_2 storage, including large closed structures (domes) above salt diapirs, good average porosity and permeability, and a good seal in the overlying Haisborough Group. Furthermore, it is a proven gas reservoir in the Southern North Sea Basin.

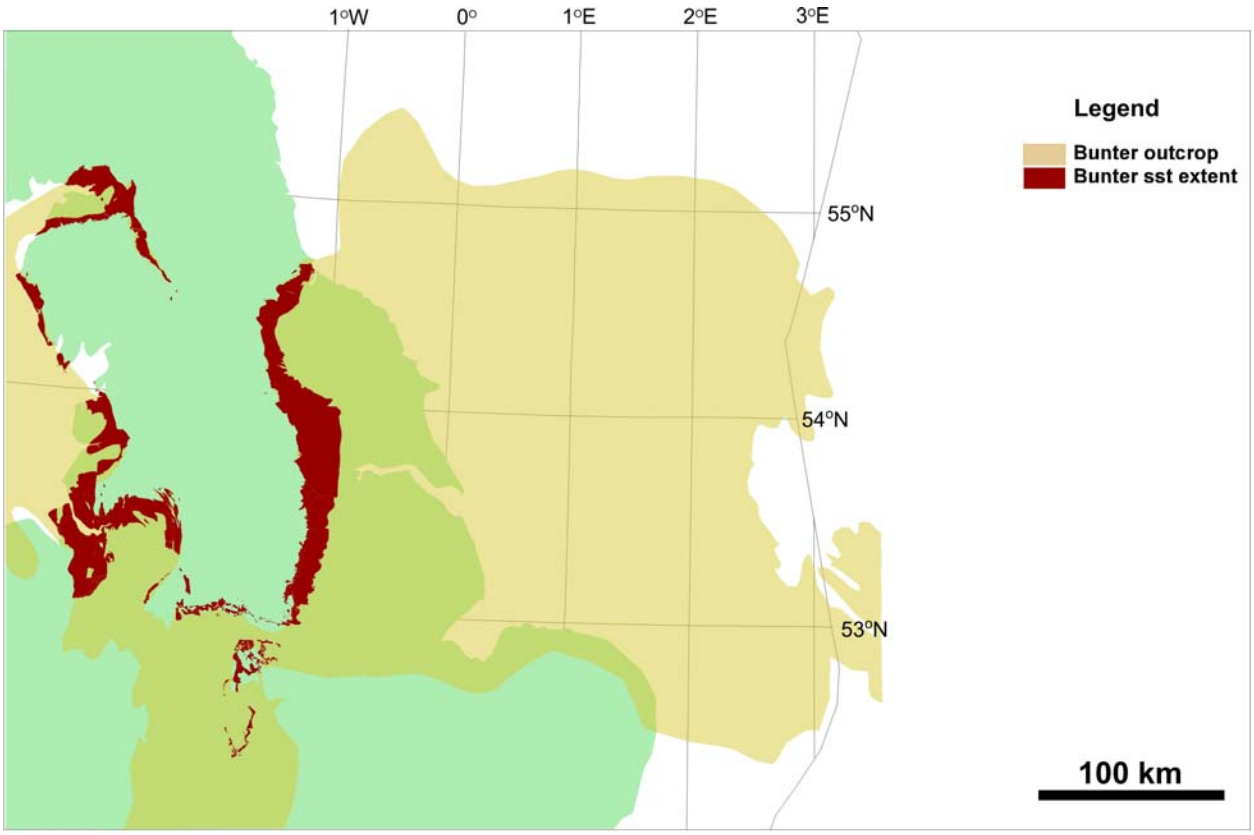

Figure 2a1.1 Map of the Bunter Sandstone Formation extent in the southern North Sea and Eastern England

Stratigraphy of the Bunter Sandstone Formation

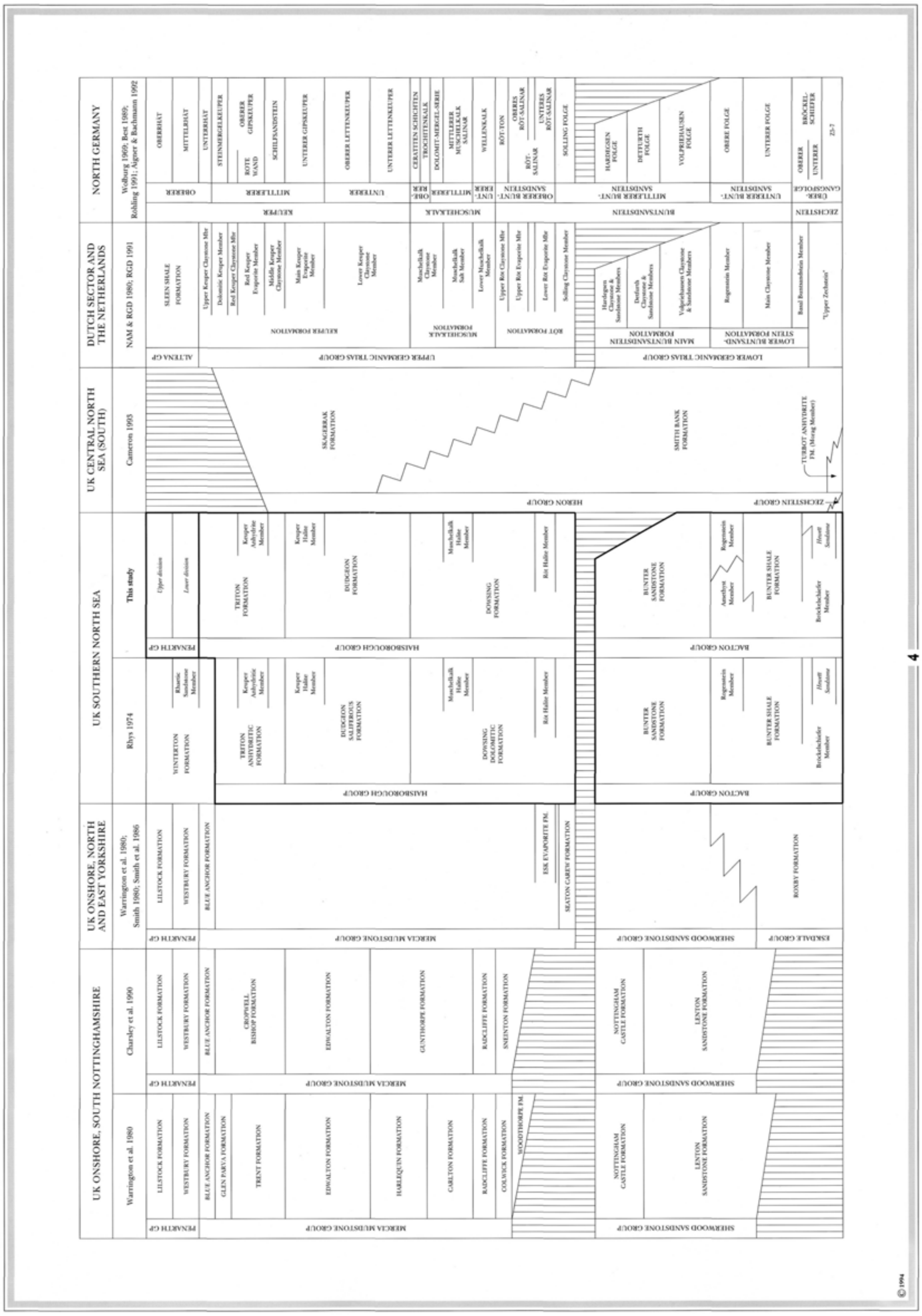

Figure 2a1.2 Stratigraphic relationships of the Bunter Sandstone and surrounding formations in the UK onshore and offshore areas, the Netherlands and Germany

The basal part of the Bunter Sandstone progressively passes laterally into the Bunter Shale Formation between onshore eastern England and the centre of the southern North Sea Basin. Immediately offshore the sandstone in the lower part of the formation becomes interbedded with shales, and this interval of mixed lithologies is known as the Amethyst Member (of the Bunter Shale Formation). Further to the east the proportion of interbedded sandstone decreases almost to zero and this unit passes into the Rogenstein Member of the Bunter Shale Formation. This relationship is highlighted in Figure 2a1.3 (dashed line denotes uncertainty). The top of the Bunter Sandstone is laterally isochronous throughout eastern England and the offshore area (Figure 2a1.2), except immediately adjacent to the London Platform onshore, where younger sandstones are present.

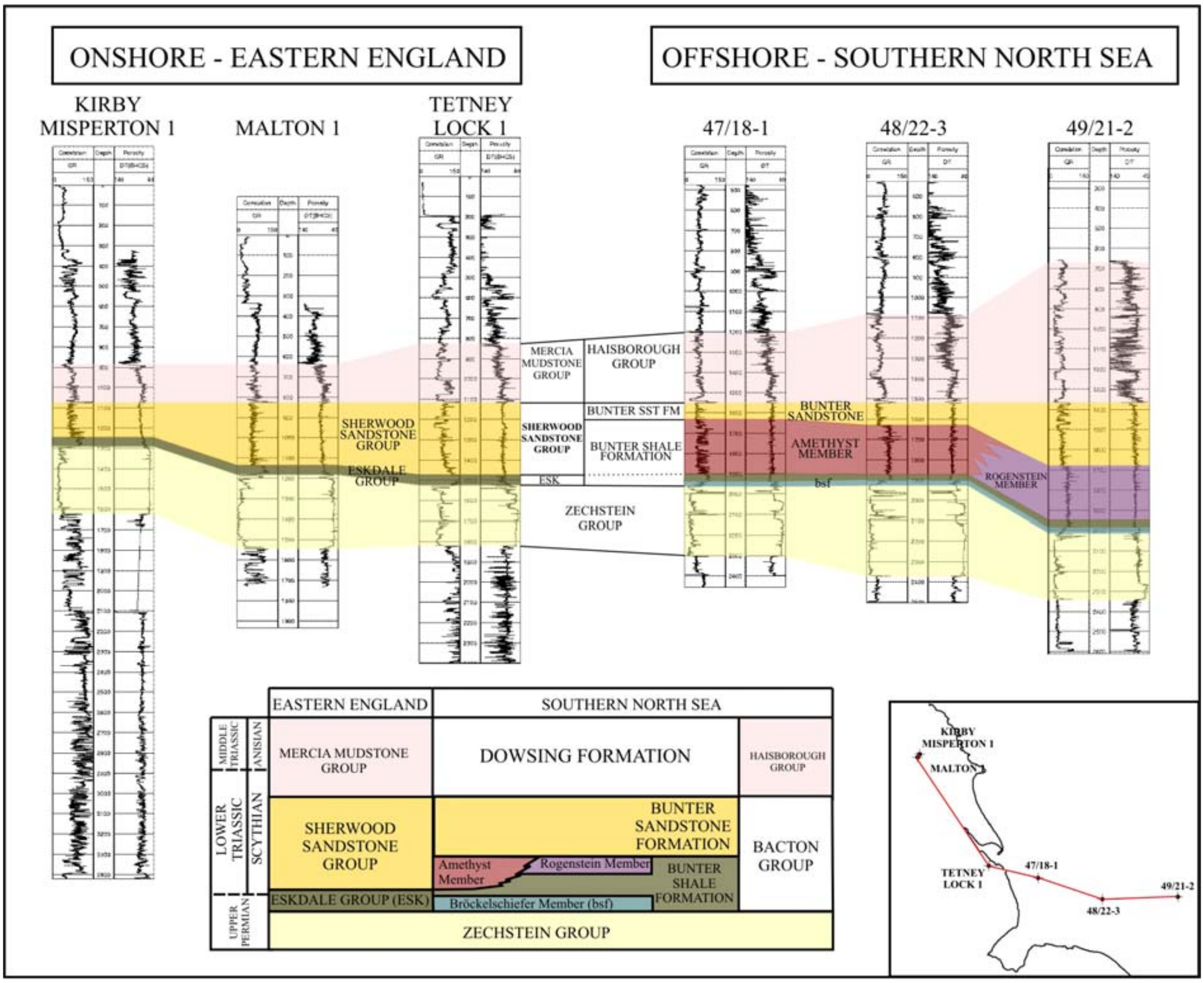

Figure 2a1.3 Correlation diagram illustrating the transitional nature of the base Bunter Sandstone/Top Bunter Shale Formations

Depth and thickness of the Bunter Sandstone Formation

The top of the Bunter Sandstone lies at depths of up to 3000 m, in general deepening from the outcrop towards the east (Figures 2a1.4 and 2a1.5).

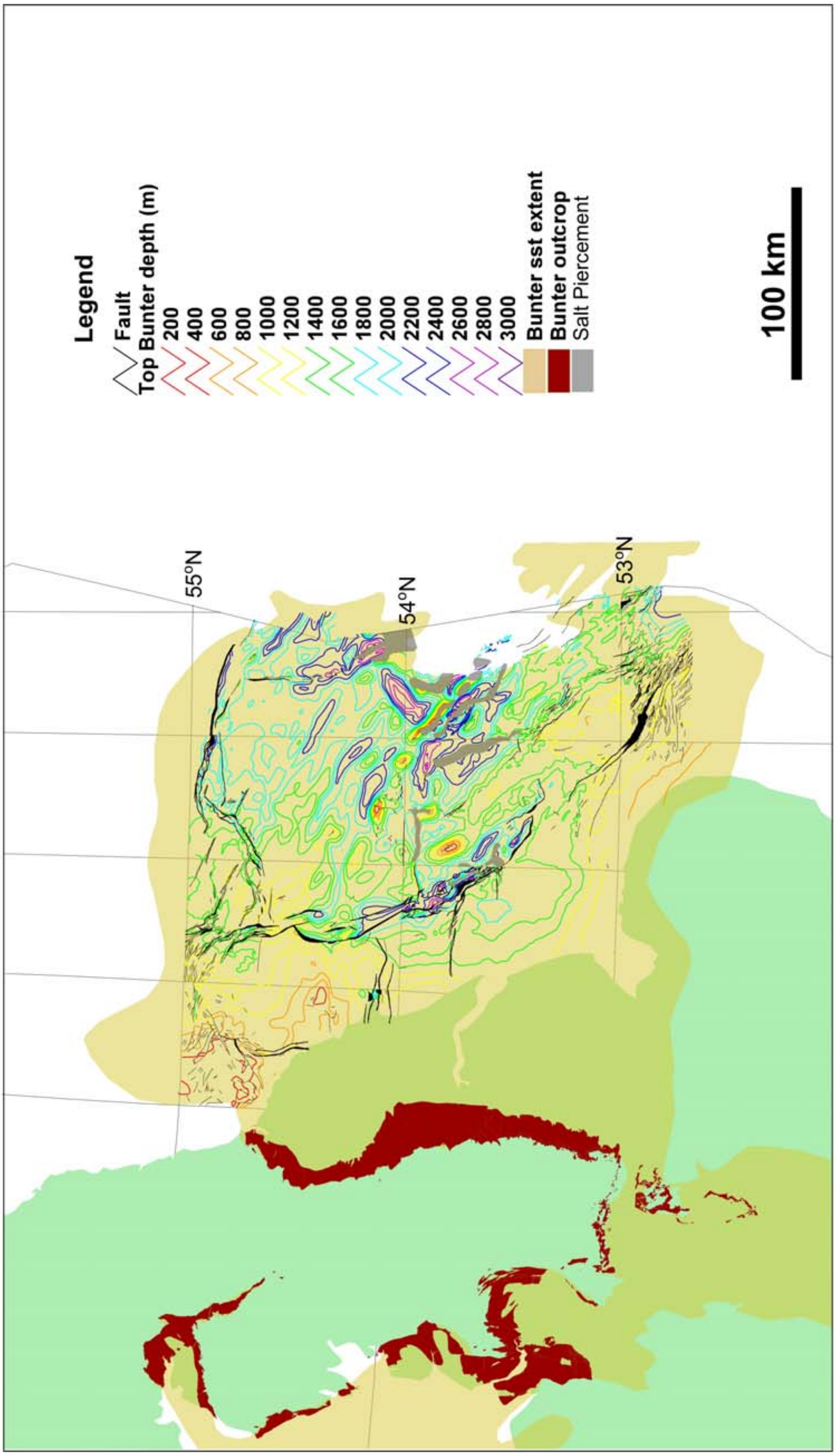

Figure 2a1.4 Depth map of the top of the Bunter Sandstone Formation in the southern North Sea

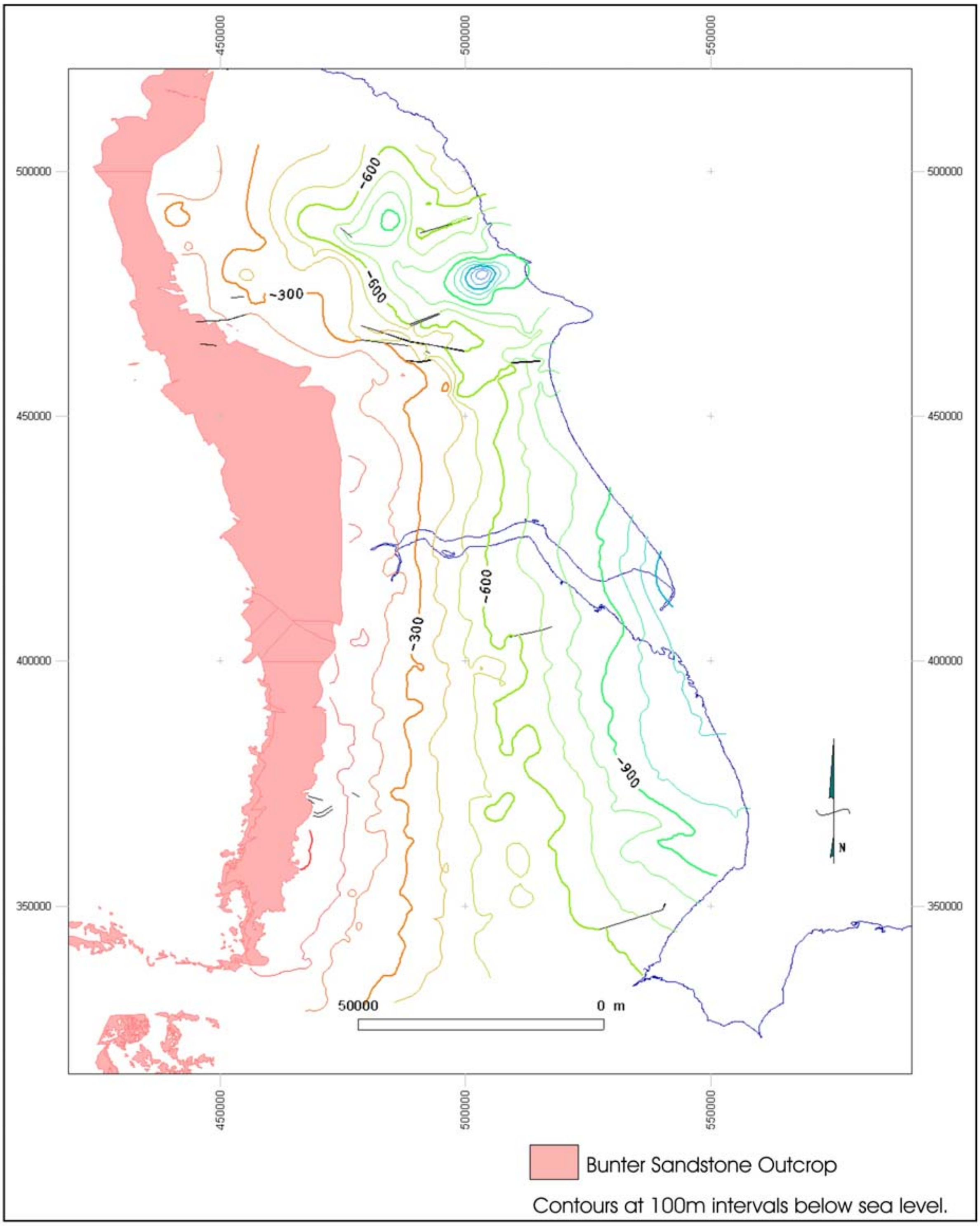

Figure 2a1.5 Depth map of the top of the Bunter Sandstone Formation, Eastern England

The Bunter Sandstone Formation ranges in thickness from 0 - 350m in the southern North Sea, but typically has a thickness of about 200 m (Figures 2a1.6 and 2a1.7). Overall the Bunter Sandstone thickens towards the centre of the southern North Sea Basin (Figure 2a1.6).

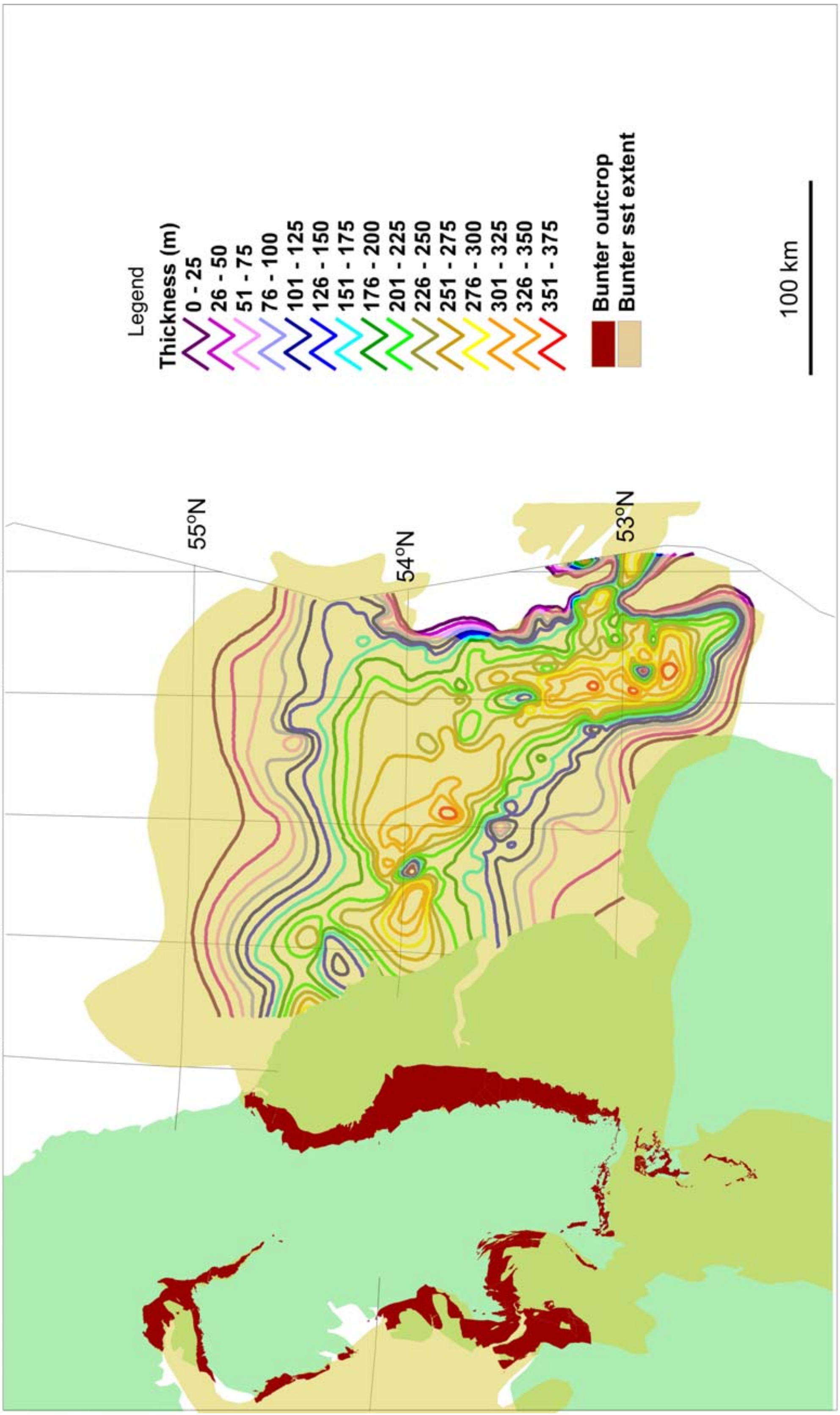

Figure 2a1.6 Isopach map of the Bunter Sandstone Formation in the southern North Sea

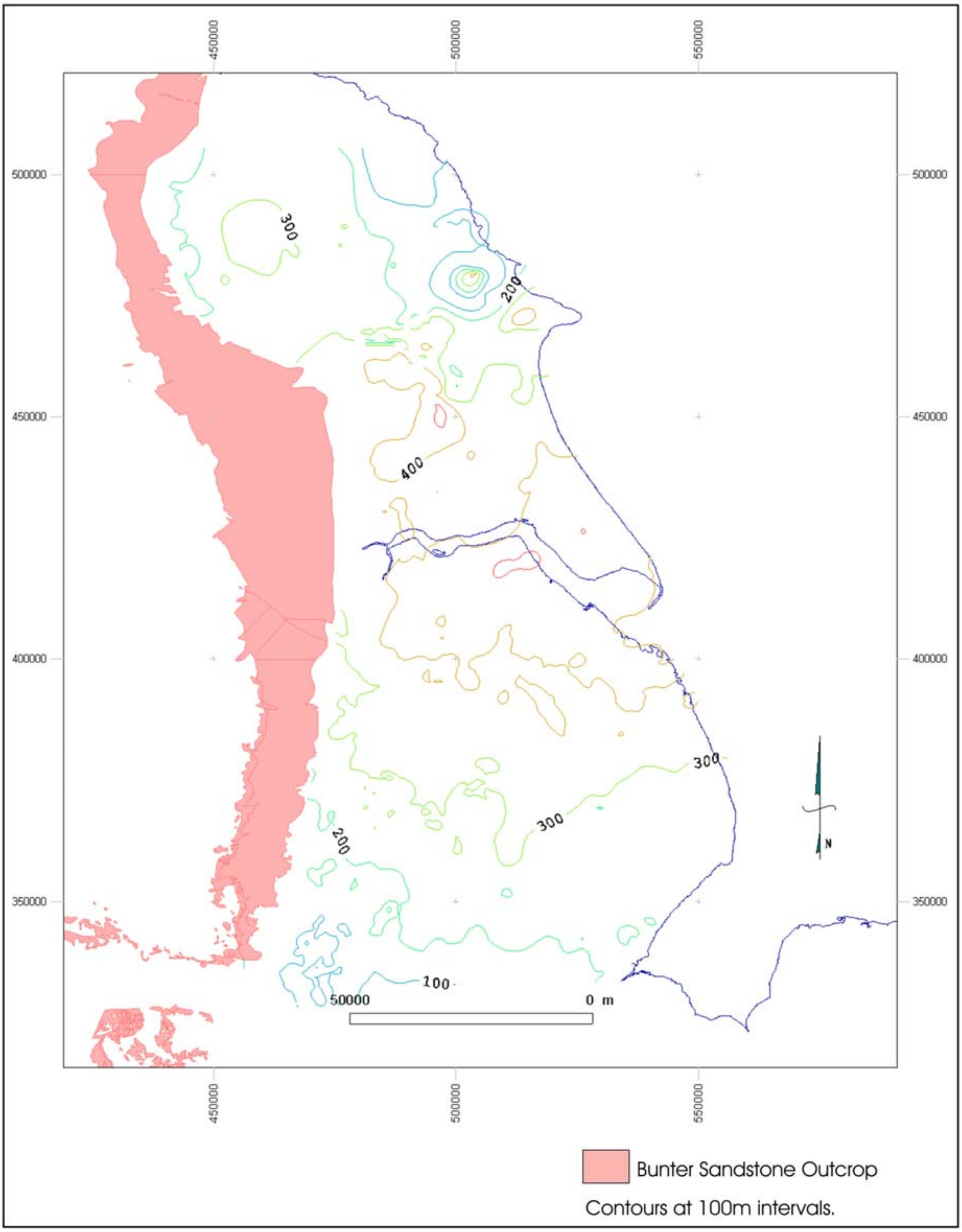

Figure 2a1.7 Isopach map of the Bunter Sandstone Formation, Eastern England

Depth limitations on CO_2 storage in the Bunter Sandstone

At its western edge and over much of the onshore area and part of the offshore area, the top Bunter Sandstone is at depths of less than 800m. Given that the geothermal gradient (correct at the Cleethorpes borehole) to the Sherwood Sandstone in eastern England is approximately 30°C/km (Figure 2a1.8), this area can probably be discounted for CO_2 storage because any CO_2 stored at these depths will be too close to the dense phase/gas phase boundary for safety, or in the gas phase and therefore not dense enough for economic storage.

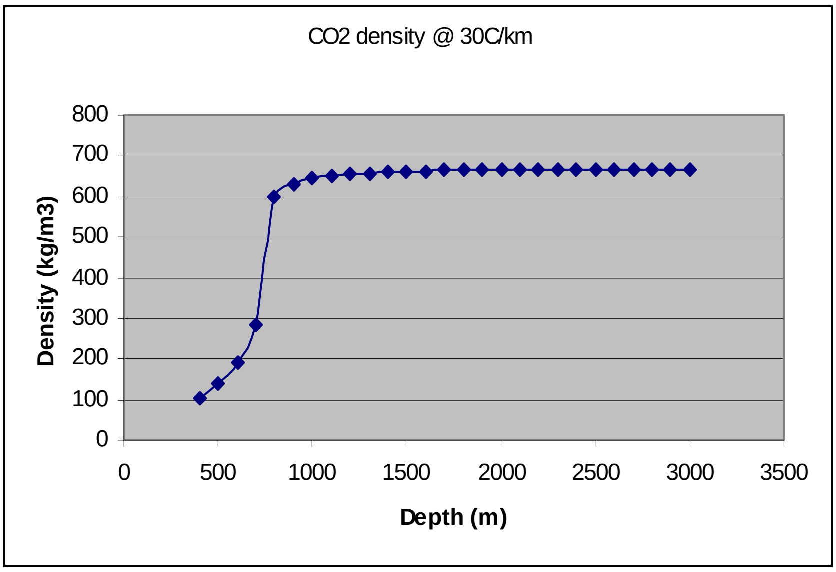

Figure 2a1.8. CO_2 density versus depth at a geothermal gradient of 30°C km^{-1}

Depositional history of the Bunter Sandstone

The sedimentary architecture and reservoir characteristics of the Bunter Sandstone are related to its depositional environment. The Bacton Group (of which the Bunter Sandstone is the uppermost unit, see Figures 2a1.2 and 2a1.3) as a whole represents a phase of clastic deposition in a non-marine environment which became established when the pre-existing Permian Zechstein Sea withdrew. Consequently, largely non-marine strata were deposited in the form of red mudstones, shales and sandstones (Glennie, 1986).

The Bunter Sandstone is made up mainly of a series of red, medium to coarse-grained sandstone units laid down in metre-scale coarsening upward cycles (Rhys, 1974). These are interbedded with coarser sandstones and conglomerates, which usually occur in relatively thin, metre-scale beds (Figure 2a1.9). In terms of depositional environments, the strata deposited near the basin margins probably formed as a series of coalescing alluvial fans which were dissected by braided river channels deposited in a semi arid to arid climate. In the centre of the basin there are far fewer conglomerates and the sandstone was probably mostly deposited by sheet floods on a large flat plain.

Figure 2a1.9. Sherwood Sandstone at outcrop, Great Heck Quarry, Mansfield Nottinghamshire. Metre-scale sandstone beds are interbedded with conglomerates

Lithology of the sandstones

In most places, the sandstone is made up mainly of well sorted and rounded to sub-rounded quartz, feldspar and rock fragment grains. At outcrop in eastern England it is commonly weakly cemented and friable. In the shallow subsurface, towards the margins of the basin it is commonly cemented by calcite, other carbonates, anhydrite, and quartz and feldspar overgrowths. Additionally, in the centre of the basin in the southern North Sea, the porosity and permeability of the Bunter Sandstone varies greatly due to the presence of secondary halite cement in the pore spaces. Where halite is present in pores virtually no porosity is preserved; where it is absent, porosity may be up to 25%.

Detrital mineralogy of the sandstones

Burley (1984) showed that, in the UK, there is a gradual decrease in grain size and an associated change in detrital mineralogy away from the proximal areas of Bunter Sandstone deposition in the south and southwest UK, towards distal areas of deposition in the North Sea and Irish Sea. Considering the UK, southern North Sea and eastern England in more detail, the area around Nottingham, where coarse grained and pebbly, more proximal sandstones are common towards the base of the formation, was a proximal area. Thus, by inference, the

London Platform (or London-Brabant Massif) as far north as Nottingham may have been the main source area affecting sand supply to eastern England and the southern North Sea. This is supported by inferences from study of the Hewett gas field, which is close to the London Platform (Cooke-Yarborough 1991). Core, log and microscopic descriptions confirm that the UK southern North Sea was a distal area of deposition, as was much of the northern and central part of the eastern England outcrop and subcrop, north and east of Nottingham

In proximal regions, feldspar and rock fragments are abundant and the sandstones are lithic arkoses to sub-arkosic litharenites. Feldspar, almost invariably a potassian variety, may account for as much as 30% of the whole rock, whilst in the more lithic sandstones up to 50% of the whole rock may consist of a mixture of sedimentary, igneous and metamorphic rock fragments. Simple and polycrystalline quartz make up the bulk of the remaining detrital constituents, with mica, heavy minerals and opaque minerals being only minor constituents.

In distal regions, where the sandstones are mostly fine-grained, they are dominantly sub-arkoses, sub-litharenites and quartz arenites. Simple quartz is the dominant detrital component, always accompanied by subordinate polycrystalline quartz. Together they typically amount to at least 50-65% of the whole rock. Feldspar, averaging around 5-10% and again dominantly potassian, and rock fragments (averaging 10-15%) are much less abundant than in proximal regions. Mica, heavy minerals and opaque minerals are only minor components.

No whole rock mineral analyses are available for the UK southern North Sea. However, point count analysis of two samples of the Sherwood Sandstone from the Cleethorpes 1 well, drilled on the North Sea coast of the UK, are shown in Table 1 below. These indicate a quartz content of around 50% (including quartz cement, which is difficult to separate from detrital quartz), a feldspar content of 11-19% and a rock fragment content of about 4-5%, indicating a distal detrital mineralogy.

Table 1 Point count analyses, based on approximately 400 counts per sample, of the Sherwood Sandstone in the Cleethorpes 1 well, UK (figures are percentages).

Quartz	**K-feldspar**	**Plagioclase feldspar**	**Rock fragments**	**Mica**	**Clay matrix**	**Quartz cement**	**K-feldspar cement**	**Calcite cement**	**Dolomite cement**	**Illite**	**Porosity**
38.2	15.7	3.7	4.0	0	4.7	12.5	0	0	2.5	4.0	14.7
39.8	11.0	0.0	5.3	0.8	1.8	9.0	0	0	7.5	0.3	24.8

From Czernichowski-Lauriol et al, 1996).

The detrital mineralogy of the Bunter Sandstone in the UK sector of the southern North Sea is likely to be similar to that at Cleethorpes, except that some of the porosity is likely to be occluded by halite cement. This is commonly observed in North Sea Bunter Sandstone cores (e.g. Bifani 1986).

Diagenesis

Eodiagenesis

Burley (1984) showed that a suite of early diagenetic (eodiagenetic) changes can be recognised across the whole area of deposition of the Bunter Sandstone. These are the result of reactions between the sediment and the atmosphere before the sandstone was buried, and subsequent reactions between the sediment and near surface pore waters that took place when the sediment was shallowly buried. They are:

Grain dissolution

Grains have been leached and broken down according to their stability in the atmosphere or the intrastratal solutions that were present when the sandstones were buried in the shallow subsurface. Feldspars, rock fragments and heavy minerals have been intensively leached such that no pyroxene, amphibole or olivine is present. Large oversize pores are commonly present, some of which contain relics strongly suggestive of the former presence of ferromagnesian minerals. Feldspars in the rock are mostly K-feldspar, with plagioclase being a minor component. Usually microcline and plagioclase are unaltered but orthoclase and perthite are intensively leached. Heavy minerals usually comprise a suite consisting of zircon, rutile, tourmaline, staurolite, and opaques suggesting that the more unstable heavy minerals that were likely to have been present have completely dissolved.

Grain replacement

Many grains have been entirely or partly replaced on a molecule by molecule basis by a variety of authigenic minerals; mainly clays, haematite and carbonates. Authigenic clay replacement starts preferentially along planes of weakness within the minerals, e.g. along cleavage planes.

Precipitation of authigenic minerals as cements

Depending on the physico-chemical conditions in the pore spaces in the shallow subsurface environment, minerals have been precipitated as a variety of cements. These cements are likely to have been derived at least in part from the dissolution processes described above. Small incipient quartz overgrowths coated with authigenic clay are common. Feldspar overgrowths are abundant on orthoclase and perthite grains. Feldspar also occurs as discrete pore-filling crystals and as a cement on detrital quartz grains. Authigenic clays, typically mixed layer illite-smectite, commonly occur as pore-lining cements.

Early carbonate cements are typically non-ferroan dolomites, often associated with clay replacements of former ferromagnesian mineral grains. Dolomite also occurs as small nodules that are probably incipient caliche horizons - these are commonly concentrated near the tops of the fluvial beds.

Mesodiagenesis

Although there is no direct data available from the North Sea, in the Wessex Basin, an onshore basin in southern England some 300 km southwest of the southern North Sea, a set of mesodiagenetic effects that appear to be related both to depth of burial and the nature of the later-circulating pore fluids are superimposed on the eodiagenetic changes. Where early cements were absent, compaction reduced porosity to very low levels. Grains typically have long and sutured contacts and intergranular porosity is negligible. However, where early framework-preserving pore filling cements (anhydrite in the Wessex Basin) were extensively dissolved, widespread secondary porosity was developed.

The halite cement recorded in cores in the southern North Sea is therefore probably an early framework-supporting cement that has been partially dissolved.

Porosity and permeability of the Bunter Sandstone

The average porosity of 603 core plugs taken from wells in the UK sector of the North Sea is 18.7%. However, in individual wells the average core porosity ranges from 2.4% (well 42/10a-1) to 22.02% (42/25-1).

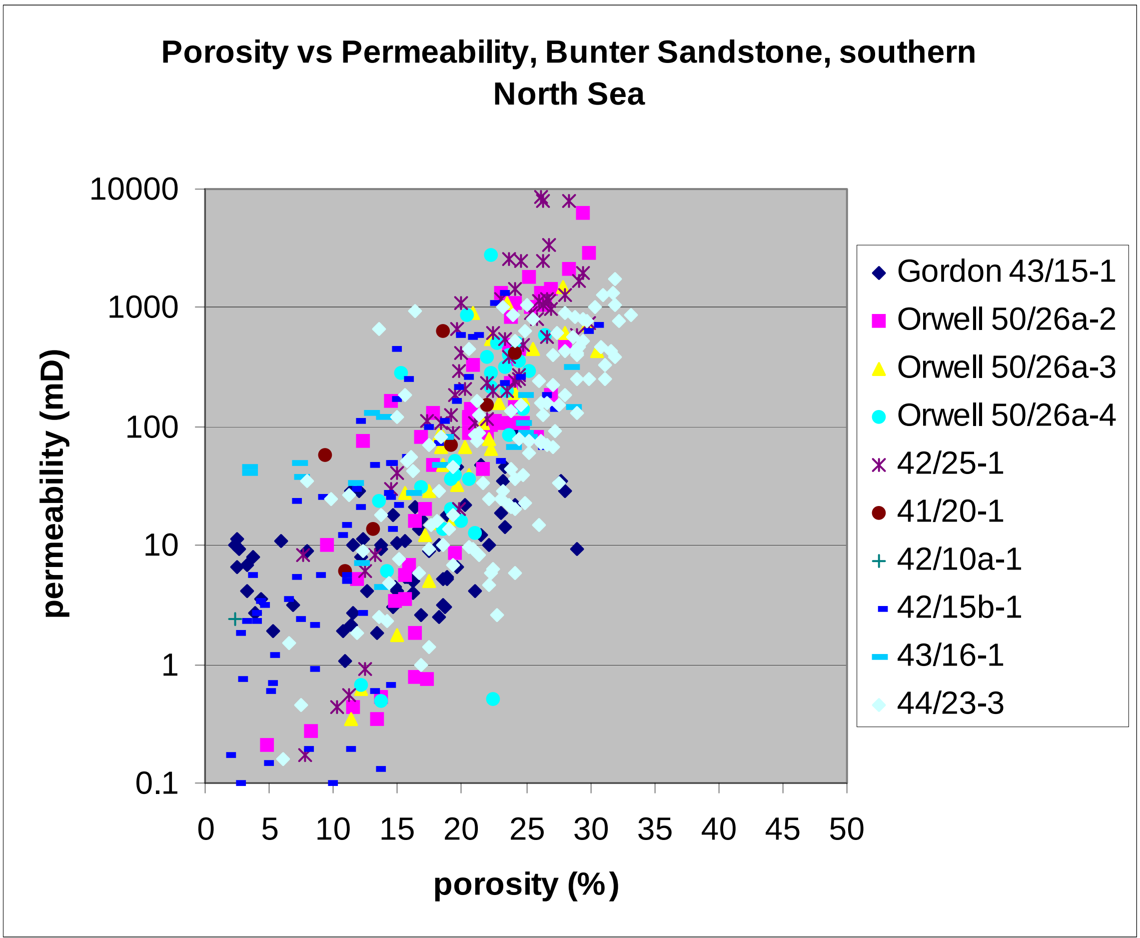

Figure 2a1.10. Crossplot of porosity versus permeability determined by conventional and special core analysis in the Bunter Sandstone, southern North Sea.

Additionally, porosity and/or permeability in 4 fields are quoted in Abbotts (1991):

Table 2 Porosity/permeability of four Southern North Sea gas fields

Field Name	Average porosity (%)	Average permeability (mD)
Hewett	21	500
Indefatigable	25	450
Little Dotty	21	350
Esmond	No data available	86.7

Figure 2a1.10 shows that there is wide scatter in the relationship between porosity and permeability when the entire dataset of 603 points is considered together, making it difficult to predict porosity and permeability distribution in the basin or even porosity vs. permeability relationships. This is an important risk in exploration for CO_2 storage prospects. Log analysis of porosity is hampered by the presence of halite cement, which tends to create a falsely high porosity reading on density logs and a pronounced false gas effect on density/neutron logs.

Pore fluids in the Bunter Sandstone

In the southern North Sea, in the absence of halite cement and hydrocarbons, the pore space is filled with highly saline salt-saturated water. In the Esmond field this has a salinity of 13 000 to 205 000 ppm. The specific gravity of the brine is approximately 1.21 g/cc at 60°F.

Seal Description

The Bunter Sandstone is sealed by the mudstones and evaporites which make up the Upper Triassic Haisborough Group (Figure 2a1.2). Most of the Haisborough Group was deposited in the distal floodplains of a subsiding onshore basin. However, intercalations of evaporites and coastal sabka deposits indicate intermittent widespread marine incursions across the basin.

The Haisborough Group comprises three formations. The lowest is the Dowsing Dolomitic Formation which reaches a maximum thickness of 420m in the Southern North Sea Basin (figure 2a1.11). It is dominated by red, silty mudstones but towards the base is the Rot Halite Member which forms the main seal for much of the Bunter Sandstone. Overlying the Dowsing Dolomitic Formation is the Dudgeon Saliferous Formation which consists of thick, predominantly green mudstones up to 100m thick. The Keuper Halite forms the boundary between the Dudgeon Saliferous Formation and the overlying Triton Anhydritic Formation. The Triton Anhydritic formation has a maximum thickness of 250m in the southeast of the Basin. It consists of a monotonous sequence of red mudstone with a few layers of anhydrite that form the Keuper Anhydritic Member.

This series of halites, mudstones and anhydrite forms an excellent, thick and laterally continuous layer above the Bunter Sandstone that could make an excellent seal for CO_2 if the Bunter Sandstone was to be used for storage.

The Bunter Sandstone is a major gas producing reservoir in the Southern North Sea. In the UK sector it is one of the reservoirs in the Hewett and Little Dotty fields and the only reservoir in the Esmond, Forbes, Gordon and Orwell fields. This proves the seal efficiency of the Haisborough Group at a wide range of locations. In the case of the Esmond gas complex the main seal is the Rot Halite Member, which is part of the Dowsing Dolomite Formation (Ketter, 1991). The presence of gas in the Bunter Sandstone proves that the Haisborough Group can trap gas for geological timescales.

The Zechstein salt underlying the Bunter Sandstone and Shale would also likely act as a seal (Figure2a1.12), as it does for the underlying Rotliegend gas fields.

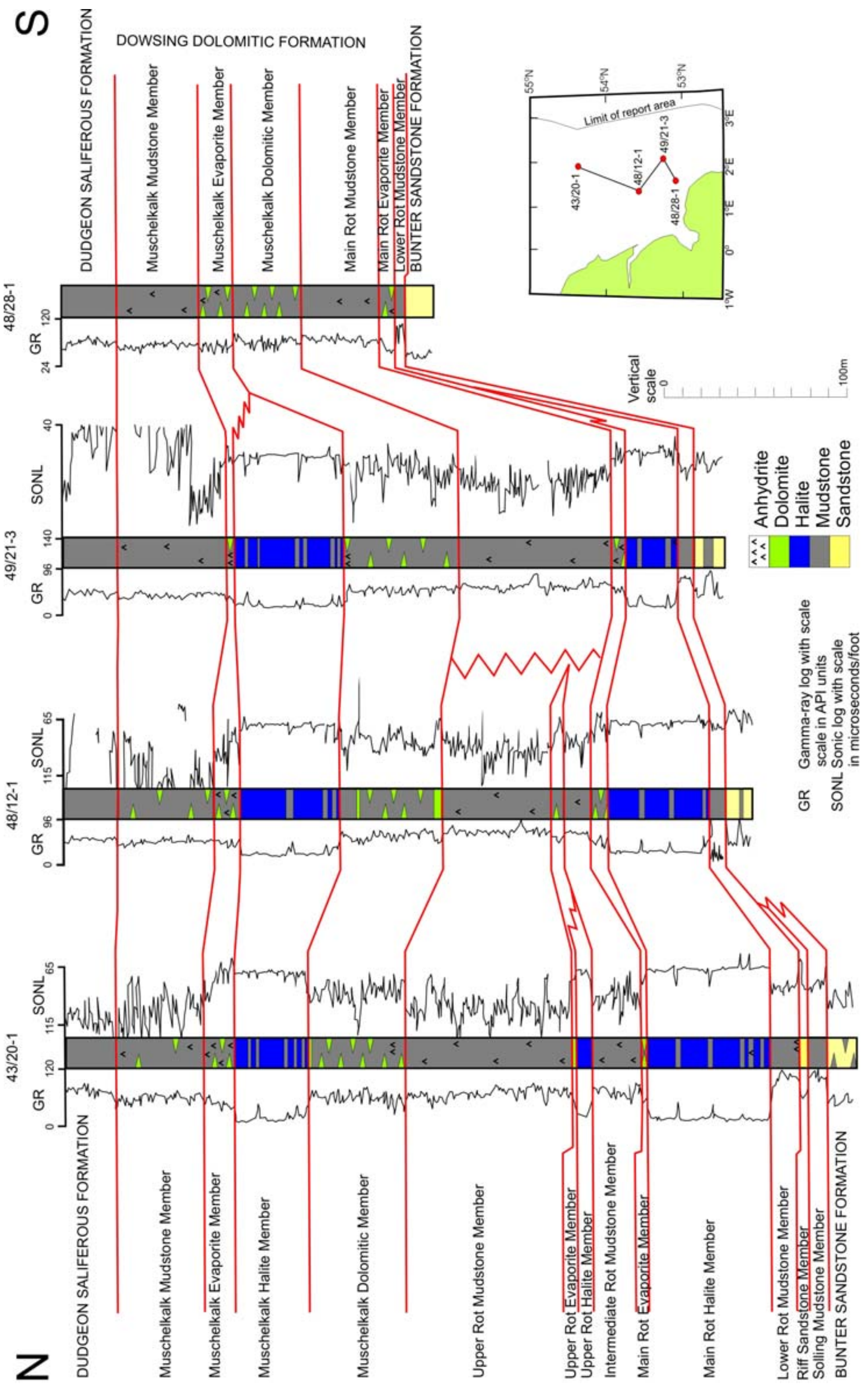

Figure 2a1.11 Correlation of the Dowsing Dolomitic Formation in 4 offshore wells (adapted from The geology of the southern North Sea)

Structure

The dominant structural fabric of the Bunter Sandstone Formation offshore is a result of mobilisation (or creep) of the Zechstein Salt in response to the differential loading effect of overlying strata. The salt mobilised into a series of very large pillows and domes and resulted the folding of the overlying strata. Most of the salt movement postdates the deposition of the Bunter Sandstone Formation and thus the salt movement resulted in the formation of a series of very large closed structures in the sandstone.

Salt movement resulted in extension and ultimately faulting of the overlying strata on the crests of some structures. These crestal faults may compromise the integrity of the seal above the Bunter aquifer. Faulting is particularly prominent on steep sided diapirs where the overlying sediments are tightly folded at the apex of the structure. In lower relief pillow and anticlinal structures the faults tend to have smaller offsets or, in very low relief structures, are completely absent (Figure 2a1.12). In many cases the overlying Rot salt may have subsequently sealed the faults. However, cases like this should be avoided in site selection, as the uncertainty of the seal integrity is greater.

The salt withdrawal into the diapiric structures also produced migration windows for gas to migrate from the rich Carboniferous source up into the Bunter Sandstone Formation. This could only occur in areas where the salt withdrew sufficiently such that the Zechstein salt became very thin or completely absent. However, these migration windows are relatively few and far between. As a result it is probable that many structural traps in the Bunter sandstone Formation remain devoid of hydrocarbons, but could potentially be sound and utilised as CO_2 storage facilities.

CO_2 could also be stored in regional flat lying areas, as is currently happening is in the flat lying Utsira sand at the Sleipner gas field. In such areas CO_2 might become trapped beneath thin shales within the formation, or in very small closures on the underside of the cap rock However, a more detailed regional analysis of migration paths would be necessary to assess the chances of migration to points where the CO_2 might leak to the sea bed.

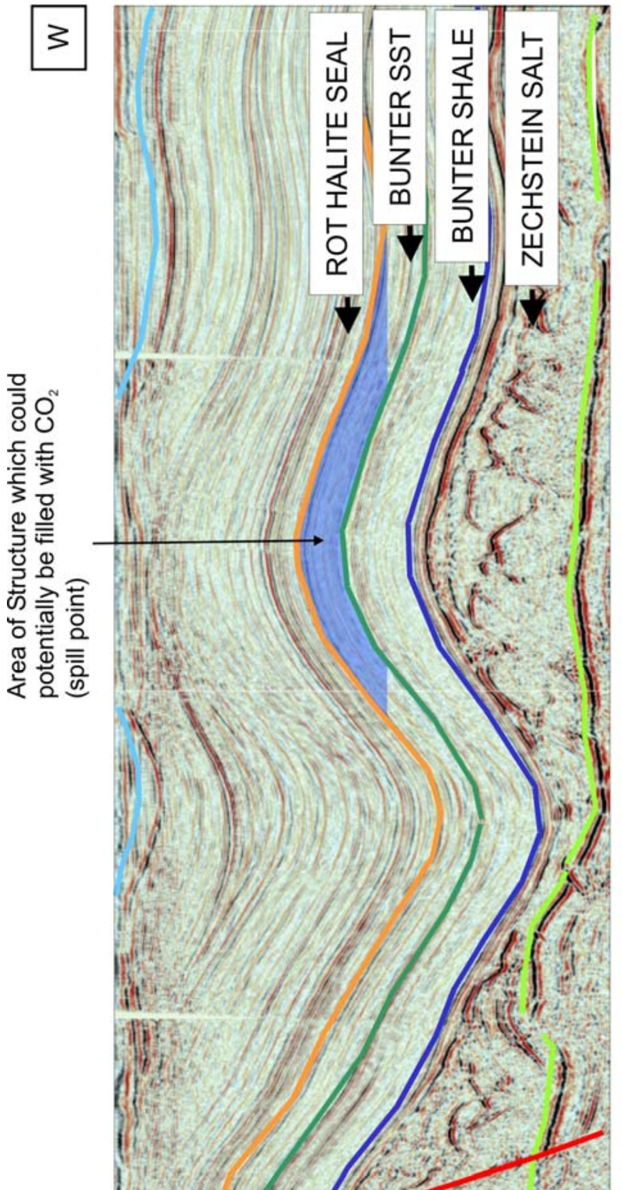

Figure 2a1.12 Seismic line showing Salt related closure in the Bunter sandstone (data courtesy of WesternGeco)

Injectivity of the Bunter Sandstone

There is significant uncertainty over the rate and volumes of CO_2 that could be injected into the water-filled porosity of the Bunter Sandstone. In order to enter the reservoir rock, CO_2 would either have to displace the reservoir pore water or compress the water and expand the rock that makes up the reservoir. In practice it is likely that a combination of these two processes would operate.

In the former case, if the pore water could be displaced easily, large volumes of CO_2 might be injected before an unacceptably high reservoir pressure was reached in the area around the well. Although the Bunter Sandstone is hydrostatically pressured, implying connectivity with the surface, over much of its extent in the UK sector of the southern North Sea it is well sealed by the Zechstein evaporites beneath and the Rot salt and Haisborough Group mudstones above. Furthermore, the preferred injection sites (the major closed structures) are a minimum of several tens of kilometres from the outcrop in the UK onshore area. Thus the primary opportunity for pore water (and thus the pore fluid pressure) to bleed off from the formation in the area of the well is likely to be through breaches in the overlying strata caused by faulting rather than displacement in the far field. In order for the injected CO_2 to remain trapped, these breaches would have to be outside the area occupied by the CO_2, requiring careful site selection.

If only the latter process operated, the maximum compressibility of the reservoir pore water and expansion of the rock is likely to be in the order of 2%. The volume of reservoir over which this compression could take place, and thus the volume of CO_2 that could be injected, would depend largely on the volume of well-connected permeability within the reservoir.

Reservoir simulations using the Esmond gas field reservoir model were undertaken to try to better understand the volumes of CO_2 that might be injected into the Bunter Sandstone. A cross section through the Esmond Field is shown in Figure 2a1.15. The reservoir was modelled as if it were a virgin aquifer. Two end members of a range of aquifer sizes were simulated:

In the first aquifer simulation, the field was (unrealistically) assumed to be fully bounded (i.e impermeable) at the gas-water contact. This is known not to be the case as there was aquifer activity in the Esmond field; water influx into the field occurred from the underlying water-bearing sandstone when the gas was produced (Ketter, 1991). In this simulation, some 3.5 million tonnes of CO_2 could be injected into the field before a limiting reservoir pressure of approximately 1.35 times the hydrostatic pressure (207 bar = 3000 psia) was reached.

In the second simulation, no lateral boundaries were assumed to the reservoir rock, i.e. the Bunter Sandstone Formation was considered to continue from the top of the structure to infinity with the same mean thickness and mean permeability. In this simulation approximately 31.6 million tonnes of CO_2 could be injected before the limiting reservoir pressure was reached. This represents 65% of the Esmond Field pore volume. [However, the Esmond field did not fill the Esmond structural closure to spill point (Bifani 1986) so the average CO_2 saturation over the whole structural closure would be less than 65%].

These simulations indicate:

1. That the intrinsic permeability of the Bunter Sandstone reservoir rock at Esmond is adequate for CO_2 storage; the limiting factors are whether, and where, there are major permeability boundaries within the Bunter Sandstone reservoir, or leak-off points that would allow fluid to be discharged to other strata.
2. Given Esmond rock properties, the likely average CO_2 saturation that could be achieved in the Bunter Sandstone will be less than or equal to 65%.

Location of potential storage structures

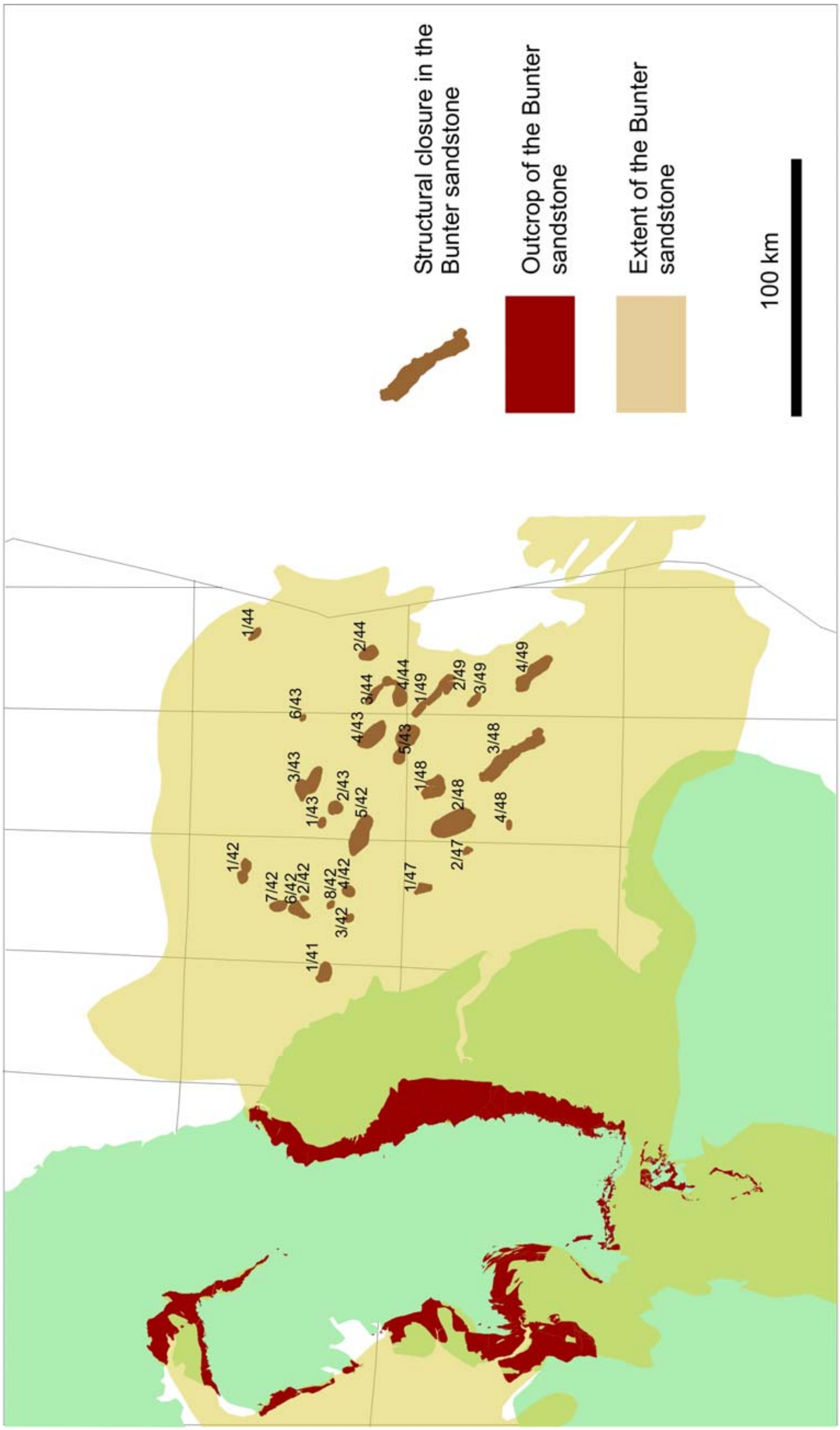

Figure 2a1.13 Location of the major structural closures in the Bunter Sandstone Formation offshore in the southern North Sea

Storage Capacity

The total storage potential of the Bunter Sandstone Formation was calculated as follows:

Closed structures were identified using seismic reflection data and maps (figure 2a1.13) digitised from originals provided by the UK DTI. The area of the closures was calculated using ArcView 3.2a. Average core porosities were used. The close spacing of wells permitted the reservoir thickness to be calculated for each individual structure. The reservoir temperature was calculated from the depth assuming a surface temperature of 10°C and a geothermal gradient of 30°C/km. The reservoir pressure was assumed to be hydrostatic. Pore space saturation of 40% CO_2 was assumed for each of the structures. The storage capacity was calculated in tonnes of CO_2 using the equation below.

Amount of CO_2 tonnes = (Area x thickness x porosity x density of CO_2) x 0.4

Table 3 Storage capacities of the major structural closures in the southern North Sea

Closure Name	Area (m^2)	Depth (m)	Thickness (m)	Average Core Porosity	Pressure (Mpa)	Density of CO_2	Total Pore Volume (m^3)	CO_2 stored (MT) 40% pore space saturation
5/43	106604196	1600	262.5	0.18	162.6688	0.6624376	5037048283	8342
4/43	87874997.8	1800	250	0.18	182.8774	0.6641573	3954374902	6566
1/43	8218386.06	1200	150	0.18	122.2516	0.6541464	221896423.5	363
1/48	62737184.5	800	300	0.18	81.8344	0.6009652	3387807962	5090
2/48	180678309	1100	375	0.18	112.1473	0.6497103	12195785838	19809
3/48	177715633	1200	275	0.18	122.2516	0.6541464	8796923844	14386
2/44	36634215.9	1400	175	0.18	142.4602	0.6594876	1153977800	1903
4/44	54592459.3	1400	225	0.18	142.4602	0.6594876	2210994603	3645
3/44	19519238.7	1600	212.5	0.18	162.6688	0.6624376	746610881.6	1236
3/43	87325385.9	1400	150	0.18	142.4602	0.6594876	2357785419	3887
1/41	38389372.8	400	175	0.18	41.4172	0.1007283	1209265245	305
4/49	94649284.8	1200	250	0.18	122.2516	0.6541464	4259217814	6965
4/48	3315938.42	1600	175	0.18	162.6688	0.6624376	104452060.1	173
2/42	2853850.66	1000	137.5	0.18	102.043	0.6428487	70632803.74	114
4/42	17254618.1	1400	187.5	0.18	142.4602	0.6594876	582343361.4	960
3/42	6145169.83	1200	237.5	0.18	122.2516	0.6541464	262706010.4	430
1/42	32248591.7	1200	37.5	0.18	122.2516	0.6541465	217677994.1	356
3/49	13079112.4	1400	212.5	0.18	142.4602	0.6594876	500276050	825
5/42	117520230	1400	150	0.18	142.1602	0.6594876	3173046221	5231
6/42	34269721.3	1300	162.5	0.18	132.3559	0.6572377	1002389348	1647
7/42	22673167	1100	112.5	0.18	112.1473	0.6497103	459131632.3	746
2/43	25473682.6	1000	200	0.18	102.043	0.6428487	917052572.2	1474
1/44	8638407.32	1600	25	0.18	162.6688	0.6624376	38872832.94	64
1/47	17747806.7	1700	112.5	0.18	172.7731	0.6634092	359393085.3	596
2/47	4751521.89	1600	225	0.18	162.6688	0.6624376	192436636.4	319
1/49	48444370.1	800	225	0.18	81.8344	0.6009652	1961996988	2948
2/49	10610630	1400	225	0.18	142.4602	0.6594876	429730513.3	709
8/42	4176487.53	1200	187.5	0.18	122.2516	0.6541464	140956454.2	231
6/43	1930226.57	1600	150	0.18	162.6688	0.6624376	52116117.26	86
			Total Storage Capacity of the Bunter Closed Structures					89404.7775

The storage capacity of the Bunter Sandstone as calculated is subject to the following limitations:

It takes no account of the possibility of CO_2 leakage from any of the mapped closed structures. It is recommended that a detailed study of all the major structures should be carried out using 3D seismic surveys to detect and characterise any faults.

It takes no account of potential storage of CO_2 by dissolution in the formation pore water or reaction with the reservoir rock.

It is assumed that CO_2 injection would take place directly into a large closed structure. Thus it takes no account of the potential storage of CO_2 in small unmapped closed structures on the base of the cap rock that will occur outside the major structural closures.

The potential storage capacity of the Bunter Sandstone gas fields is included in Table 6. Water influx occurs into at least some of these fields (Ketter, 1991; Cooke-Yarborough, 1991), so they may not contain significant volumes of low pressure pore space after production ceases. Therefore for the storage potential calculation they were treated in a similar manner to the water-filled structures in the Bunter Sandstone, i.e. it was assumed that 40% of their pore volume could become saturated with CO_2.

The total pore volume of the Bunter Sandstone Formation in the UK southern North Sea was calculated by deriving its area from maps and taking an average CO_2 density, sandstone thickness and porosity. Net:gross ratio was taken from the Bunter Sandstone Formation in the Esmond gas field.

Table 4. Total pore volume of the Bunter Sandstone Formation

Area m^2	Average depth m	Average thickness m	Net: Gross	Average porosity	Pressure MPa	Average CO_2 density t/m^{-3}	Total Pore Volume m^3
5.3641E+10	1296.55	191.81	0.82	0.18	131.997	0.634	152E+10

Comparison of Tables 3 and 5 indicates that approximately 3% of the pore volume of the Bunter Sandstone Formation is in closed structures.

POTENTIAL CONFLICTS OF INTEREST THAT MIGHT IMPACT ON CO_2 STORAGE IN THE BUNTER SANDSTONE

In the onshore area, the most obvious potential conflict of interest is with the water industry. The Bunter Sandstone is used for the supply of potable groundwater (Figure 2a1.14) and the potential contamination of this groundwater by mobilised brines or CO_2 is clearly a potential threat. There might also be a conflict of interest with the mining industry in eastern England as, stratigraphically, the Sherwood Sandstone is not far above the Coal Measures and there might be potential for CO_2 to leak into mine workings. There might also be potential for contamination of the low enthalpy geothermal resource identified in the Sherwood Sandstone in the Cleethorpes borehole. However, CO_2 sequestration is not likely to take place onshore - because there are no large closures suitable for CO_2 storage in the part of the onshore area that lies below 800 m (shown in Figure 2a1.14). These potential conflicts of interest become more remote when considered in relation to CO_2 storage in the centre of the Southern North Sea basin. Nonetheless, some modelling of the likely impact of displaced saline brines on the onshore Sherwood Sandstone aquifer might be necessary.

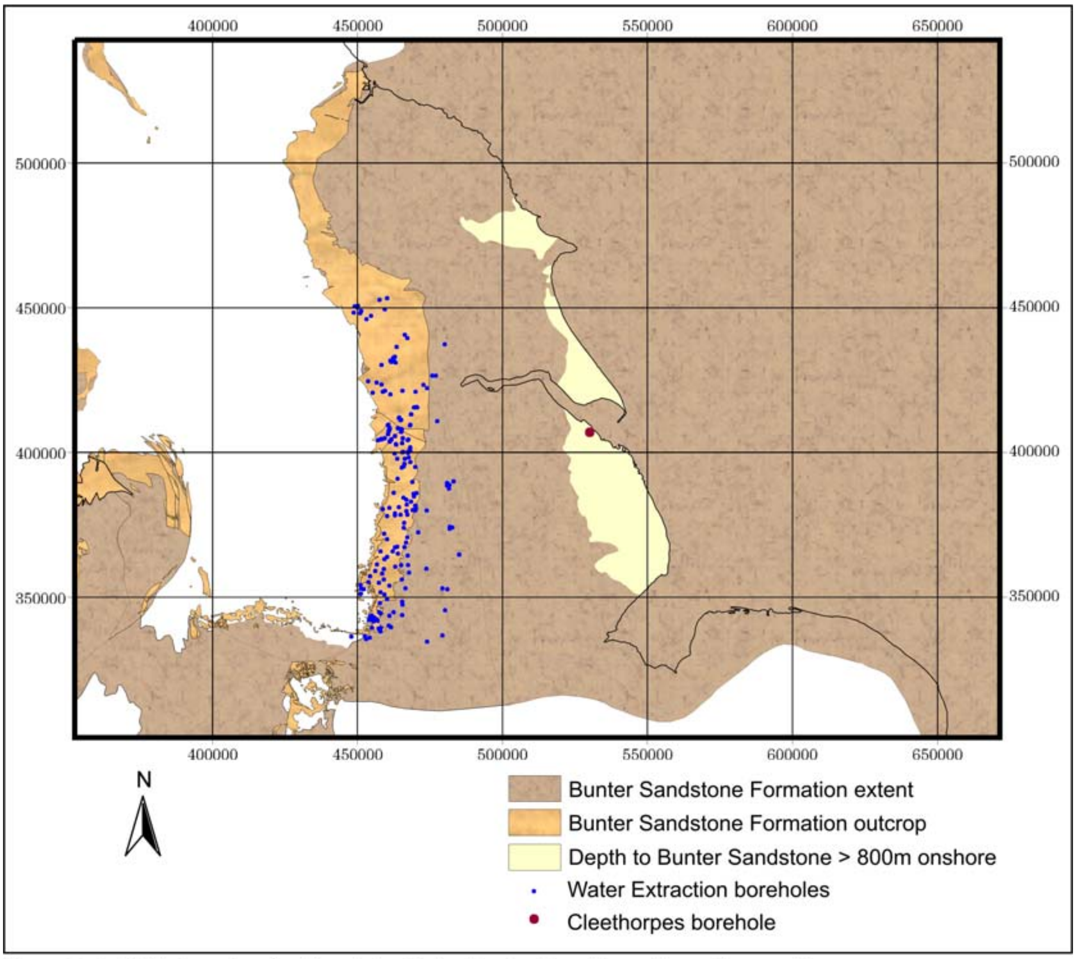

Figure 2a1.14 Water extraction boreholes in the Bunter Sandstone Formation aquifer

Offshore, there are potential conflicts of interest with the hydrocarbon production industry. For example, acidic, CO_2-rich brines could corrode production wells that pass through storage structures. If a CO_2 repository were to leak, then there could be conflicts of interest with the fishing and shipping industries and also consequences for marine life.

SAFETY AND SECURITY OF STORAGE IN THE BUNTER SANDSTONE FORMATION, OFFSHORE UK

Introduction

Potential security of storage issues associated with the injection of CO_2 into a closed structure (e.g. a dome) developed in a reservoir rock are considered to be as follows:

Geochemical issues

- Corrosion of the reservoir rock matrix by CO_2/water mixtures, leading to the compaction or collapse of the formation and thus to the development of cracks and new migration paths through the cap rock
- Precipitation of minerals in the pore spaces of the reservoir rock, leading to injection problems. This could mean that injection would have to be abandoned if a safe pore fluid pressure was likely to be exceeded
- Dissolution of components of the cap rock by CO_2/water mixtures, leading to its collapse or failure as a seal
- Dehydration of the cap rock, leading to shrinkage and the creation of new pathways through it for CO_2.
- Dissolution of CO_2 into the pore fluid and transport out of the structure by natural or induced pore fluid flow

Pore fluid pressure issues

- Fracturing of the cap rock, due to increased pore fluid pressures in the reservoir.
- The opening up of pre-existing but closed migration paths (e.g. faults) through the cap rock, caused by increased pore fluid pressures during injection
- Gas pressure in the CO_2 accumulation exceeds the capillary entry pressure of the overlying cap rocks, resulting in CO_2 transport through the cap rock

Well issues

- Escape of CO_2 via poorly sealed pre-existing wells or by failure of the injection well
- Escape of CO_2 due to corrosion of cement or steel in wells penetrating the storage structure or cement holding the borehole casing to the surrounding rock

Other issues

- The presence of unidentified migration paths through the cap rock
- Escape of CO_2 via a spill point at the base of the closed structure, e.g. due to underestimated viscous fingering or incorrect mapping of structural closure

These are examined below with reference to the Bunter Sandstone of the UK sector of the southern North Sea.

Geochemical issues

Potential for the corrosion of the reservoir rock due to the injection of CO_2. Potential for CO_2 injection to cause precipitation of minerals in the pore spaces of the reservoir rock.

Effects of CO_2/water mixtures on the Bunter Sandstone

The effects of CO_2/seawater and CO_2/de-ionised water mixtures on the Bunter Sandstone at the Cleethorpes well and elsewhere onshore in the UK have been tested experimentally (Czernichowski-Lauriol et al. 1996). The main reactions that occurred were:

- Dissolution of K-feldspar
- Dissolution of dolomite cement
- Very rarely, development of secondary calcite within the sandstone
- Possible precipitation of secondary clay (this was only tentatively identified), associated with the corroded K-feldspar
- Slight increases in porosity for most samples

These reactions occurred over the several months duration of the experiments. For an actual CO_2 storage scenario, many years would be available for reaction to occur, and so slower processes (such as calcite precipitation) might have long enough to make a bigger impact.

Unfortunately, no experiments have yet been conducted using CO_2 and highly salt-saturated water mixtures. Nor have any experiments been conducted on samples containing halite cement. It is likely that any introduction of fresh water or seawater would result in dissolution of halite cement near the injection well. CO_2 solubility is lower in salt-saturated waters than in more dilute waters. It is not considered that the high concentration of NaCl in the pore fluid would affect the general reactions described above significantly. A proviso with this however, is that some reactions might be accelerated. For example, highly saline CO_2-rich waters are known to be more aggressive to metals, and so corrosion of steel at the base of the borehole might be increased.

The effect of CO_2/water mixtures on anhydrite ($CaSO_4$) was also investigated experimentally by Rochelle, Bateman and Pearce (in Czernichowski-Lauriol et al., 1996). Anhydrite cement occurs in the Bunter Sandstone at Cleethorpes and also in the southern North Sea. Anhydrite remained unaltered in contact with supercritical CO_2 alone. Anhydrite was severely affected by the CO_2/water mixtures used. However, most of this reaction appears to have been due to the anhydrite equilibrating with the solutions used, with only a smaller amount of reaction being due to the presence of CO_2.

Effect of injecting dry CO_2 on highly saline pore fluid

Formation water will evaporate into the injected dry CO_2-rich gas phase, causing rising concentrations of solids dissolved in the formation water and eventually to the precipitation of salt. According to simulations (May, *this project*), salt precipitation from the highly concentrated brines will start early in the vicinity of the injection well. The permeability reduction due to salt precipitation is dependent on the actual pore size distribution and geometry. It should be determined experimentally on rock samples for better quantification of likely near-well permeability reduction. This could be very important for the injectivity of the well and might require periodic fresh water flushing.

<u>Potential for corrosion or dissolution of components of the cap rocks above and below the Bunter Sandstone</u>

The seal below the Bunter Sandstone Formation

The Bunter Sandstone is underlain by the Bunter Shale Formation, beneath which occurs the Zechstein Group.

The Bunter Shale Formation consists of two members:

- The Amethyst Member, which consists of interbedded sandstones and shales and immediately underlies the Bunter Sandstone over much of the southern North Sea. It occurs at the top of the Bunter Shale Formation and is underlain by the Bunter Shale Member. It is best developed in proximal areas, i.e. in the western part of the southern North Sea near the UK coast. Further east it shales out into the Bunter Shale Member.
- The Bunter Shale Member. This consists largely of red mudstones. It seals the lower Bunter gas accumulation in the Hewett field (Cooke-Yarborough, 1991) and thus can provide an efficient gas seal on its own.

The Zechstein Group is a thick succession of carbonates and evaporites that forms the main seal to the underlying Rotliegend and Carboniferous gas fields. Methane derived from the underlying Carboniferous strata is trapped everywhere that the Zechstein is thickly developed and not cut by faults. The only places in the UK sector of the southern North Sea where it appears to be less than 100% effective as a seal are where it is thin and cut by faults near the margins of the Basin, e.g. in the Hewett field (Glennie, 1997) and in areas where salt withdrawal into domes and pillows have reduced its thickness and broken up its bedding. Bifani (1986) concludes that the Esmond, Forbes and Gordon fields have been charged with methane via areas of salt withdrawal.

The seal above the Bunter Sandstone

The Bunter Sandstone is overlain over most of the UK sector of the southern North Sea by the Haisborough Group , except in the southeast of the UK sector where it has been removed by erosion over the Cleaver Bank High.

The Haisborough Group is a succession of mudstones and evaporites up to about 900 m thick. It contains up to 3 thick halite formations, known in upwards succession as the Rot Halite Member, The Muschelkalk Halite Member and the Keuper Halite Member. The distribution of these halites is more limited than that of the Haisborough Group as a whole (Cameron *et al.*, 1992), but they are expected to provide an excellent seal where present. Ketter (1991) states that the lowest members of the Haisborough Group; the Rot shale and the Rot halite, form the seal to the Bunter gas accumulations in the Esmond, Forbes and Gordon fields.

The likely effect of CO_2/water/rock reactions on the integrity of the Haisborough Group seal above the Bunter Sandstone

Experiments and analyses conducted on the Mercia Mudstone Group (the onshore equivalent of the Haisborough Group) by Rochelle, Bateman and Pearce (in Czernichowski-Lauriol, 1996), indicate that the main effect of CO_2/water mixtures on the mudstone element of the Haisborough

Group is likely to be corrosion of dolomite. Detrital dolomite is an important component of the rock, especially in the Dowsing Dolomitic Formation, which is the lowest formation in the Haisborough Group. Thus there could be a significant increase in mudstone porosity. However, it is not really known how widespread this corrosion would be in an injection situation, because reaction would be limited to areas where CO_2-rich waters actually contacted fresh mudstone.

In the experiments, dry CO_2 did not appear to affect the mudstones.

Anhydrite is an important component of the Haisborough Group, particularly in the Triton Anhydritic Formation, the highest formation in the Haisborough Group. As mentioned above, in experiments, anhydrite was severely affected by CO_2/water mixtures, because of the solubility of anhydrite ($CaSO_4$) in water rather than due to any direct effect of CO_2.

In summary, circulating CO_2-rich waters, undersaturated for NaCl and $CaSO_4$, could adversely affect the integrity of the Haisborough Group. This is partly because of the corrosion of dolomite (and potentially other carbonates and K-feldspar) by CO_2-rich water and partly because of the high solubility of anhydrite and halite in water. The amount of reaction with the rock would be limited by the amount of water able to penetrate the formation, the rapid saturation of that water with respect to NaCl and $CaSO_4$, and the buffering of the acidity of CO_2-rich water by carbonate dissolution.

Possibility of dehydration of the cap rock, leading to shrinkage and the creation through it of new pathways for CO_2

If the injected CO_2 is dry (probably the case to avoid corrosion) then it will initially take up water from the aquifer. However, with a rising plume of CO_2 there is the possibility that over time, the core of the plume could become progresively drier. If such dry CO_2 reached, and then ponded under, a clay-rich cap rock, then in theory it could take water out of it and cause shrinkage. In the experiments described above, conducted on the Mercia Mudstone (the onshore equivalent of the Haisborough Group), dry CO_2 did not appear to affect the mudstones. Furthermore, there are no known observations of this phenomenon in natural CO_2 fields.

Possibility of dissolution of CO_2 into the pore fluid and transport out of the structure by natural or induced pore fluid flow

It is estimated that a maximum of approximately 22 kg CO_2 m^{-3} brine could dissolve in the Bunter sandstone pore waters found in the southern North Sea. Given that there is unlikely to be any natural fluid flow in the aquifer below the CO_2 'bubble' injected into a closed structure in the Bunter Sandstone, the only opportunities for transport of CO_2 out of the structure as a dissolved phase are likely to occur during the injection period or shortly afterwards when pressure re-equilibration is taking place. As little CO_2 is likely to dissolve in the pore fluid during the injection phase (e.g. van der Meer 1996) this issue is probably a minor one.

Pore fluid pressure issues

Fracturing of the cap rock, due to increased pore fluid pressures in the reservoir

Natural pore pressure gradients in the Bunter Sandstone

The Bunter Sandstone in the UK sector of the southern North Sea is hydrostatically pressured (e.g. Cooke-Yarborough, 1991) and therefore, prior to CO_2 injection, there should be little or no natural fluid flow within the reservoir itself as there is no significant pore fluid pressure gradient to cause it.

Likely leak-off pressure

The leak-off pressure in the basal part of the seal overlying the reservoir (the Haisborough Group) should not be exceeded during the injection period because this could cause fluid to leak off into the cap rock (and possibly fracture it). In the absence of any data, the likely leak-off pressure had to be estimated empirically, using a function derived from an extensive set of well leak-off pressure data and RFT data:

The formula used is: the maximum allowable reservoir pressure is 1.35 times hydrostatic pressure for a depth down to 1000 m; this factor is increased to 2.4 for depths ranging from 1000 down to 5000 m (see Wildenborg *et al.*, 1996).

For example, for the Esmond gas field, with its reservoir depth of 1363 m ss, the leak off pressure was estimated as follows: 1.35 + (1363 –1000)/(5000-1000).(2.4-1.35) = 1.35 + 0.095288 = 1.445. So the injection pressure will be: 1.445* 1363 * 0,105 = 206.8 bar = 3000 psi. In which 0.105 is taken to be the mean density gradient of formation water.

Reservoir simulation of pore fluid pressure increases likely to be induced by injection of large volumes of CO_2

Reservoir simulation (described briefly above under injectivity) indicates that significant pore fluid pressure rise is to be expected when CO_2 is injected into the Bunter Sandstone.

Using the Esmond field reservoir model as representative of Bunter Sandstone geology, Obdam (2001) simulated the injection of CO_2 into the Bunter Sandstone aquifer in order to estimate how much CO_2 could be injected into the structure before the limiting reservoir pressure of 206.8 bar was reached. ECLIPSE input files containing a highly detailed, history matched reservoir model of the field were kindly made available by BHP Billiton UK.

The greatest modelling issue in this simulation was the question of where to define the lateral limits of the Bunter Sandstone aquifer. In the absence of any data suggesting any boundaries to the Bunter Sandstone reservoir in the Esmond area, the Esmond field reservoir model was extended by adding an infinite aquifer of the same permeability as the field to the model. This was done because there seemed no justification for introducing any boundaries into the model, or for extending the limits of the model with an aquifer of higher or lower permeability.

A summary of the simulation is given below:

Geology
The Esmond gas field is an almost circular dome-shaped closure in the UK sector of the southern North Sea that has now ceased gas production (Bifani 1986). The producing formation was the Bunter Sandstone, which is about 107 m thick at this location (Figure 2a1.15).

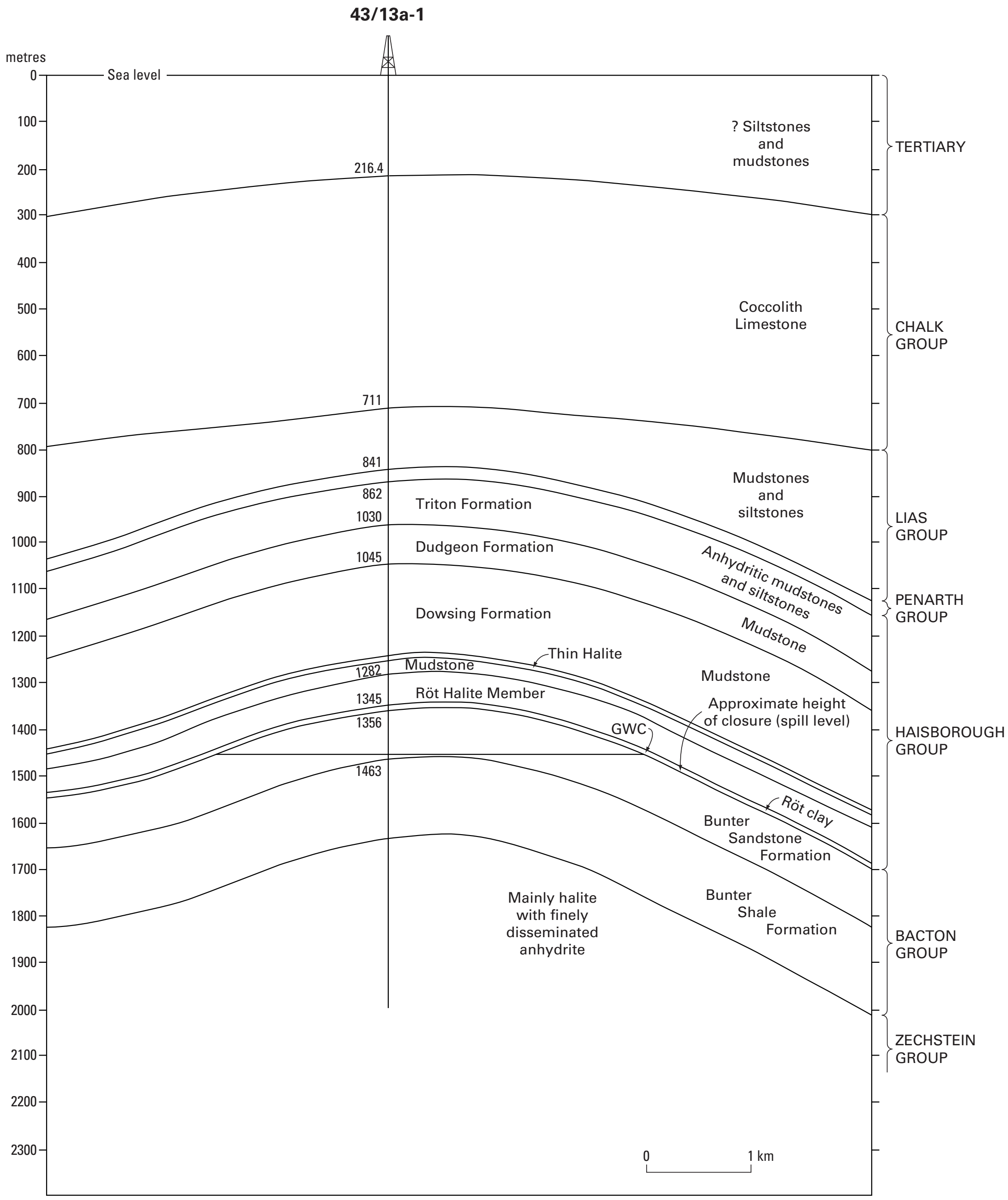

Figure 2a1.15. Schematic cross section through the Esmond gas field and overlying strata

It is overlain by Triassic mudstones and evaporites of the Dowsing Formation and then by higher formations of the Haisborough Group, Penarth Group, Lias Group, Chalk Group and Tertiary rocks. The Rot Claystone Member of the Dowsing Formation forms the first layer in the seal. It consists of anhydritic claystone approx. 12 m thick. The Rot Halite Member directly overlies these claystones. This consists of 63 m of halite with 2 thin mudstone bands in it. Halite has zero permeability and therefore should provide a perfect capillary seal if continuous and undisturbed. Above this is a further 570 m of mudstone and silty mudstone before the Chalk is reached.

The thickness of the gas-bearing layers of the Bunter Sandstone in the field totals 107 m. 7 zones or layers are present:
Zone 1:
The uppermost sandstone, 3.75 m thick; separated from lower parts of the Bunter Sandstone by a 6 - 12 m thick silty mudstone
Porosity 9 – 23%; mean = 18%
N/g: 0.90 except where halite cementation is present
Zone II
Deep red mudstone; effective seal for gas accumulated in the sandstones below it; no reservoir potential
Zone III
Uniform sandstone, thickness 11 – 27 m, thickening towards the SE.
Porosity = 20%
N/g: 0.95%
Zone IV
Complex; inconsistent thickness 12 – 19 m, thins to the north and south-east; contains more authigenic clays and illite, also anhydrite and halite cements.
Porosity 12-20%; average 14%
N/g: 0.70 – 0.80
Zone V and VI
Alternating intervals of high and low poroperm zones; authigenic cements
Zone VII
Similar; lowermost 6-9 m has lower poro/perm due to cements
Porosity 16 – 24 %; average 19%
N/g broad range due to cementation

Other properties of the Esmond field

Depth to top reservoir	1355.75 m subsea
Net Pay	80.16 m
Net:Gross Ratio	0.818312
Average permeability	86.7 mD
Gas/water contact	1453.9 m
Gas initially in place	10.79 BCM
Dry gas, composition	91% C1; 8% N_2, no H_2S ; 1 Mol% CO_2; 5% N2;
Recovery factor	60 – 90% of GIIP: due to depletion combined with aquifer influx
Initial pressure	157.2 bara
Initial temperature	57.2 °C
Water Saturation	16.8%
Salinity of formation water	130 000 ppm to 205 000 ppm NaCl eq.
Specific gravity water	1.21 at 60 °F;
Water density	1050 kg/m^3
Water viscosity	0.5025 cP
CO2 density	641.7362 kg/m^3
CO2 viscosity	0.0507

Simulation run
The black oil simulator ECLIPSE was used to make the simulations. A run data set for ECLIPSE was built using the data given above. The following run was executed:

- The formation is assumed to be 100% water saturated and CO_2 is injected via 2 wells into the structure. The ultimate reservoir pressure (at which CO_2 injection was stopped) is equal to the estimated well leak off pressure (206 bar, 3000 psi).

Aquifer
The ECLIPSE data set that was originally provided has no aquifer activity at all. In other words, the model has a zero permeability boundary at the gas/water contact. When the simulation was run with this boundary, the effect was severe; only 3.5 Million tonnes CO_2 could be stored before the maximum allowable reservoir pressure was reached. Sensitivity studies showed that although the geological detail included in the data set is extensive, this did not contribute to the minimal storage capacity; the lack of aquifer activity was the main factor. To allow modelling of aquifer activity, a Carter-Tracy aquifer was connected to the model area. This aquifer was given the same mean thickness and mean permeability as the reservoir.

Results
The results of the simulation were as follows:

Table 5 Results from simulation of CO_2 injection into the Bunter Sandstone aquifer as represented by the Esmond field geological model with (1) a zero permeability barrier at a depth of 1453m BSL and (2) with an infinite Carter-Tracey aquifer of the same mean thickness and permeability as the reservoir model.

Esmond case	Initial reservoir pressure [psia] [bar]	Reservoir pressure after up to 25 years of injection [psia] [bar]	Max well Injectivity index [scf/psi] [m^3/bar]	CO_2 Injected [Bscf] [10^9 m^3] [10^6 tonne]
1-Aquifer closed	2280 157	2998 207	298.06 122.4	63.12 1.79 **3.5**
2-Aquifer open	2280 157	2998 207	791.4 325.0	564.69 15.99

Discussion
The effect of linking an active Carter-Tracy aquifer to the model is very large. The conclusion drawn is that the total compressibility of water and rock dominate the storage process. Enlarging the contributing volume of water, to eventually an infinite volume, has a large effect on the accommodation. The volume of CO_2 injected in Run 2 was some 65% of the pore volume of the Esmond gas field.

In order to test which factors influenced the distribution of CO_2 within the reservoir, a number of further runs were executed, in which the internal reservoir structure was changed to the mean values of thickness and permeability, and the geological details were cut out. The subdivision into 7 layers, of which the second one is a shale layer, was maintained however. No dramatic pattern change was observed from these test runs. Apparently the layering together with the top reservoir configuration dictate the areal distribution of the CO_2 injected.

Thus, in the simplest terms, the modelled rate of pressure buildup in the reservoir caused by a given rate of CO_2 injection is limited by the size of the aquifer, because a greater volume of aquifer rock and pore fluid is available to be compressed when the size of the aquifer is increased.

Discussion of the reservoir simulation

Whilst the simulation undertaken to date throws some light on the factors that control CO_2 injection into the Bunter Sandstone, it does not provide all the answers. Given that the ultimate control is the rise in pressure within the aquifer, further simulation should try to take account of the possibility of pore fluid bleeding off into other aquifers. Closures close to, but not including, bleed-off points might be the best initial targets. It should also try to demonstrate the relationship between the size of the aquifer into which the CO_2 is injected and the pressure increase within it, and the optimum spacing of injection projects.

Creation of fractures in the cap rock, or propagation of fractures induced in the reservoir rock, form the most basic mechanism whereby CO_2 could leak from the containing closure. It is proposed that in order to ensure safe and stable containment of the CO_2, the fracture pressure of the reservoir and overlying cap rocks should not be exceeded. This should still allow the injection of significant quantities of CO_2 into the Bunter Sandstone.

Possibilities for the opening up of pre-existing but closed migration paths (e.g. faults) through the cap rock, caused by increased pore fluid pressures during injection

Faults are commonly found in strata overlying the crests of salt domes. Indeed these can be observed in the sparse grid of seismic reflection data available for this study and it appears that these faults become larger and of greater throw and penetration the more steeply dipping are the limbs of the dome. The question of whether these faults could re-open as a result of CO_2 injection remains unresolved. However, similar faults are present in the crest of the natural gas storage reservoir in the Bunter Sandstone that underlies the Spandau district of Berlin. These faults have been cored and are filled with salt, presumably derived from the Rot halite. These faults do not allow natural gas to leak from the storage structure, even though the reservoir is subject to rapid changes in reservoir pressure.

It is assumed that fluids are only likely to leak downwards into the Rotliegend Sandstone via areas of salt withdrawal, thin Zechstein Group or where faults cut the Zechstein and Bunter Shale.

Gas pressure in the CO_2 accumulation exceeds the capillary entry pressure of the overlying cap rocks, resulting in CO_2 transport through the cap rock

The Rot halite is likely to be impermeable to carbon dioxide and therefore this is not a risk.

Well Issues

Escape of CO_2 via poorly sealed pre-existing wells or by failure of the injection well

The failure of the injection well during operation should be prevented by best oilfield practice. Even in the event of a blowout, remedial action can be taken.

Escape of CO_2 due to corrosion of cement or steel in wells penetrating the storage structure or cement holding the borehole casing to the surrounding rock

The highly saline pore fluid of the Bunter Sandstone is likely to be very corrosive to carbon steel wells and in the long term, the corrosion of wells drilled before injection started must be an issue, although how long typical steel casings in the southern North Sea actually take to corrode is not known precisely.

Similarly, the acidic CO_2/water mix that will result from CO_2 injection is likely to be highly corrosive to borehole cements. However, the rates of corrosion, especially in the natural environment, are not known precisely. The ability of carbonate to buffer the acidity in the pore water means that corrosion will be much more effective if circulating water is present around the well bore.

Other issues

The presence of unidentified migration paths through the cap rock

By definition this is very difficult to deal with. However, uncertainty about the presence of migration paths through the cap rock can be reduced by the following methods.

- Detailed interpretation of a baseline 3D seismic survey.
- Pressure testing of the reservoir (pumping from the storage reservoir and seeing if the effect of this pressure drawdown can be detected in overlying potentially porous formations, in this case the Chalk.

Any escaping CO_2 should be detectable in the Chalk by well logging or time-lapse (4D) sesimic surveys.

Escape of CO_2 via a spill point at the base of the closed structure, e.g. due to underestimated viscous fingering or incorrect mapping of structural closure

It is proposed that CO_2 should be stored in the large closed domes in the Bunter Sandstone. During and after CO_2 injection, the pore pressure in the storage structure will be raised and fluid will be 'pushed' out of the structure at its spill points. The injection point and projected migration paths for the injected CO_2 should be designed to be well away from these spill points, so that the fluid that spills from the structure is the formation fluid. Once pressure has declined to hydrostatic after injection has ceased, there will again be no fluid flow along the Bunter Sandstone Formation and the CO_2 will be effectively trapped within the structure, providing it cannot leak through the cap rock.

Monitoring techniques such as time-lapse 3D seismic surveys should be able to image the CO_2 in the reservoir and make sure that injection stops before CO_2 gets close to a spill point.

Conclusions

It is clear that whilst the large domes found in the Bunter Sandstone in the southern North Sea appear to be attractive targets for CO_2 storage, there are many uncertainties about how secure storage in the Bunter Sandstone would be. The most important concerns are related to injectivity, in particular the potential for undesirable rapid pore fluid pressure rises to occur in the reservoir.

There is a risk that unidentified permeability barriers may occur within the reservoir, effectively compartmentalising it or reducing its permeability on the macro-scale. These could be either stratigraphic barriers (such as shales), fault-related barriers or barriers resulting from pervasive cementation e.g. by salt (halite). This could result in the threshold reservoir pressure being reached very early and the possible failure of the project. It might also result in the opening of pre-existing faults. The best way to resolve this question would be by injection tests into the reservoir rock. However, these are likely to be extremely costly offshore.

The risk that salt will be precipitated and fill the pore space near the well as a result of water dissolving into the dry CO_2 injected down the well might also be important. This could possibly be remediated by injecting fresh water that would dissolve the salt cement.

Issues relating to pre-existing wells may also be important. The highly saline pore water in the Bunter Sandstone is likely to be made more aggressive towards steel, and certainly more so towards cement, by the addition of CO_2. However, at present very little is known and nothing has been published about the state of casings or cement plugs and bonds in the exploration and production wells in the southern North Sea, even though some have been in place for nearly 40 years.

There is potentially a trade-off between the presence of wells in the structure, which can provide direct data on porosity and permeability, etc., and the absence of wells in the structure which means one less group of potential escape paths to worry about.

Some of the issues raised above could be minimised by careful choice of the injection site. A good site might be:

- a dome with no crestal faults (likely to be a low amplitude dome)
- good porosity and permeability confirmed by wells around the dome
- a site where there is the possibility for pore fluids to bleed off into other formations but not to the sea bed. This might prevent excessive pore fluid pressure build-up without polluting the sea water with highly saline brines

The question of whether a pre-existing well in the dome itself is a good or bad idea is considered to be an open one at the moment.

Some of the issues raised above could perhaps be resolved or further constrained by further research, e.g. fracture pressure of the Bunter Sandstone and Haisborough Group, and the lifetime of well casings and cement plugs.

STORAGE POTENTIAL IN OTHER FORMATIONS IN THE SOUTHERN NORTH SEA

The Rotliegend Sandstone Formation

There is significant storage potential in the Permian Rotliegend Sandstone Formation in the southern North Sea. This formation is the reservoir for many of the major gas fields in the UK sector.

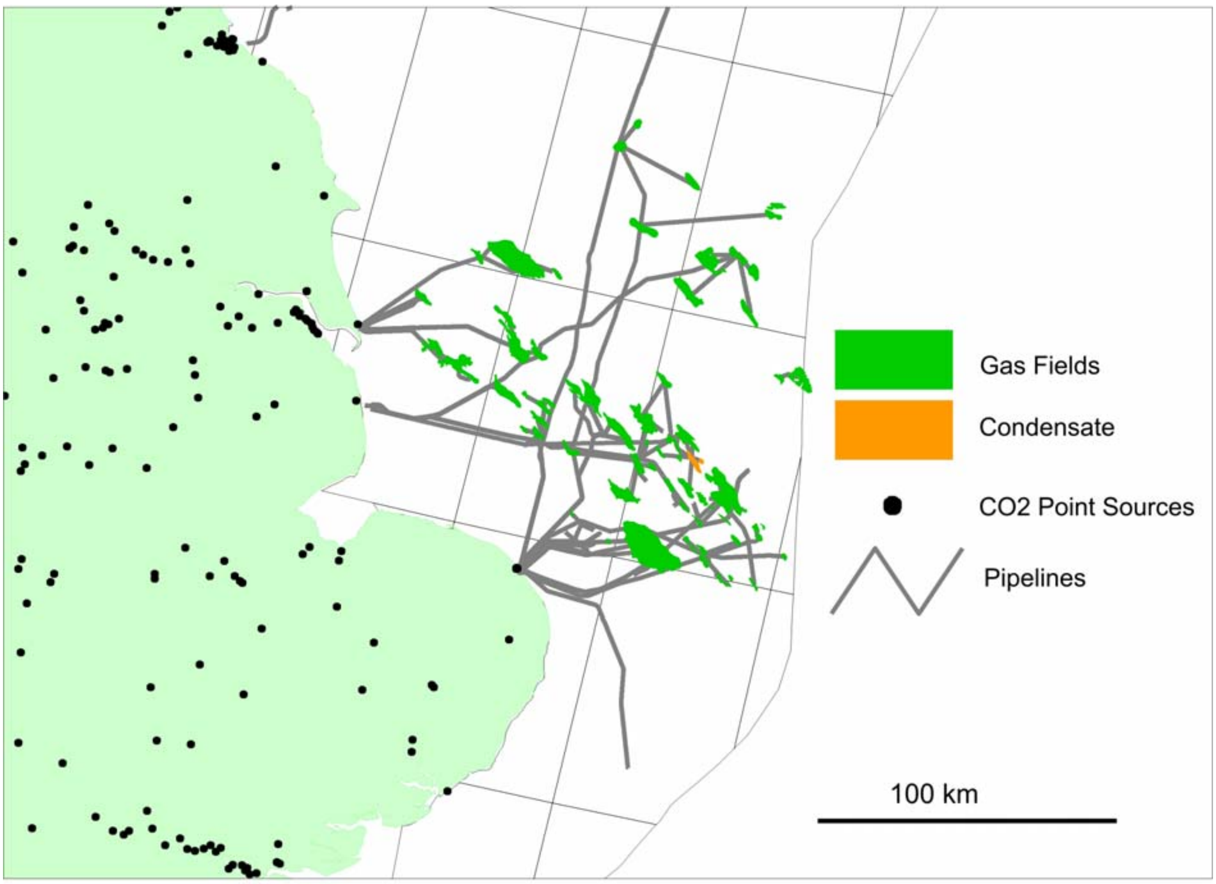

Figure 2a1.16 Gas fields in the UK sector of the southern North Sea

In the UK sector gas fields (Figure 2a1.16), the porosity and permeability of the Rotliegend Sandstone Formation typically vary from 13 to 18% and 76.8 to 322.8 mD respectively (Abbotts, 1991). Where well developed, its thickness ranges between 50 and 200 metres. The gas is trapped in fault bounded structures, efficiently sealed by thick overlying Zechstein salt and other evaporite minerals.

There is good reason to suppose that the most of the major gas resources in the Rotliegend Sandstone have been discovered (Maynard & Gibson, 2001) and that nearly all closed structures in the Rotliegend Sandstone contain gas. Thus the analysis of the CO_2 storage potential of the gas fields provides a good guide to the total potential storage capacity of this reservoir. It is known that in at least some of the gas fields there is little water influx as the gas is produced, e.g. in the Indefatigable gas field <2% of the depletion energy comes from water drive and compression of the reservoir matrix (Pearson, Young & Smith, 1991). So once the gas in the field has been depleted, there should be large volumes of pore space occupied by low pressure methane, which should be available for CO_2 sequestration, provided that this takes place shortly after depletion, before reservoir pressure recovers to hydrostatic as a result of gradual water invasion.

The theoretical CO_2 storage capacity of the gas fields of the UK sector of the southern North Sea (adapted from Schuppers et al., 2002) is shown in Table 5.
At 3086 Mt, it corresponds to approximately 25 years supply from the largest twenty UK industrial sources of CO_2. Only a small number of fields might need to be exploited to deliver a high proportion of the total theoretical storage capacity. For example, the theoretical storage capacity of the Leman, Indefatigable, Viking, West Sole and Galleon fields is approximately 1744 million tonnes CO_2, more than 56% of the total.

Table 6. Storage potential of the Permian and Triassic gas fields of the UK sector of the southern North Sea

FIELD NAME	Status	Age	Startup	Storage capacity (Mt)
Leman	Producing	Permian	1966	966.17
Indefatigable & Indefatigable SW	Producing	Permian	1983	246.17
Viking	Producing	Permian	1965	238.32
West Sole	Producing	Permian	1965	150.92
Galleon	Producing	Permian	1985	142.96
Hewett	Producing	Triassic and P	1966	139.66
Indefatigable	Producing	Permian	1966	122.99
Barque & Barque S	Producing	Permian	1966	98.54
Victor	Producing	Permian	1972	81.63
Ravenspurn N.	Producing	Permian	1984	66.13
Vulcan	Producing	Permian	1983	59.06
Audrey	Producing	Permian	1976	54.99
Clipper N	Producing	Permian	1983	51.22
Amethyst E & W	Producing	Permian	1970	51.08
Sean N. & S.	Producing	Permian	1969	49.25
Pickerill	Producing	Permian	1984	43.02
Ravenspurn S.	Producing	Permian	1983	40.63
Thames, Yare, Bure & Wensum	Producing	Permian	1973	34.28
Rough	Producing	Permian	1968	25.13
Skiff	Producing	Permian	1995	23.85
Neptune	Producing	Permian	1986	23.28
Ganymede	Producing	Permian	1989	23.24
Welland	Producing	Permian	1984	22.22
Excalibur	Producing	Permian	1988	21.50
Cleeton	Depleted	Permian	1983	21.01
Anglia	Producing	Permian	1985	20.04
Lancelot	Producing	Permian	1986	19.26
Markham	Producing	Permian	1984	19.07
Camelot N, C&S	Producing	Permian	1967	18.82
Gawain	Producing	Permian	1988	18.19
Johnstone	Producing	Permian	1985	17.81
Corvette	Producing	Permian	1996	17.20
Valliant S.	Producing	Permian	1970	13.81
Bell	Producing	Permian	1994	12.49
Galahad	Producing	Permian	1975	12.49
Esmond	Depleted	Triassic	1985	12.12
Vixen	Producing	Permian	1999	12.00
Sean E	Producing	Permian	1983	10.11
Orwell	Producing	Triassic	1990	9.61
Valiant N.	Producing	Permian	1971	8.78
Bessemer	Producing	Permian	1989	8.66
Europa	Producing	Permian	1972	8.42
Hyde	Producing	Permian	1966	7.90
Baird	Producing	Permian	1993	7.38
Ann	Producing	Permian	1966	7.29
Guinevere	Producing	Permian	1988	7.26
Millom	Producing	Triassic	1988	7.05
Vanguard	Producing	Permian	1982	5.51
Gordon	Depleted	Triassic	1985	5.25
Forbes	Depleted	Triassic	1985	2.24
Total Triassic				**175.93**
Total Rotliegend				**2910.07**
Grand Total				**3086.00**

CO_2 storage potential of other formations in the southern North Sea

Carboniferous rocks

The Carboniferous reservoir rocks of the southern North Sea form important gas reservoirs to the east of the area in which the Rotliegend Sandstone occurs. These could possibly have some potential for CO_2 storage but this is hard to quantify because the reservoir rocks generally have only localised low to fair porosity and permeability, which means that there may be injectivity problems. The best prospects are probably the gas fields but their potential storage capacity has not been quantified here.

The Chalk Group

The only other widespread porous and permeable reservoir rock in the southern North Sea is the Chalk. This occurs widely in the southern North Sea. However, the top of the Chalk occurs at depths >700 m only in a few restricted areas, mainly near the median line east of East Anglia and in the northern and north eastern part of the southern North Sea Basin. Here it is overlain by Palaeocene and younger mudstones and may have some potential as a CO_2 repository. This potential has not been quantified because of lack of seismic reflection data or suitable maps of the top Chalk surface. It may warrant further investigation.

Conclusions

Although there may be some CO_2 storage potential in the Chalk and Carboniferous rocks of the southern North Sea, the bulk of the potential is thought to lie in the gas fields of the Rotliegend Sandstone and the large domes in the Bunter Sandstone.

The total CO_2 storage potential of the UK sector of the southern North Sea is as follows:

- Closed structures (principally domes) in the Bunter Sandstone: 14.3 gigatonnes
- Gas fields, principally in the Rotliegend Sandstone 3.09 gigatonnes
- Closed structures in Carboniferous and Chalk reservoirs unquantified but probably low

The total quantified CO_2 storage potential of this area is about 17.4 gigatonnes and is unlikely to exceed 20 gigatonnes overall. It should be noted that this storage potential does not include any detailed analysis of trap integrity and thus represents a theoretical maximum for closed structures in the southern North Sea.

This compares with annual UK CO_2 emissions of about 558 million tonnes, of which around 200 megatonnes (22%) come from industrial point sources. However, it is unlikely to be practical to store the CO_2 emissions from more than say the top 20 UK emissions sources, which emit about 122 megatonnes (Brook et al., 2002). Given that the energy penalty associated with CO_2 capture and storage might be in the range 25-40%, if adapted for CO_2 capture, these sources might send for storage some 150-170 megatonnes CO_2 annually. Thus the CO_2 storage potential in the southern North Sea might represent some 100 years capacity for these emissions.

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