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Industrial carbon dioxide emissions and carbon dioxide storage potential in the UK

Sustainable and Renewable Energy Programme

Commercial Report CR/06/185 (NC)

BRITISH GEOLOGICAL SURVEY

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Foreword

This report is the product of a study by the British Geological Survey (BGS) undertaken for AEA Technology plc as part of agreement C/07/00384/00/00. It considers the UK emissions of carbon dioxide from large industrial point sources such as power stations and the potential geological storage capacity to safely and securely store these emissions.

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Summary

Carbon dioxide capture and geological storage (CCS) is a technology that has the potential to significantly reduce the UK's CO_2 emissions to the atmosphere. At its simplest, CCS technology consists of three steps: capturing CO_2 from a large industrial point source such as a fossil fuel-fired power plant, transporting it (by pipeline or ship) to a suitable geological storage site and storing it underground in geological formations - for millennia or longer – which prevents the stored CO_2 entering the atmosphere and acting as a greenhouse gas.

CCS has aroused considerable interest because it is a way of reducing emissions from fossil fuel combustion, which is predicted to remain the dominant source of primary energy for at least the next few decades – decades in which it will be necessary to reduce carbon emissions to the Earth's atmosphere if serious climate change and ocean acidification are to be avoided.

This report describes the results of a survey of (a) the UK's major industrial sources of CO_2 and (b) potential geological storage sites in which large quantities of CO_2 could be isolated from the atmosphere to prevent them acting as a greenhouse gas.

All the major industrial point sources of CO_2 in England and Wales, Scotland and Northern Ireland that emit >10,000 tonnes of CO_2 per year report their emissions to the Environment Agency, the Scottish Environmental Protection Agency (SEPA) and the Northern Ireland Department of the Environment respectively. The 2004 data from these agencies was collated to produce a database of UK emissions from industrial sources.

Total UK CO_2 emissions in 2004 amounted to approximately 575 Mt (million tonnes). The total CO_2 emission from all reporting industrial sites was 283 Mt (49% of total emissions).

Most of the major sources of CO_2 are power plants, although the UK's three integrated steel plants, and the larger refineries/petrochemicals complexes are also important sources. The 4000 MWe coal-fired power plant at Drax, Yorkshire is the largest single source, it emitted >20 Mt CO_2 in 2004.

The database of UK industrial sources of CO_2 shows that CCS technology could make a significant reduction in UK emissions if it was applied to a relatively small number of industrial plants. For example, fitting the 20 largest power plants for CCS could reduce UK emissions by approximately 20%.

The CO_2 storage capacity of the UK can be considered in the same terms as any other resource: parts of it are well known and there is relative certainty about the existence and magnitude of this fraction, whereas other (larger) parts of the resource are much more speculative and poorly quantified. It can be helpful to consider the UK's CO_2 storage potential as a resource pyramid, which has a very wide base consisting of speculative potential, and an apex consisting of well-quantified and relatively certain capacity. This resource pyramid can be divided into three parts. At the base is *theoretical* CO_2 storage capacity, consisting of speculative, poor quality and poorly quantified or unquantified potential. In the middle is *realistic* capacity – capacity which meets a range of geological and engineering criteria and which can be quantified with a fair degree of confidence. At the apex is *valid* capacity, consisting of potential storage sites that meet additional criteria and can be considered in terms of the annual CO_2 storage rates that they might accommodate.

The theoretical storage capacity of the UK is very large, because the UK Continental Shelf contains many sedimentary basins, which contain very large volumes of saline water-bearing reservoir rocks. However, putting a number on the total theoretical storage capacity would not necessarily be particularly helpful, and could be misleading to policymakers because a large fraction of such capacity is unlikely ever to be economically accessible, and, on further analysis, may prove to be technically unsuitable. Moreover it would require vast amounts of geological data and other resources that are not available at present. Therefore the approach taken here to

estimating UK CO_2 storage capacity is to study in detail the most promising areas of theoretical capacity and, where possible, upgrade them into (quantified) realistic capacity or valid capacity. This is an incremental approach, based on basin-by-basin geological analysis, and further research would undoubtedly improve the estimates.

The UK's major potential sites for the long-term geological storage of CO_2 are offshore oil and gas fields and offshore saline water-bearing reservoir rocks: the onshore coal seams have low permeability (evident in the lack of success in establishing coalbed methane production).

It is our opinion that there is only limited CO_2 storage potential in the UK onshore area in general: the oil and gas fields are with one exception too small and the major aquifers are widely used for potable water extraction.

The CO_2 storage capacity of the UK's oil fields was estimated by assuming:

- Only fields that originally contained >100 million barrels of oil, are still producing and are technically suitable for EOR will be used as storage sites
- Their storage capacity is equal to the mass of CO_2 that would be retained in the reservoir(s) as a result of economically optimised EOR.

These are conservative assumptions, because CO_2 storage could continue after the end of economic EOR. Field-by-field calculations made by ECL for the DTI were summed to obtain the total storage capacity of the UK's oil fields, which is estimated to be approximately 1175 million tonnes (Mt) CO_2. The vast majority of this storage capacity is in the northern and central North Sea, although there is minor potential elsewhere, particularly in the Faeroes-Shetland Basin and the East Irish Sea Basin.

The CO_2 storage capacity of the UK's gas fields was estimated by an established method, previously applied by other authors to the Alberta Basin, Canada. The total CO_2 storage capacity of the UK's gas fields is estimated to be approximately 5140 Mt CO_2. The majority of this estimated storage capacity is in the Southern North Sea Basin (3886 Mt), but there is also substantial capacity (1043 Mt) in the East Irish Sea Basin.

The CO_2 storage capacity of the UK's gas/condensate fields (which are in the Northern and Central North Sea Basin) was estimated by the same method used for the gas fields, to be approximately 1200 Mt CO_2.

Rounding these figures, the total potential CO_2 storage capacity of the UK's oil and gas fields is estimated to be approximately 7500 Mt. The gas and gas/condensate field capacity is considered to fall into the *realistic* category of the resource pyramid and the oil field capacity is considered to fall into the *valid* category, but whether all of it can actually be used is a matter of individual project economics, which will be affected by, amongst other things, the dates at which the various fields are abandoned, at which point their wells are likely to be plugged and their infrastructure removed.

The CO_2 storage capacity of saline water-bearing reservoir rocks (saline aquifers) depends not only on the characteristics of the reservoir formation itself but those of its internal and external boundaries (e.g. faults and surrounding formations). Very little CO_2 could be injected into a porous and permeable water-filled formation with completely impermeable boundaries because none of the original pore fluid could be displaced to make room for it. Thus a range of geological and engineering factors needs to be considered if a realistic estimate of the CO_2 storage capacity of part or all of a saline water-bearing reservoir formation is to be made. These include:

- the porosity, permeability and heterogeneity of the reservoir rock
- whether the reservoir rock is divided into compartments
- the nature of the top seal and other boundaries
- the prevailing pore fluid pressure and stress regimes within the reservoir

Estimates of the maximum realistic aquifer storage capacity were made in the Southern North Sea Basin and East Irish Sea Basin only: these estimates are *up to* 14.25 Gt (10^9 tonnes) CO_2 and *up to* 0.63 Gt CO_2 respectively.

The CO_2 storage capacity of the Northern and Central North Sea Basin was also considered but could not be fully quantified due to the lack of the necessary data and resources. Hence it falls into the *theoretical* category of the resource pyramid. It is complicated by the fact that most of the Cretaceous and older reservoir rocks are naturally overpressured and therefore potentially unsuitable for CO_2 storage. However, there is likely to be significant CO_2 storage capacity in the extremely large Palaeocene and Eocene fan sandstones found in this basin – not only in structural and stratigraphic traps but also as a result of CO_2 dissolution into the saline water already present in these formations and as a residual saturation along the migration path of CO_2 within the reservoirs.

Other basins that were considered were the Bristol Channel Basin and the St George's Channel Basin, which lie to the south and west of Wales respectively. The Bristol Channel Basin does not have any significant CO_2 storage capacity and the St George's Channel Basin probably has only limited capacity. Insufficient resources were available to make even outline estimates of CO_2 storage capacity for the remaining UK offshore sedimentary basins. Table 1 summarises the quantified CO_2 storage capacity of the UK and its continental shelf.

Table 0-1 Estimated CO_2 storage capacity of the UK and its continental shelf

Category	**Location**	**Estimated CO_2 storage capacity (million tonnes)**
Oil fields	Offshore	1175
Gas fields	Offshore	5140
Gas/condensate fields	Offshore	1200
Saline aquifers	Southern North Sea Basin	Up to 14250
	East Irish Sea Basin	Up to 630
	Northern and Central North Sea Basin and other offshore basins	Not quantified but potentially large
	Onshore	Not quantified but potential small
TOTAL QUANTIFIED CO_2 STORAGE CAPACITY		Up to **22395**

Thus the total realistically quantified storage capacity of the UK and its continental shelf exceeds 7.5 Gt CO_2 and may exceed 22 Gt CO_2 – this depends mainly on uncertainties within the aquifer storage capacity estimates. This is almost certainly only a fraction of the theoretical capacity: undertaking basin-by-basin geological analyses could incrementally increase the realistic storage capacity of the UK.

The study has highlighted the need to better quantify the storage potential in gas fields and aquifers. It is proposed that the following further studies be undertaken:

1. Realistic CO_2 storage potential of the saline water-bearing reservoir rocks of the Northern and Central North Sea basin, including the Inner Moray Firth basin. These have excellent theoretical potential.

2. Realistic CO_2 storage potential of the saline water-bearing reservoir rocks of the East Irish Sea Basin. A more detailed analysis including numerical simulation of the potential for storage by dissolution and residual saturation is recommended.
3. A detailed study, using 3D seismic surveys and numerical simulation of CO_2 injection, of the large domes in the Bunter Sandstone of the Southern North Sea Basin would refine estimates of their storage capacity
4. A detailed, seismically-based study of those parts of the UK landmass that are considered to have theoretical potential, to identify realistic potential.
5. Numerical simulations of CO_2 injection into generic Southern North Sea and East Irish Sea gas fields would result in a more precise estimation of UKCS gas field storage capacity.

The study concludes that there is sufficient realistic quantified CO_2 storage capacity in the UKCS oil and gas fields to store *all* current UK industrial emissions of CO_2 for between 13 and 38 years, and there is great potential to increase this figure through further studies of the UKCS aquifers. However, there is far greater uncertainty associated with aquifer storage capacity than oil and gas field storage capacity, particularly in poorly explored (non-hydrocarbon-bearing) basins, because of the sparse geological information available.

1 Introduction

Carbon dioxide capture and geological storage (CCS) is a technology that could be used to reduce carbon dioxide emissions to the atmosphere from large, stationary point sources such as fossil fuel-fired power stations by 80-90%. It involves the capture of carbon dioxide (CO_2) at a large industrial installation such as a fossil fuel-fired power plant, its transport to a geological storage site, and its long-term isolation in a geological storage reservoir. The technology has aroused considerable interest because it can help reduce emissions from fossil fuels, which are likely to remain the dominant source of primary energy for decades to come – decades in which it will be necessary to reduce carbon emissions to the Earth's atmosphere if serious climate change and ocean acidification is to be avoided. Most other emission reduction options involve the displacement of fossil fuels as an energy source.

This report details the main industrial point sources of carbon dioxide emissions to the air in the UK and the storage capacity of geological reservoirs that have the potential to isolate the CO_2 from the atmosphere for millennia or longer.

2 Industrial sources of CO_2 emissions in the UK

All the major industrial point sources of CO_2 in England and Wales, Scotland and Northern Ireland that produced >10,000 tonnes of CO_2 per year report their emissions to the Environment Agency, the Scottish Environmental Protection Agency (SEPA) and the Northern Ireland Department of the Environment respectively. These data for 2004 were collated to produce a database of CO_2 sources for the project. The collated data also includes emissions from many offshore oil and gas installations as well as onshore installations. Some of its main features are summarised below.

In 2004 the UK emitted approximately 575 Mt (million tonnes) of CO_2, of which 283 Mt came from reporting industrial plants. Fossil fuel-fired power plants accounted for 61% of the total reported industrial emissions in 2004 (Figure 2-1).

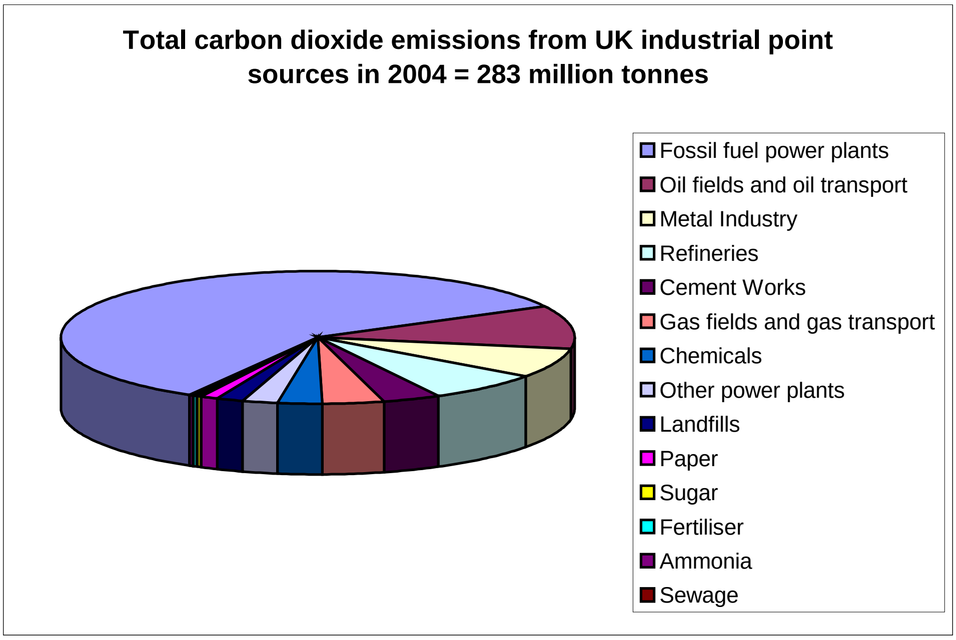

Figure 2-1. Breakdown of CO_2 emissions from industrial point sources in the UK (Data from the Environment Agency, SEPA and Northern Ireland DoE, 2004)

The emissions from the 50 largest industrial point sources are shown in Table 1.1 and their locations are shown in Figure 2-2.

Table 2-1 CO_2 emissions from the 50 largest industrial sources in the UK

ID	Facility Name	CO_2 emissions (Mt, rounded)
1	Drax Power Station	20.5
2	West Burton Power Station	9.2
3	Ratcliffe on Soar Power Station	9.2
4	Cottam Power Station	9.0
5	Longannet Power Station	8.8
6	Ferrybridge 'C' Power Station	8.0
7	Kingsnorth Power Station	7.8
8	Eggborough Power Station	7.3
9	Scunthorpe Steel Works	7.2
10	Port Talbot Steel Works	6.6
11	Fiddlers Ferry Power Station	6.6
12	Redcar Steel Works	6.6
13	Aberthaw Power Station	6.3
14	Didcot A Power Station	5.2
15	Teesside Power Station	5.1
16	Grangemouth Refinery / Petrochemicals Complex	4.7
17	Tilbury B Power Station	4.6
18	Rugeley Power Station	4.1

19	Connah’s Quay Power Station	4.0
20	Peterhead Power Station	3.6
21	Salthead Cogeneration Co Ltd	3.5
22	Centrica SHB Ltd	3.5
23	Fawley Refinery	3.2
24	Cockenzie Power Station	3.0
25	Barking Power Station	2.8
26	Stanlow Refinery/Petrochemicals complex	2.7
27	Kilroot Power Station	2.7
28	Lynemouth Power Station	2.7
29	Didcot B Power Station	2.6
30	Ironbridge Power Station	2.6
31	Humber Refinery	2.4
32	Coryton Refinery	2.3
33	Avonmouth LNG Facility	2.3
34	Pembroke Refinery	2.3
35	Rocksavage Power Station	2.1
36	Lindsey Oil Refinery	2.0
37	Sutton Bridge Power Station	1.9
38	Ballylumford Power Station	1.9
39	Keadby Power Station	1.9
40	Medway Power Station	1.9
41	Damhead Creek Power Station	1.8
42	Little Barford Power Station	1.7
43	Coryton Power Station	1.6
44	Huntsman Olefins Plant	1.3
45	Rye House Power Station	1.3
46	Lyme and Wood Pits	1.3
47	Killingholme A Power Station	1.2
48	Great Yarmouth Power Station	1.2
49	Northfleet Cement Works	1.2
50	Milford Haven Refinery	1.2
	Total	**208.6**

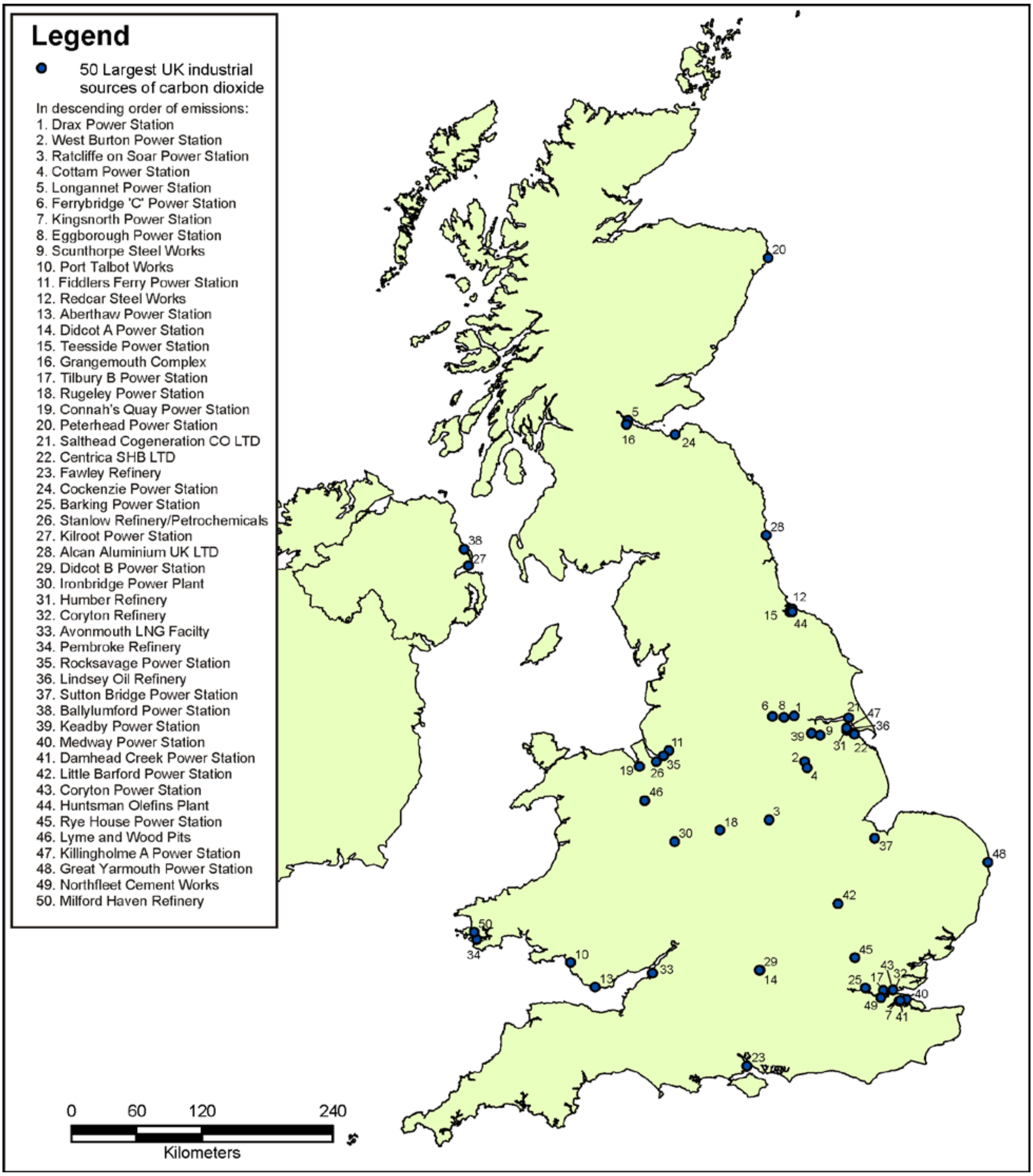

Figure 2-2. Map showing the 50 largest industrial sources of carbon dioxide in the UK

The 50 largest sites consist of 37 power or CHP plants, 3 integrated steel plants, 8 refineries, 1 chemicals plant and 1 cement plant. Consequently all the largest sites contain relatively low percentages of CO_2 in their waste streams and would need to be fitted for CO_2 capture. There are one ammonia plant, one fertiliser plant and two gas terminals among the 100 largest emitters. Along with the refineries[1], these may warrant further investigation for pure or nearly pure streams of CO_2.

[1] Some refineries may contain hydrogen plants that could emit pure streams of CO_2, depending on the manufacturing process involved.

UK emissions could be reduced significantly even if CCS was implemented at only a few of the largest sources. For example, the 20 largest power stations emit a total of 132 million tonnes CO_2 in 2004. If these emissions could be reduced by 80-90% it would reduce total UK emissions by 18-20%.

3 Potential Sites for the Geological Storage of CO_2

3.1 ESTIMATING CO_2 STORAGE CAPACITY

Two main categories of issues complicate the estimation of CO_2 storage capacity:

- questions about the economic or practical availability of storage capacity
- difficulties caused by the lack, or sparsity, of geological and other data, and the resources necessary to make realistic estimates of storage capacity

Estimates of the availability of many geological resources such as minerals and fossil fuels commonly divide them into at least two categories: *resources* (accumulations of anything that is useful and potentially accessible to mankind) and *reserves* (that part of a resource that is available for production now, by being economically recoverable under current technological conditions).

Potential CO_2 storage space in geological formations can be considered as a resource because it is potentially useful to man. However, very little of it appears to be economically exploitable now under current technological conditions and thus qualify as a reserve: incentives are required to make the geological CO_2 storage cost-effective, except in some enhanced oil recovery projects.

Hence some means of subdividing the resource is required. Bradshaw et al. (*in press*) propose that the degrees of geological and economic uncertainty associated with various parts of the resource can be considered in terms of a techno-economic resource pyramid. Figure 3-1, adapted from Bradshaw et al. (*in press*) shows an example of such a pyramid.

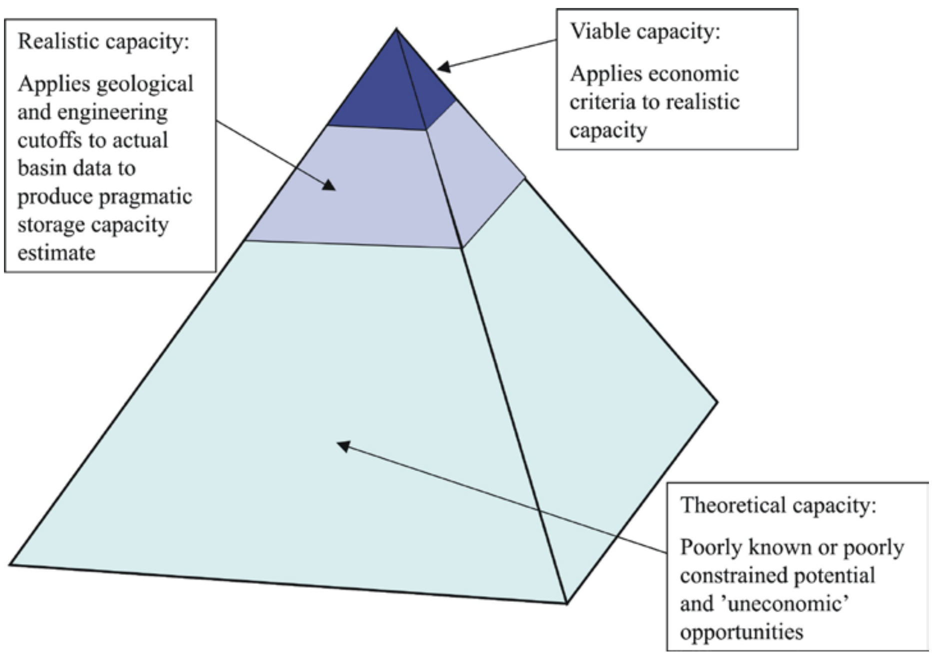

Figure 3-1. A techno-economic resource pyramid for geological CO_2 storage space. Adapted from Bradshaw et al. *in press*.

At the apex of the pyramid are those storage sites or formations that have good geological characteristics, large storage capacity and are located close to emission sites with low costs of capture. At the base of the pyramid are the extremely difficult sites, with problematic geological conditions, and/or small storage capacity, which potentially may be located at great distance from sources with large capture costs – and, most importantly, the resources that are speculative or poorly known. At present we are in the early stages of assessing potential storage sites, and the total potential storage capacity at the base of the pyramid is very much greater than that at the top, largely because much of the theoretical storage capacity is very poorly understood.

In order to take the analysis further, it is important that the boundary conditions and assumptions that have been used in any storage capacity assessments are adequately defined, such that their position on the resource pyramid can be defined. Bradshaw et al. (*in press*) suggest classification into *theoretical, realistic* or *viable* capacity:

Theoretical capacity assumes that the whole of a reservoir formation is accessible to store CO_2 in its pore volume, or the whole of the formation water in a reservoir formation is available to have CO_2 dissolved into it, or the whole of a coal seam is available for CO_2 storage by adsorption. This provides an upper limit to a capacity estimate. However, it is an unrealistic number as in practice there will always be technical and economic limitations across a region that prevent parts of the reservoir formation from being accessed and/or fully utilized. The whole of the volume of the resource pyramid comprises theoretical capacity but only part of this can be considered realistic.

Realistic capacity applies a range of technical (geological and engineering) cut-offs to elements of an assessment, e.g. quality of the reservoir (permeability, porosity, heterogeneity) and seal, depth of burial, pressure and stress regimes, size of the pore volume of the reservoir and trap, nature of the boundaries of the trap, and whether there may be other competing interests that could be compromised by injection of CO_2 (e.g. existing subsurface resources such as oil, gas, coal, water, or surface resources such as national parks). This is a much more pragmatic estimate that can have some degree of precision, and gives important indications of technical viability of CO_2 storage. These estimates are within the main body of the resource pyramid, but exclude the basal parts, which are solely theoretical.

Viable capacity is the capacity arrived at by also considering economic, legal and regulatory barriers to geological CO_2 storage, and thus builds upon the realistic capacity assessment. Detailed source/sink matching is performed at this stage to match the best and nearest storage sites to large emission sources. The source/sink matching should extend beyond just geotechnical aspects, and include social and environmental aspects of locating storage sites. Cost curves may also be derived and Monte Carlo simulations performed to help estimate the level of uncertainty and upper and lower ranges in the known and derived data versus the actual data that become available once a project is built and running. At this level of assessment, it may be possible to also express the capacity estimate as an injection rate, not just as a total volume. Because the direct match of nearby suitable sites to emissions sources has been performed, the figures quoted become an annual sustainable rate of injection, where economics, supply volume and reservoir performance are integrated to define the viability of the resource. These capacity estimates are at the apex of the resource pyramid.

Bradshaw et al. (*in press*) also recommend that all estimates of geological CO_2 storage capacity should (a) clearly state the limitations that existed (data, time, knowledge) at the time the assessment was made and (b) indicate the purpose and future use to which the estimates should be applied. Assessments that lack documentation of constraints (or justification for their use) cannot be easily compared with other assessments.

3.2 POTENTIAL GEOLOGICAL CO_2 STORAGE SITES IN THE UK

The UK's major potential sites for the long-term geological storage of CO_2 are oil and gas fields and saline water-bearing reservoir rocks. There is thought to be only limited quantifiable CO_2 storage potential in coal seams in the UK for the following reasons:

1. UK coal seams generally have low permeability, which is evident in the lack of success in establishing coalbed methane production in the UK. Jones et al. (2004) point out that 13 wells had been drilled in 6 different projects to November 2004, and no commercial production had been established.

2. Coal is an important energy mineral and its use for CO_2 storage would limit the potential for mining or underground gasification of the coal in the future. Because of these potential conflicts of interest, it is not considered likely that coal resources at depths above 1500 m would be allocated for CO_2 storage in the UK.

There are significant coal resources in the UK at depths below 1500 m (Jones et al. 2004). However, their permeability is likely to be lower even than that inferred in shallower seams because of the increased lithostatic pressures at depth. Moreover, the process by which CO_2 is trapped in coal seams at temperatures above the critical point (31.1°C) is not well understood. It seems that adsorption is gradually replaced by absorption and the CO_2 diffuses or "dissolves" into the coal. Carbon dioxide is a "plasticizer" for coal, lowering the temperature required for its transition from a glassy brittle structure to a softer, rubbery, plastic structure. Indeed in one case, this transition temperature was interpreted to drop from about 400°C at 3MPa to <30°C at 5.5 MPa. Coal plasticization or softening may adversely affect any permeability that would allow CO_2 injection. Coal also swells as CO_2 is adsorbed and/or absorbed, which reduces permeability by orders of magnitude or more (Shi & Durucan 2005). Some studies suggest that injected CO_2 may react with coal, further highlighting the difficulties in injecting CO_2 into low-permeability coal (IPCC 2005).

4 Oil and Gas fields

Oil and gas fields are regarded as prime potential sites for CO_2 storage for the following reasons:

1. They have a proven seal which has retained buoyant fluids, in many cases for millions of years

2. A large body of knowledge about their geological and engineering characteristics has been acquired during the exploration and production phases of development.

3. In some cases there may be economic benefits to be gained from enhanced oil or gas recovery (EOR or EGR respectively) in conjunction with CO_2 storage.

4.1.1 Oil fields

Most of the UK's large offshore oil fields are in the Northern and Central North Sea Basin (Figure 4-1). However, there are three major fields (Clair, Foinaven and Schiehallion) in the Faroes-Shetland Basin, two (Douglas and Lennox) in the East Irish Sea Basin, and one (Beatrice) in the Inner Moray Firth Basin. There are also a number of onshore fields, most of which are very small. These are concentrated in the East Midlands and the Wessex Basin (in southern England). By far the largest of these is the Wytch Farm field, which underlies Poole harbour, on the south coast of England (Figure 4-1).

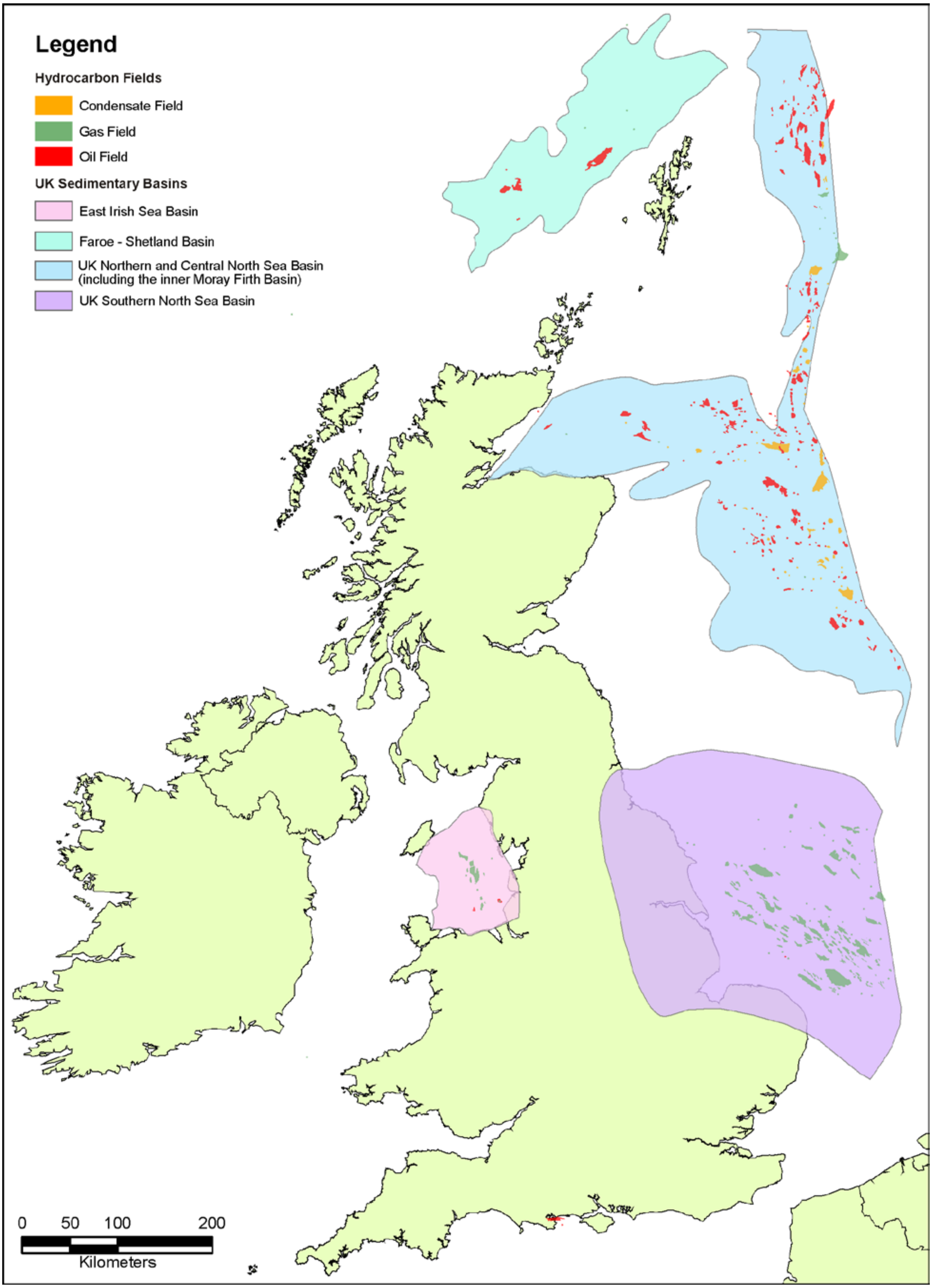

Figure 4-1. Map showing the location of offshore hydrocarbon fields and the major oil and gas-bearing sedimentary basins

It is considered likely that any CO_2 storage in a UK oil field would take place in conjunction with enhanced oil recovery (EOR) because the potential returns from the additional oil recovered are thought likely to exceed the extra costs involved. However, the costs of adapting offshore platforms and other infrastructure for EOR as opposed to pure CO_2 storage are not well known at present. Moreover, the economics of EOR offshore are dependent on the oil price and potentially on the price of CO_2 in the EU ETS, both of which have shown volatility over the last few years.

Two main methods of EOR potentially have application in the UK: Gravity-Stable Gas Injection (GSGI) and Water Alternating with Gas injection (WAG). Gravity stable gas injection would likely be applied towards the end of a field's life. It involves the injection of gas usually into the crest of an anticline or dipping reservoir. The oil is pushed downwards through the reservoir towards production wells and the CO_2 ensures that the reservoir is efficiently swept of oil. Large volumes of CO_2 are likely to have to be injected relatively slowly to maintain a gravity-stable CO_2-front moving down through the oil field. The WAG process would likely be applied a few years before the end of a field's life. It involves injecting alternating slugs of CO_2 and water into an oil reservoir. The CO_2 mixes with the oil, decreasing its viscosity and swelling it, and because it is lighter than water, it may rise through the reservoir, following different pathways from, and recovering oil that would not be contacted by, injected water. The following slug of water helps move the CO_2/oil mixture towards the production wells. WAG is the application most likely to be used in the majority of UK offshore fields, partly because the payback time is generally shorter, but GSGI tends to store more CO_2 in the field per unit of oil recovered.

4.1.1.1 Storage Capacity of the UK's Onshore Oil Fields

Most of the UK's onshore oil fields are too small to have any significant CO_2 storage capacity. The only one of potentially significant size is the Wytch Farm oil field, Dorset. The potential storage capacity of this field is included in the estimate for offshore fields given in Section 4.1.1.2 below.

4.1.1.2 Storage Capacity of the UK's Offshore Oil Fields

The most detailed estimate of the CO_2 storage capacity of the UK's oil fields in the public domain is an estimate of the mass of CO_2 likely to be retained in the fields as a result of stand-alone EOR. It is based on field-by-field CO_2-EOR retention estimates, made for the DTI between 1989 and 1991, and collated by ECL (Exploration Consultants Limited) in 2001. The study included an initial screening in which fields were excluded from consideration if they had already ceased production, their predicted close of production dates were too close, the stock tank oil initially in place was less than 100 million barrels, they were field types where the outcome of EOR was uncertain, viz. viscous oil fields, thin oil rims, fractured reservoirs, gas/condensate fields, or they were not considered suitable candidates for EOR for other technical reasons. The results of this study were updated in 2006, and include graphs showing the window of opportunity for CO_2 storage and potential annual CO_2 storage rates resulting from EOR.

The total CO_2 storage capacity of the oil fields is estimated to be 1175 million tonnes. There may be upside potential because this figure does not include any CO_2 storage that might take place after stand-alone EOR had ceased. On the other hand it may be optimistic because it assumes that EOR will be deployed at all the technically suitable large oil fields.

Currently, the data indicate that the window of opportunity for EOR stretches out to 2030, and 2011 is a key year for implementing CO_2 storage associated with EOR in the UK's oil fields as the available storage capacity drops markedly thereafter. However, latest start dates for EOR in each field are influenced by close of production dates which themselves are influenced by economic factors including the price of oil, which has risen greatly during the last few years.

The level of technical detail that has gone into these estimates is high, and potential annual CO_2 storage rates have been calculated, although field-by-field estimates are not in the public domain. Therefore they can probably be considered "viable capacity" in terms of the Bradshaw et al. (*in press*) classification of resources.

It is possible that economic EOR could either continue for longer and thus store more CO_2, or be optimised to store more CO_2, if a value could be assigned to CO_2 storage via a mechanism such as the EU Emissions Trading Scheme (EU ETS). For example, Tzimas et al. (2005) estimated the maximum CO_2 storage capacity of the oil fields in the UK sector to be 1.8 Gt CO_2 when standard practices were applied. Standard practices imply the minimization of CO_2 usage and the maximization of CO_2 recovery after injection underground, to reduce the costs of the process, by reducing CO_2 purchases. If however, the storage of CO_2 had a commercial value, for example through emissions trading, CO_2-EOR operations could be designed to maximize the retention of CO_2 underground. In this case, the UK storage capacity could increase to approximately 3.5 Gt.

4.1.1.3 Estimating the CO_2 storage capacity of the UK's oil fields by assuming that a percentage of the pore space in a field will be filled with CO_2

An alternative approach to estimating the CO_2 storage capacity of the UK's oil fields is to:

1. Assume that a percentage of the space occupied by the recoverable reserves of the field is available for CO_2 storage, then
2. Calculate the mass of CO_2 that could fill that pore volume at the relevant reservoir temperature and pressure. For an oil field that did not originally have a gas cap, the calculation can be expressed as:

$$M_{CO2} = (V_{OIL}\ (stp).B_o)\ .\ \rho CO_2 \qquad \text{(Equation 1)}$$

Where:

M_{CO2} = CO_2 storage capacity (10^6 tonnes)

stp = standard temperature and pressure

V_{OIL} (stp) = volume of ultimately recoverable oil at stp (10^9 m^3)

B_o = oil formation volume factor (the ratio between a volume of oil and the dissolved gas that it contains at reservoir temperature and pressure and the volume of the oil alone at stp)

ρCO_2 = density of CO_2 at reservoir conditions (kg m^{-3})

The recoverable oil reserves in each field, the formation volume factor, the reservoir temperature and pressure and the density of CO_2 at reservoir conditions has been included in an accompanying spreadsheet (Appendix 1) so that CO_2 storage capacity can be calculated in this way if required. The density of CO_2 at reservoir conditions was calculated from an equation of state (Span & Wagner 1996). This approach was used by Van der Straaten et al. (1996). They assumed that 100% of the underground volume of the initially recoverable reserves could be replaced by CO_2, because the average oil recovery by conventional methods worldwide is only about 35% of the oil initially in place. They concluded that 2.6 Gt CO_2 could be stored in the UK's offshore fields.

Estimates produced in this way could be considered to be less rigorous than the estimates produced by ECL, because they do not involve any assessment of the geology of the individual fields. They should probably be considered to be "theoretical capacity" estimates in terms of the Bradshaw et al. resource classification.

4.1.1.4 Summary of the CO_2 storage capacity of the UK's oil fields

The potential CO_2 storage capacity of the UK's oil fields depends on assumptions about how they will be exploited. The potential ranges from approximately 1.175 Gt CO_2 to approximately 3.5 Gt CO_2. It is considered that the most rigorous estimates are those of ECL summarised above, and therefore the realistic potential is much closer to the former figure than the latter.

4.1.1.5 How much oil could be recovered by EOR in the UK oil fields?

ECL (2002) estimate that approximately 2 billion additional standard barrels of oil could be recovered by economic EOR on the UKCS.

Tzimas et al (2005) estimate that, disregarding economics, approximately 2.7 billion barrels (range 1.8 and 3.7 billion barrels depending on the achievable oil recovery from each oil field), or 58% of the UK proven reserves in 2003, could be recovered from the UK sector of the North Sea.

CO_2-enhanced oil recovery in North American onshore oilfields regularly recovers 4-12% of the oil initially in place (Goodyear et al. 2002). A study of a section of the Forties oil field (UK North Sea) indicated that WAG CO_2-EOR could recover up to an additional 9.8% of the oil initially in place (Cawley et al. 2005). Balbinski et al. (2002) indicate that approximately an additional 10% of the oil initially in place in many UKCS fields could be recovered as a result of CO_2-EOR.

4.1.2 Gas fields

4.1.2.1 Onshore Gas Fields

The UK's onshore gas fields are all too small to have significant CO_2 storage capacity. They are also in high demand as natural gas storage sites. The largest onshore field is Saltfleetby, in Lincolnshire. This has ultimately recoverable reserves of 2.067 x 10^9 standard m^3 natural gas and is estimated to have a CO_2 storage capacity of 5 Mt CO_2 or less. Moreover, some of the infrastructure that has been installed has been laid out in anticipation of future use as a natural gas storage site (Hodge 2003), implying that it will not be available for CO_2 storage in the foreseeable future. Thus the UK onshore gas fields realistically only have potential as demonstration sites for CO_2 storage.

4.1.2.2 Offshore Gas Fields

The UK's offshore gas fields occur mainly in two areas: the Southern North Sea Basin and the East Irish Sea Basin (Figure 4-1). However, there is also one major gas field (Frigg) in the Northern and Central North Sea Basin.

The Southern North Sea fields

The gas in the fields in the Southern North Sea generally consists of methane with low levels of higher hydrocarbons. Because it contains only a small fraction of (condensable) higher hydrocarbons it is described as a dry gas. The majority of the fields are in the Leman Sandstone Formation, a reservoir sandstone of Permian age. However, there are several fields with Carboniferous sandstone reservoirs and a few with reservoirs in the Bunter Sandstone Formation, which is of Triassic age (Figure 4-2) and some small discoveries with reservoirs in Upper Permian (Zechstein) carbonates. Some of the Rotliegend gas reservoirs are highly compartmentalised. That is to say they are divided into compartments by faults that act as permeability barriers (Figure 4-3). This is significant because each compartment is likely to require a separate CO_2 injection well, potentially adding to the cost of storage if new wells are required. By contrast, the Triassic reservoirs do not appear to be significantly compartmentalised.

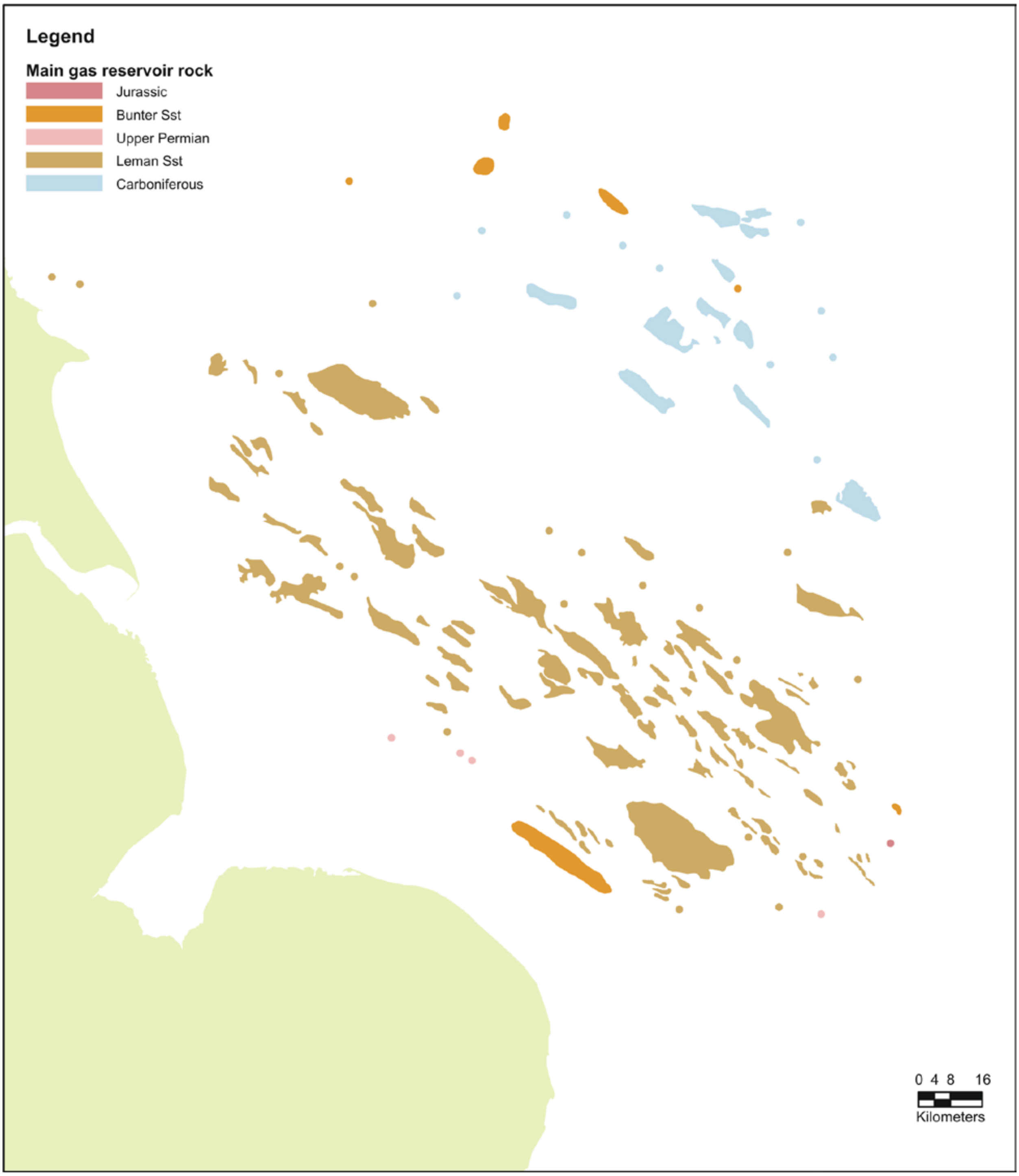

Figure 4-2. The age of the main reservoirs in the gas fields of the Southern North Sea

The majority of the fields with Rotliegend (Leman Sandstone) reservoirs are depletion-drive fields, i.e. there is little water encroachment into the field from surrounding parts of the reservoir rock during production (Figure 4-3). This means that there will be significant volumes of pore space in the field filled with low-pressure natural gas at the time that production ceases. This is advantageous for CO_2 injection because the various reservoir compartments can be filled with CO_2 and the initial reservoir pressure may never have to be exceeded, significantly lowering the risk of leakage. At least some of the Carboniferous and Triassic fields have significant water drive, i.e. water does encroach into the field from surrounding parts of the reservoir rock during production. An exception is the Triassic Hewett Sandstone reservoir in the Hewett field. Total storage capacity is estimated to be 3886 Mt CO_2.

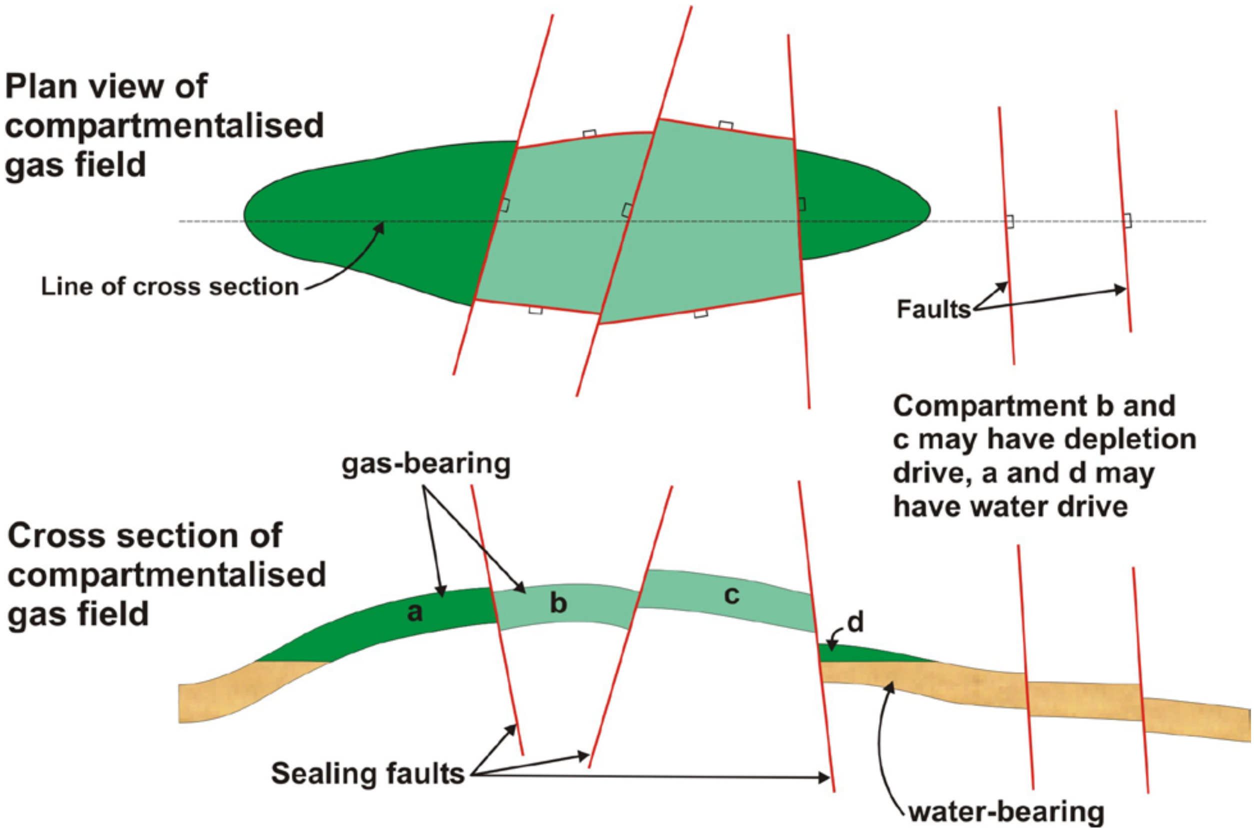

Figure 4-3. Diagram of a compartmentalised gas field and underlying aquifer.

The East Irish Sea fields

The East Irish Sea Basin fields all have reservoirs in the Ormskirk Sandstone Formation, which is of Triassic age and forms the uppermost part of the Sherwood Sandstone Group. They are sealed by the overlying Mercia Mudstone Group, which contains thick units of halite (rock salt) that provide an effective seal. The two largest fields, South Morecambe and North Morecambe are depletion drive fields. Total storage capacity is estimated at 1.034 Gt CO_2, of which 734 Mt (70%) is in the South Morecambe field and 139 Mt (13%) is in the North Morecambe field (Kirk *in press*).

Northern and Central North Sea Fields

The Frigg field is the largest of the dry gas fields in the Northern and Central North Sea Basin, and the only significantly sized field outside the Southern North Sea and East Irish Sea Basins. It straddles the UK/Norway median line (Figure 4-1). It has strong water drive, which limits the estimated CO_2 storage capacity of the UK share of the field to 171 Mt. Co-operation between the UK and Norway would be required to exploit it for CO_2 storage.

4.1.2.3 Storage Capacity of the UK Gas Fields

Methodology

The methodology used to estimate the storage capacity of the UK's gas fields is based on the principle that a variable proportion of the pore space occupied by the recoverable reserves will be available for CO_2 storage, depending mainly on the reservoir drive mechanism (e.g. Bachu &

Shaw 2003). The mass of CO_2 that would occupy the pore space in each field formerly occupied by its recoverable reserves of natural gas is calculated according to the following formula:

$$M_{CO2} = (V_{GAS}\ (stp) / Bg)\ .\ \rho CO_2 \qquad \text{(Equation 1)}$$

Where:

M_{CO2} = CO_2 storage capacity (10^6 tonnes)

Stp = standard temperature and pressure

V_{GAS} (stp) = volume of ultimately recoverable gas at stp (10^9 m^3)

Bg = gas expansion factor (from reservoir conditions to stp)

ρCO_2 = density of CO_2 at reservoir conditions (kg m^{-3})

The density of CO_2 at reservoir conditions was calculated from an equation of state (Span and Wagner 1996).

The above figure is then discounted to allow for factors that may reduce the amount of pore space in the reservoir that could be filled with CO_2. Water invasion into the reservoir during (and after) gas production is considered to be the main factor that will affect the amount of CO_2 that can be injected back into the gas field. This can most accurately be estimated by using a detailed numerical reservoir simulation. Unfortunately no reservoir simulations were available for this study. In the absence of simulations, the following factors, similar to those used by Bachu & Shaw (2003) in their study of the CO_2 storage capacity of the oil and gas fields of Alberta, were used to discount the CO_2 storage capacity calculated in Equation 1:

1. In gas fields where depletion drive dominates, i.e. those where the wells are opened up and the pressure in the gas field simply depletes as it would if the gas were being produced from a sealed tank, it is assumed that 90% of the pore space could be occupied by CO_2.

In gas fields where water drive dominates, i.e. those where water encroaches into the pore space formerly occupied by the produced natural gas reserves, it is assumed that 65% of the pore space could be occupied by CO_2.

Application

Gas Initially In Place (GIIP), Ultimately Recoverable Reserves (URR), Gas Expansion Factor (GEF), Initial Reservoir Pressure, Initial Reservoir Temperature were taken from DTI (2000) Abbotts (1991) and Gluyas & Hichens (2003) and drive mechanisms were taken from Abbotts (1991) and Gluyas & Hichens (2003). Where the drive mechanism was unpublished, the following assumptions were made: in Leman Sandstone reservoirs the drive mechanism is assumed to be depletion drive, in Triassic or Carboniferous reservoirs the drive mechanism is (conservatively) assumed to be water drive.

Results are shown in Table 4-1.

Table 4-1. Estimated CO_2 storage capacity of UK gas fields

Field name	Area	GIIP bcm	URR bcm	GEF	P bar	T °C	CO_2 density kg m^{-3}	Drive mech	Drive factor	CO_2 storage capacity (10^6 tonnes)
Frigg (UK)	C/NNS	92.07	72.48	197	198	61	714	W	0.65	170.76
Brechin	C/NNS								0.65	

Farragon	C/NNS								0.65	
Nuggets	C/NNS		10.44	128	114	31.4	786.6		0.65	41.70
Tullich	C/NNS								0.65	
Bains	EISB		1.36	128	114	31.4	786.6	U	0.65	5.43
Dalton	EISB		2.87	128	114	31.4	786.6	U	0.65	11.46
Darwen	EISB							U	0.65	
Hamilton	EISB	17.76	14.33	108	96.8	30	763.7	W	0.65	65.87
Hamilton North	EISB	6.51	5.34	120	105.8	30	784.1	W	0.65	22.68
Hamilton East	EISB							U	0.65	
Millom	EISB		6.07	128	114	31.4	786.6	U	0.65	24.25
Morecambe North	EISB	36.53	28.8	143	124	33	791.7	D	0.9	143.51
Morecambe South	EISB	155.8	149.1	146	128	32.7	800.9	D	0.9	736.08
Ormonde South	EISB							U	0.65	
Rivers Complex	EISB		8.5	128	114	31.4	786.6	U	0.65	33.95
Amethyst	SNS	31.0	23.9	235	283	88	692	D	0.9	63
Anglia	SNS	9.1	6.9	222	267	83	694	U	0.9	19
Ann	SNS	3.3	2.5	222	267	83	694	U	0.9	7
Audrey	SNS	25.0	18.9	222	267	83	694	U	0.9	53
Baird	SNS	3.4	2.5	222	267	83	694	U	0.9	7
Barque	SNS	85.5	38.7	228	264	79	710	D	0.9	108
Beaufort	SNS	1.1	0.9	228	276	91	669	D	0.9	2
Bell	SNS	5.7	4.3	222	267	83	694	U	0.9	12
Bessemer	SNS	3.7	2.8	228	278	91	672	D	0.9	8
Big Dotty	SNS	8.4	6.3	185	182	66	648	W	0.65	14
Boulton	SNS	5.8	4.0	295	447	116	741	D	0.9	9
Brown	SNS	1.0	0.7	223	274	89	675	D	0.9	2
Caister	SNS	10.3	7.5	288	428	114	732	U	0.65	12
Caister B	SNS									
Callisto	SNS	2.9	2.2	222	267	83	694	U	0.9	6
Camelot	SNS	7.9	7.1	192	193	60	712	MW	0.65	17
Cleeton	SNS	10.1	7.9	244	286	79	735	W	0.65	16
Clipper	SNS	33.2	21.3	228	265	79	712	D	0.9	60
Corvette	SNS	6.7	6.0	232	281	86	699	D	0.9	16
Davy	SNS	5.7	5.0	206	246	88	639	D	0.9	14
Dawn	SNS	0.7	0.5	164	162	64	609	D	0.9	2
Deborah	SNS	11.6	9.9	186	190	63	686	U	0.9	33
Delilah	SNS	1.3	0.7	182	196	66	677	U	0.9	2
Della	SNS	4.0	3.0	187	193	62	699	U	0.9	10
Esmond	SNS	10.8	9.7	158	157	57	656	W	0.65	26
Europa	SNS	3.8	2.9	222	267	83	694	U	0.9	8
Excalibur	SNS	9.8	7.4	222	267	83	694	U	0.9	21
Forbes	SNS	3.0	2.2	179	193	63	692	W	0.65	6

Galahad	SNS	5.7	4.3	222	267	83	694	U	0.9	12
Galleon	SNS		49.2	223			690	U	0.9	137
Ganymede	SNS	10.6	8.0	222	267	83	694	U	0.9	23
Gawain	SNS	7.8	6.1	227	284	80	729	U	0.9	18
Gordon	SNS	5.2	3.1	165	181	61	682	W	0.65	8
Guinevere	SNS	2.8	2.6	230	276	92	665	D	0.9	7
Hewett L Bunter	SNS	59.5	57.7	140	137	52	640	D	0.9	237
Hewett U Bunter	SNS	38.4	37.2	97	94	42	490	W	0.65	122
Hewett Zechstein	SNS	11.9	6.0	148	147	54	655	D?	0.9	24
Hunter	SNS							U	0.65	
Hyde	SNS	6.1	4.3	244	298	87	713	D	0.9	11
Indefatigable	SNS	158.6	133.1	228	284	91	680	D	0.9	357
Johnston	SNS	10.8	7.3	240	326	108	662	D	0.9	18
Ketch	SNS	15.8	11.5	288		114	732	U	0.65	19
Lancelot	SNS	8.8	6.6	222	267	83	694	U	0.9	19
Leman	SNS	397.0	360.0	211	208	52	783	D	0.9	1203
Little Dotty	SNS	7.1	5.3	185	189	63	685	W	0.65	13
Little Dotty	SNS	2.8	2.1	111	115	47	605	U	0.65	8
Malory	SNS	2.8	2.1	234	293	93	683	D	0.9	6
Markham	SNS	9.0	6.6	288		114	732	U	0.65	11
Mercury	SNS	3.5	2.3	228	297	96	674	W	0.65	4
Mordred	SNS	0.5	0.4	222	267	83	694	U	0.9	1
Murdoch	SNS	13.5	9.9	283	423	113	733	U	0.9	23
Neptune	SNS	9.7	8.1	253	302	80	748	W	0.65	16
Newsham	SNS	0.7	0.5	222	267	83	694	U	0.9	1
Orwell	SNS	9.8	8.1	144	146	54	650	U	0.65	24
Phoenix	SNS	23.9	14.4	243	304	85	729	U	0.9	39
Pickerill	SNS	25.5	14.2	222	275	96	646	U	0.9	37
Ravenspurn North	SNS	59.8	36.8	236	313	104	662	D	0.9	93
Ravenspurn South	SNS	34.0	19.8	240	310	93	701	D	0.9	52
Rough	SNS	13.8	10.4	256	313	92	709	D	0.9	26
Schooner	SNS	30.0	17.3	287	446	110	758	D	0.9	41
Sean East	SNS	4.0	3.6	220	267	97	630	D	0.9	9
Sean North	SNS	7.4	6.6	218	272	94	651	D	0.9	18
Sean South	SNS	17.3	13.8	225	274	89	676	W	0.65	27
Sinope	SNS	2.2	1.7	222	267	83	694	U	0.9	5
Skiff	SNS							U	0.9	
Thames	SNS	9.9	6.8	218	256	83	679	D	0.9	19
Trent	SNS	3.1	2.6	288	379	112	700	U	0.65	4
Tristan	SNS	1.5	1.1	222	267	83	694	U	0.9	3
Tyne N	SNS	4.6	2.3	288	424	116	724	U	0.65	4
Tyne S	SNS	4.2	3.0	288	437	117	731	U	0.65	5
Tyne W	SNS	1.7	1.5	288	441	117	734	U	0.65	3

V Fields	SNS	73.4	45.3	220	239	61	770	D	0.9	143
Victor	SNS	30.1	26.0	230	279	89	683	D	0.9	70
Viking	SNS	84.7	82.0	243	304	85	729	D	0.9	221
Vixen	SNS	5.5	4.1	222	267	83	694	U	0.9	12
Waveney	SNS	3.0	2.4	227	252	84	669	D	0.9	6
Welland	SNS	10.1	7.7	222	267	83	694	U	0.9	22
West Sole	SNS	72.0	53.0	239	294	85	718	D	0.9	143
Windermere	SNS	2.8	2.3	254	398	113	713	U	0.9	6
TOTAL										**5138**

Figures in blue are averages derived from full datasets with the same geological reservoir.

GIIP = Gas initially in place, URR = Ultimately recoverable reserves, GEF = Gas expansion factor, Drive mech = reservoir drive mechanism, D= Depletion drive, W = water drive, U = unknown drive mechanism. Where drive mechanism is not recorded, the following assumptions have been made: Leman Sst fields have depletion drive, Bunter Sst reservoirs have water drive, Carboniferous reservoirs have water drive, other reservoirs have water drive.

The estimates can be considered to represent realistic potential in terms of the Bradshaw et al. resource classification, although they could be improved by some numerical simulations of CO_2 injection into generic Leman Sandstone, Ormskirk Sandstone and Bunter Sandstone reservoirs, with and without water drive.

4.1.2.4 Enhanced Gas Recovery Potential

CO_2 is heavier than natural gas. So if CO_2 is injected into the base of a gas reservoir, it would tend to pool there and any remaining natural gas would tend to “float” on top of it. Thus CO_2 injection could have some potential for enhanced gas recovery (EGR) as long as significant breakthrough of CO_2 into the production wells did not occur, because then CO_2 separation would have to take place to get the gas to sales quality. Note also that natural gas recoveries in many UK gas fields are predicted to be very high without any enhanced recovery, meaning that the potential target for EOR can be very small.

Paterson (2003) has estimated that up to 4.6% EGR might be achievable in typical Leman Sandstone Southern North Sea gas fields, with low reservoir pressures and low CO_2 injection rates. However, this would require investment in an additional injection well in each compartment of the field.

4.1.2.5 When will the gas fields be available for CO_2 storage?

It is assumed that CO_2 storage will begin once the recoverable reserves of the field (as quoted in the public domain) have been produced. There is no great advantage in starting EGR before this point has been reached because the fields are likely to perform better in terms of EGR if CO_2 is injected slowly once the reservoir pressure is fully depleted (see above). Estimated Close of Production dates for the individual fields are not in the public domain, but dividing the remaining recoverable reserves by the average production over the last few years can provide a crude estimate. Some (mostly small) fields have already been depleted and are technically available for storage now.

4.1.2.6 Gas/condensate Fields

Gas/condensate fields contain principally methane, butane, pentanes and higher hydrocarbons. This hydrocarbon mixture is in the gaseous phase in the reservoir, but the pentanes and higher hydrocarbons condense to liquids at surface temperature and pressure. In the UK, gas/condensate fields are only found in the Northern and Central North Sea Basin (Figure 4-1). From a storage capacity perspective, they have been treated in the same way as dry gas fields, because EOR is unlikely to be attempted. Less field-by-field public domain information on their drive mechanism is available, but a crude estimate of their CO_2 storage capacity, using the same assumptions that were made for the dry gas fields, is 1216 Mt CO_2, see table 4.2.

Table 4-2. Estimated CO_2 storage capacity of UK gas/condensate fields

Gas/condensate field data								
Field name	Water depth	URR 10^9 m^3	GEF	P bar	T °C	Drive mech	CO_2 density kg m^{-3}	CO_2 storage capacity (10^6 tonnes)
Alwyn North*	126	17.2	275	499	120	D	763	43
Beinn	99	7	276.1	517	131		745	17
Brae East	116	43.3	268	514	124		761	111
Brae North	99	22	276	476	127		729	53
Britannia	136	85	276.1	413	137	D	654	181
Bruce	122	80.9	276.1	386	100		746	197
Drake	89	9.3	200	426	125	D	699	29
Elgin	93	25.9	276.1	517	131		745	64
Ellon	135	3.8	325	565	117	D	807	8
Erskine	100	9.36	318	961	171	D	845	23
Everest	89	19.78	276.1	517	131		745	48
Fleming	89	21.54	244	282	145	D	480	38
Franklin	93	25.65	276.1	517	131		745	62
Gannet B	95	7.41	276.1	517	131		745	18
Grant	139	4.59	314	586	118	D	814	11
Hawkins	89	3.29	245	382	136	D	629	8
Jade	79	11.22	276.1	517	131		745	27
Joanne	75	15.22	276.1	517	131		745	37
Judy	75	11.3	276.1	517	131		745	27
Kingfisher	105	7.93	295	602	128	D	798	19
Lomond	89	19.95	276.1	517	131		745	48
Marnock	93	16.85	276.1	629	149		763	42
Shearwater	90	27.29	276.1	517	131		745	66
Skene	120	16.11	276.1	517	131		745	39
TOTAL								**1216**
Figures in purple are averages of actual data. Column heading abbreviations as per table 4.1.								
All fields are in the Northern and Central North Sea Basin								

5 Saline water-bearing reservoir rocks (saline aquifers)

5.1 WHAT IS AN AQUIFER?

Aquifers are porous and permeable reservoir rocks that have the ability to store and transmit water. Figure 5-1.1 shows a typical sandstone aquifer – the Sherwood Sandstone – at outcrop in Eastern England: the red rock is the sandstone and it is overlain by a grey mudstone. In close-up and thin section (Figures 5-1.2 and 5-1.3), porous and permeable sandstones can be seen to consist of individual sand grains held together by mineral cement. Note that the cement does not occlude all the space between the grains and hence the rock has some porosity. Narrow pathways known as pore throats connect the pore spaces within the rock to each other. Hence the rock is permeable as well as porous, which allows fluids to pass through it and be stored in it. Many aquifers also contain fractures on various scales, which can enhance their permeability and, to a far lesser extent, their porosity.

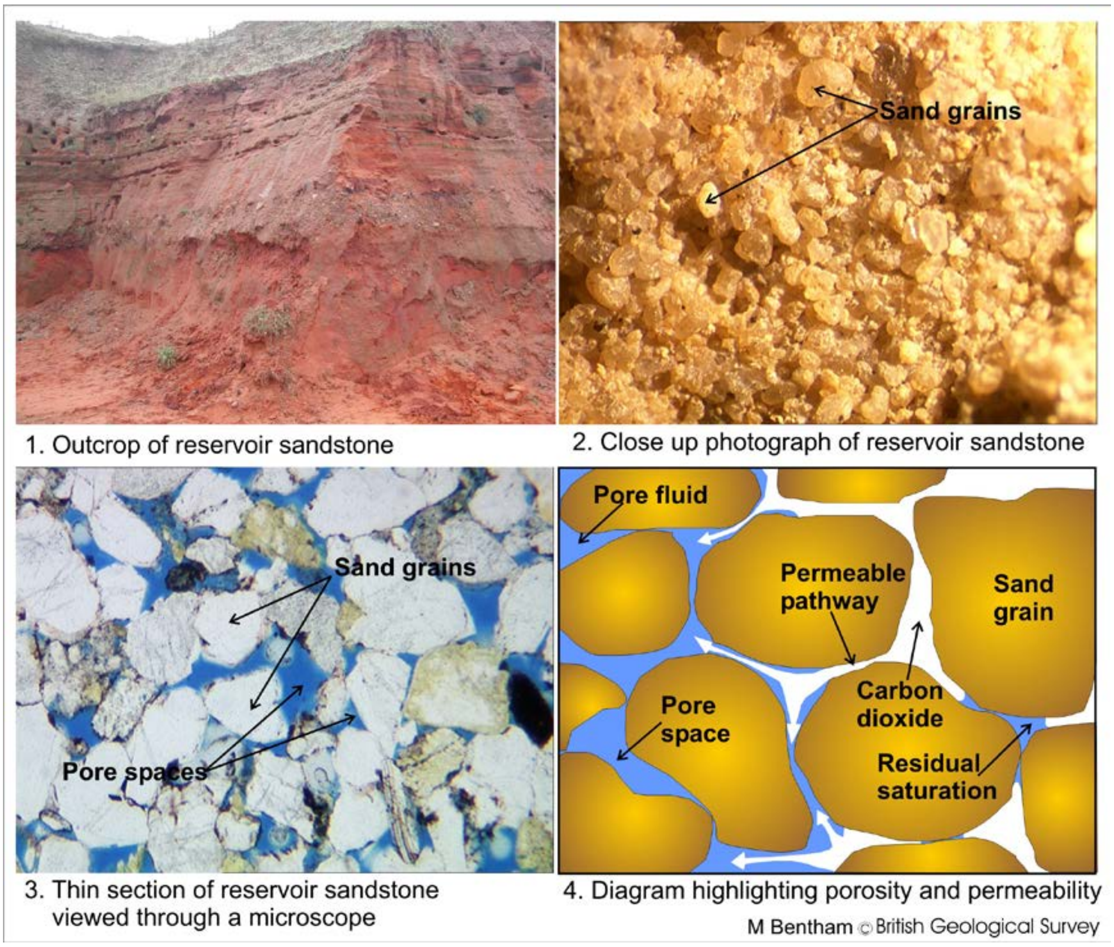

Figure 5-1. Typical sandstone reservoir rocks, shown at outcrop (1.1), in close-up (1.2) and in thin section (1.3). 1.4 shows how injected carbon dioxide would permeate the pore spaces of the reservoir rock, leaving behind a residual saturation of formation water

Aquifers are by definition, water-bearing reservoir rocks. Aquifers that crop out in onshore areas are partially filled with fresh water. Figure 5-2 shows how water enters and circulates through aquifers in onshore areas. Rainwater percolates through the soil above the outcrop of the aquifer and fills it to a level known as the water table. The water table tends to mimic, in a subdued way, the topography of the overlying land surface, and varies in elevation according to the rate of recharge via rainwater.

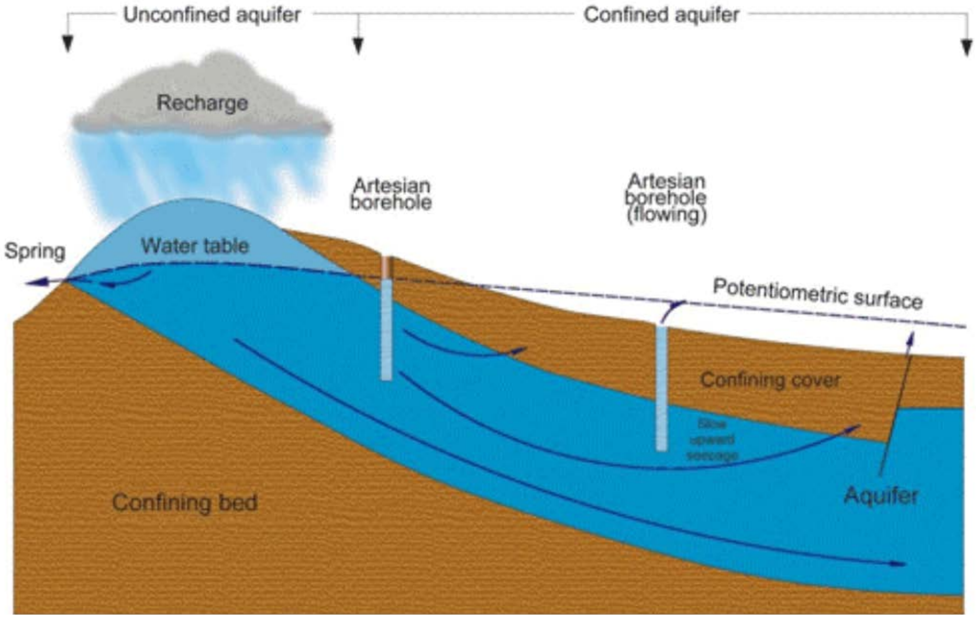

Figure 5-2. Groundwater circulation in an aquifer

Because the water table is above sea level, a slightly greater pressure than would occur if it were at sea level is present in the groundwater. This is called the hydraulic head and drives groundwater circulation. If a borehole were drilled into the aquifer below the recharge area, the pressure gradient in the aquifer would cause water to rise in it to a level called the potentiometric surface. Because of the pressure gradient, water emerges through any available pathways at levels below the potentiometric surface, e.g. springs, or rivers that intersect the water table, or by upwards transmission through overlying strata (described in more detail below). Typical flow paths for groundwater in an aquifer in the UK are shown in Figure 5-3. At and beyond the coast, groundwater may discharge into the sea. There is very little groundwater circulation far beyond the coast because at a point close to the coast any remaining hydraulic head is commonly counterbalanced by the slightly greater density of the saline groundwater that occurs in offshore areas. However, in actively subsiding basins such as the Northern and Central North Sea Basin, in which sediments are continually being laid down on the sea bed, compaction of the strata undergoing burial may lead to water being squeezed out of them. This may induce some groundwater flow from the centre of the basin towards its margin. This has been described in CO_2 storage literature as “natural fluid flow”. In hydrostatically pressured basins or reservoir formations, such as those that occur in the Southern North Sea Basin, there will be no natural fluid flow because there is no pressure gradient to cause it.

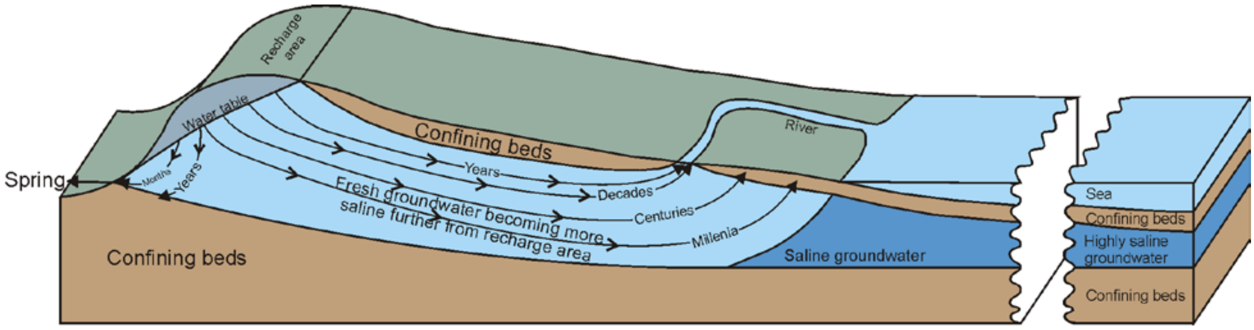

Figure 5-3. Diagrammatic representation of flow paths in typical aquifers.

5.1.1 Aquicludes and aquitards

The rocks that occur between, i.e. confine, aquifers can be divided into two classes: *aquicludes*, which are rocks such as halite that are essentially impermeable if not fractured, and *aquitards* which are rocks such as shales and mudstones that have significant porosity but, because of their very small pore and pore throat size, have very low permeability. The porosity of aquitards is usually water-filled. If they are water-wet, i.e. water occurs as a continuous phase through the pore system of the rock, water can pass through the porosity, albeit very slowly, in response to a pressure gradient. But water may also pass through both classes of strata via fractures such as faults or joints, if these are present.

5.1.2 Salinity of groundwater in aquifers

Circulating groundwater tends to be fresh close to the outcrop of an aquifer but the longer the flowpath, the more dissolved solids tend to be present. Beyond the zone of active groundwater circulation, i.e. offshore and in deep basin centres onshore, groundwater tends to be saline, partly because the water may be modified seawater that was originally present in the rock when it was deposited, partly because salts in the rock matrix dissolve into the groundwater and partly because, during burial, sometimes highly saline water may have been squeezed out of compacting surrounding strata into the aquifer. For example, the Sherwood Sandstone Group is underlain by the evaporites of the Zechstein Group and overlain by the Mercia Mudstone Group, both of which may contain thick beds of halite. Consequently highly saline waters, probably squeezed out of these surrounding strata, are found in the Sherwood Sandstone in offshore areas and deep onshore basin centres.

Thus a water-bearing reservoir formation like the Sherwood Sandstone, which is present both onshore and offshore, may be a source of potable groundwater (a fresh water aquifer) near its outcrop and a highly saline aquifer offshore, where it has few potential uses other than for CO_2 storage.

Oil and natural gas can accumulate in structural or stratigraphic traps in what were previously exclusively water-bearing reservoir rocks, providing they are on a migration path from where the oil or gas was generated. Thus oil and gas fields typically occupy small parts of very much larger saline water-bearing reservoir formations, the parts of which that remain filled with water generally being known as the aquifer. Typically oil and natural gas are found in the highly saline parts of reservoir formations because oil and gas are generated at considerable depths and are generally associated with the expulsion of saline fluids from fine-grained strata surrounding the reservoir.

5.2 CO_2 TRAPPING MECHANISMS IN AQUIFERS

5.2.1 Some physical properties of CO_2 stored at depth in geological reservoirs

Depending on the precise pressure and temperature conditions in the storage reservoir, CO_2 undergoes a relatively rapid change in density at depths between about 600 and 1000 m, becoming a dense phase supercritical fluid rather than a gas (Figure 5-4). Supercritical CO_2 is only slightly miscible with water or brine. Under the pressure-temperature conditions commonly found in the subsurface, both gaseous and supercritical CO_2 are less dense than the water or brine that is found within the void spaces of aquifers, i.e. they are buoyant relative to water or brine. CO_2 stored in the dense phase occupies much less space in the subsurface and so would be desirable considering the large masses that need to be stored.

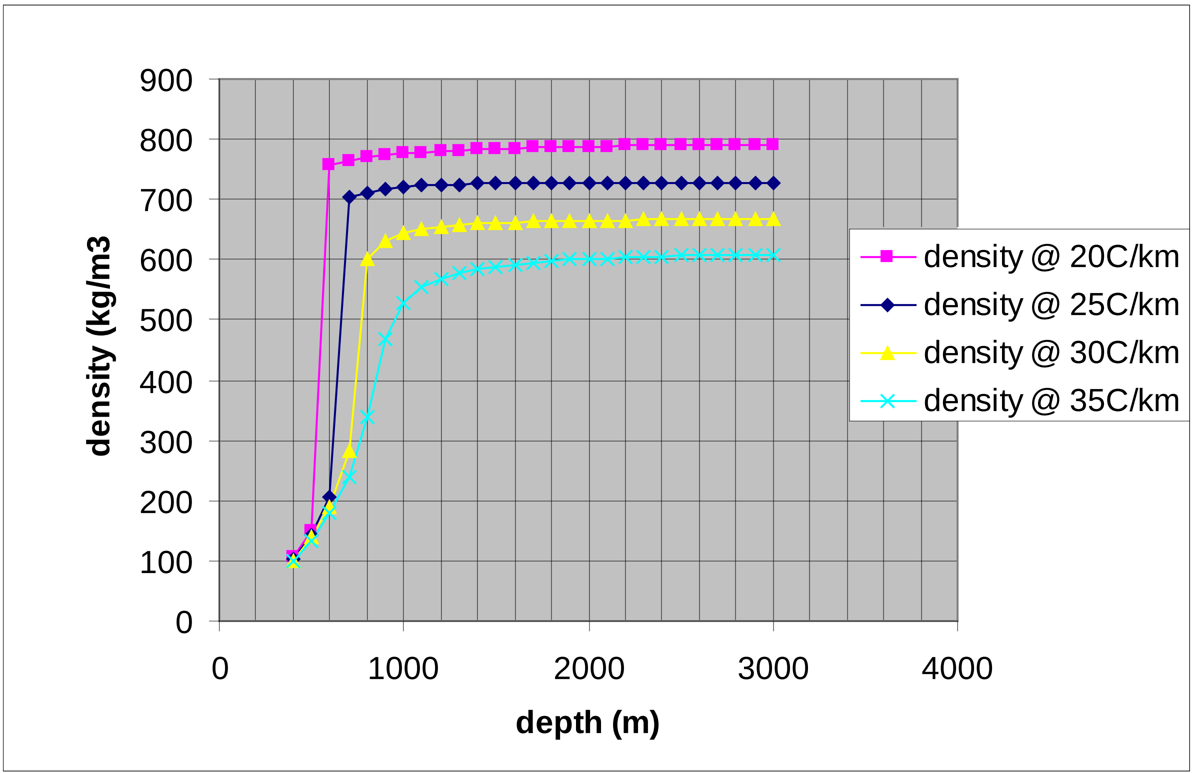

Figure 5-4. Variation in the density of CO_2 with depth at a range of realistic geothermal gradients likely to be found in sedimentary basins, assuming a surface temperature of 10°C and a hydrostatic pressure gradient.

The main mechanisms that can trap CO_2 injected into saline water-bearing reservoir rocks are:

- Trapping as a result of the buoyancy of CO_2 compared to water or brine, in structural or stratigraphic traps (e.g. domes) beneath cap rocks (aquitards and aquicludes). The relative buoyancy of CO_2 causes it to rise up through a permeable reservoir rock until it encounters a natural geological barrier that prevents it from rising further.
- Trapping as a residual saturation along the CO_2 migration path within the reservoir rock
- Dissolution into the native pore fluid (in aquifers, most commonly brine)
- Reaction of acidified groundwater with mineral components of the reservoir rock

5.2.2 Structural and stratigraphic trapping

Geological storage of gaseous or supercritical CO_2 in structural or stratigraphic traps requires a combination of a porous and permeable reservoir rock that will act as the storage reservoir and an aquitard or aquiclude in a configuration that will isolate the CO_2 from the atmosphere (Figure 5-5).

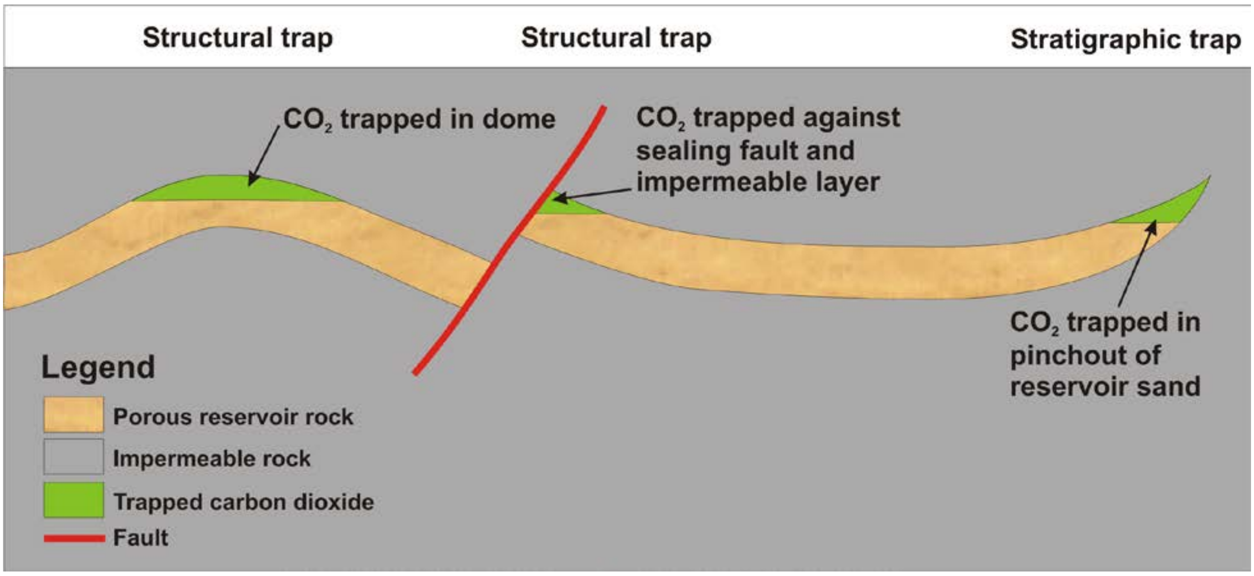

Figure 5-5. Diagram showing some typical structural and stratigraphic traps in which CO_2 could be stored.

However, many reservoir formations are subdivided into compartments by faults, which may prevent, inhibit or allow the transmission of fluids (Figure 4-6). If the reservoir compartments are small and the faults are sealing or only transmit fluids when large pressure differences develop across them (e.g. Gaarenstroom 1993), it may not be possible to pump CO_2 into them at all, or, more likely, there might be a rapid pore fluid pressure rise within the compartment into which injection was taking place. This could cause the fracture pressure of the reservoir rock or cap rock matrix to be exceeded, which could result in migration of CO_2 out of the intended storage site. Thus the CO_2 storage capacity of aquifers is a function not only of their intrinsic rock properties (e.g. porosity, permeability and heterogeneity) but also their size and, importantly, the nature of their boundaries. At least some part of the boundary of the reservoir (or reservoir compartment if any) must be able to transmit the pore fluid displaced by the injected CO_2. Ultimately the displaced fluid will be accommodated by fluid movement to the seabed or water table, or by a slight expansion of the geological system into which injection was taking place (van der Meer 1992).

5.2.3 Dissolution

The rate of trapping by dissolution into brine will depend on how well the CO_2 mixes with the formation water once it is injected into the reservoir. Once a CO_2 accumulation has reached a stable position within the reservoir, if the interface between the injected CO_2 and the underlying brine was perfectly stable, mixing would be by diffusion only, and could be very slow. Diffusion would of course be faster in a thin but widespread accumulation, with a high surface area to volume ratio. However, for many accumulations, dissolution could be slow; in the order of a few thousand years for typical injection scenarios (Ennis-King & Paterson 2001), unless there is some form of active mixing induced by fluid convection within the reservoir. Convection has been predicted because the density of CO_2-saturated brine is approximately 10 kg/m^3 greater than that containing no CO_2. Molecular diffusion of CO_2 into the brine will thus set up an unstable hydrodynamic layer at the CO_2/brine interface that will create convection currents within the brine as the CO_2-rich brine descends towards the base of the reservoir formation and CO_2-free brine rises to take its place, even though it is held in the porous medium of the reservoir rock (Lindeberg & Wessel-Berg 1997). Such mixing is predicted to be more rapid and comprehensive in thick, relatively homogeneous reservoirs such as the Utsira Sand - the reservoir at the Sleipner CO_2 injection project - than in thin low permeability reservoirs (Lindeberg & Bergmo 2003).

5.2.4 Water/rock reaction

Dissolution results in acidification of the brine into which the CO_2 dissolves, which can enable water/rock reactions, particularly the dissolution of carbonate minerals such as calcite and, at much slower rates, basic aluminosilicate minerals. The reaction of acidified brines with basic aluminosilicate minerals could lead to the precipitation of carbonates and thus so-called mineral trapping of carbon as a solid phase. However the kinetics of such reactions are very slow; time spans in the order of hundreds to thousands of years may be necessary for significant storage by this mechanism (Xu et al. 2003). Moreover, in the very long term such reactions might be reversed if there was natural fluid flow within the formation that restored the pre-injection chemical equilibrium within the reservoir formation.

5.2.5 Residual saturation

Residual saturation trapping occurs because a small proportion of the injected CO_2 remains behind when a plume of injected CO_2 sweeps through the reservoir rock. This is trapped by capillary forces and in very small-scale structural or stratigraphic traps. Residual CO_2 saturation may be in the order of 5-30% (Ennis-King & Paterson 2001) and thus it could be an important trapping mechanism (Spiteri et al. 2005), particularly if CO_2 is injected near the base of heterogeneous reservoir formations (Flett, Gurton & Taggart 2005). In such cases, wide plumes may form and, when CO_2 injection ceases, the rock volume through which the CO_2 passes as it migrates towards the top of the formation is likely to contain a residual CO_2 saturation. In the long term, residual CO_2 saturations are likely to dissolve into the surrounding formation water.

5.3 CONSTRAINTS ON CO_2 STORAGE CAPACITY IN AQUIFERS

The discussion above indicates that not all aquifers or parts of aquifers are suitable for CO_2 storage. From a UK perspective:

1. Those parts of aquifers that contain potable water are not considered suitable.
2. Parts of aquifers where leakage of injected CO_2 realistically could lead to contamination of potable water are not considered suitable. However, definition of these areas requires judgement or modelling, and planners and/or regulators would probably require assurance that contamination of potable water would not take place.
3. Typically the geothermal gradients in the UK sedimentary basins are 30°C/km or less and storage will be in the dense phase at depths below 800m (Figure 5-4). Whilst there is no intrinsic reason why CO_2 storage should not take place at depths <800 m, very large rock volumes would be required to store significant amounts of CO_2. Therefore most parts of aquifers where the top of the formation is above 800 m depth are not likely to be suitable for storage, but there may be some exceptions where there are particularly large structural or stratigraphic traps above this depth.
4. The natural overpressure in the Cretaceous and younger rocks in the centre of the Northern and Central North Sea Basin is potentially an issue for CO_2 injection. The limitations actually depend on the degree of overpressure and the size of the relevant overpressured compartment. However, all naturally overpressured aquifers are treated as

unsuitable for CO_2 storage in this study because there are insufficient resources to investigate the issue further.

5. Aquifers or parts of aquifers where there is not a realistic expectation of an effective trapping mechanism and/or seal are considered unsuitable.

The CO_2 storage capacity in the saline water-bearing reservoir rocks of the UK is considered below by subdividing it into the onshore and offshore, and then into geological provinces. Individual aquifers in these geological provinces are discussed. However, in almost all cases there is insufficient public domain information available to determine the pore volume of potential structural and stratigraphic traps in individual aquifers and thus make a realistic estimate of their storage capacity.

5.4 CO_2 STORAGE POTENTIAL IN UK ONSHORE SALINE WATER-BEARING RESERVOIR ROCKS

5.4.1 Summary

Amongst the major deep aquifers of onshore Britain, only the Lower Greensand, Portland Sand, Sherwood Sandstone and Permian sandstones are considered sufficiently porous and permeable to have large-scale CO_2 storage potential (Holloway & Baily 1996). The areas that have theoretical CO_2 storage potential are shown in Figure 5-6. In general there is a correspondence between sandstones that have sufficient porosity and permeability to form a low-enthalpy geothermal resource (Downing & Gray 1986) and those that have the potential for CO_2 storage.

Maps derived from seismic data would be needed to identify significantly sized structural or stratigraphic traps and thus upgrade the theoretical CO_2 storage capacity of the UK onshore area into realistic capacity.

5.4.2 Geological overview

Igneous and metamorphic rocks in the UK have no potential for conventional large-scale CO_2 storage because they do not have sufficient porosity and permeability.

Over much of Northern Ireland, thin Quaternary strata overlie a succession of Cainozoic basalts. The basalts unconformably overlie rocks of Cretaceous to Palaeozoic age preserved in a series of concealed deep basins known as the Ulster Basins. Little is known about the Cretaceous and older rocks at depth in these basins, as there are few released deep wells, although it is known that the Sherwood Sandstone has good reservoir properties. No structural or stratigraphic traps have been defined however, and it is not known whether the overlying strata form an effective seal. Thus there is theoretical CO_2 storage potential in the Ulster Basins of Northern Ireland, but at present this cannot be quantified.

The sedimentary reservoir rocks of the UK mainland can conveniently be considered on a basin-by-basin basis. The sedimentary basins of the UK can be divided into four groups: Lower Palaeozoic basins, pre-Permian Upper Palaeozoic basins, Permian and Mesozoic basins and Cainozoic basins.

5.4.2.1 LOWER PALAEOZOIC BASINS

Over most of the country, the Lower Palaeozoic basins were intensely deformed in the Caledonian Orogeny. Near the surface they are strongly indurated and have only weak fracture permeability (Robins 1990, Downing & Gray 1986). There is no reason to suppose that their aquifer properties will improve at depth and thus they do not appear to have any potential for CO_2 storage and are not considered further.

5.4.2.2 Pre-Permian Upper Palaeozoic basins

The pre-Permian Upper Palaeozoic basins of the UK are better explored than the Lower Palaeozoic basins because oil and gas have been found in Carboniferous rocks in the East Midlands and the Midland Valley of Scotland. However, the Upper Palaeozoic rocks of the UK were affected by compression and folding during the Variscan Orogeny and are relatively hard and compact with low porosity and permeability. Water flows through them mainly in fractures and fissures, and drilling deep wells in the hope of encountering good aquifer properties would be a very speculative venture (Holliday 1986).

The Nottinghamshire/Lincolnshire/South Humberside region of the East Midlands has by far the most data on the aquifer properties of upper Palaeozoic rocks at depths below 800 m and acts as a yardstick against which other regions can be evaluated (Holliday 1986). The oil and gas fields of the East Midlands have proven seals above their reservoirs, which are, in most cases, early Westphalian sandstones. However, a CO_2 injection trial at the Egmanton oil field (Gair et al. 1980) suggests that the rate at which CO_2 could be injected into them is very low. All the Carboniferous oil and gas fields are small and the amounts of CO_2 that could be stored in them are very small in terms of UK emissions.

Although seismic resolution is good in the East Midlands, in some areas of Upper Palaeozoic strata, e.g. parts of the Midland Valley of Scotland, it may be poor, and therefore it may be difficult to identify large closed structures suitable for CO_2 storage.

Because they are part of the Coal Measures, in many parts of the country CO_2 injection into Westphalian sandstones could give rise to conflicts over use of the subsurface with the (present or future) coal mining industry, or leakage into abandoned coal workings; Westphalian coals have been extensively mined in the UK – to depths of a kilometre or more in parts of eastern England and up to 1200 m in Lancashire.

Namurian sandstones (often described in the Pennines and adjacent areas as Millstone Grit) commonly form minor aquifers near their outcrop. However, water flow in these strata is dominated by fissures and tends to decrease rapidly with depth (Holliday 1986).

Permeability in the Carboniferous limestones is generally low, commonly less than 10mD (e.g. Browne, Hargreaves & Smith 1985). The limestones owe most of their properties as aquifers to bedding planes and fractures and, because primary porosity is also low, they have no potential for CO_2 storage.

Therefore it is concluded that, although there may be niche opportunities, pre-Permian Upper Palaeozoic reservoir rocks are not likely to have significant CO_2 storage potential in the UK onshore area.

5.4.2.3 Permian and Mesozoic basins

There are several porous and permeable reservoir rocks in the Permian and Mesozoic basins of the UK. These basins have been only slightly deformed, by the Alpine Orogeny. Permian and Triassic reservoirs with significant theoretical storage potential (Figure 5-6) occur in the Wessex Basin, the Worcester Basin, the Cheshire Basin, west Lancashire, the Solway Basin and, towards the east coast, beneath parts of Yorkshire, Lincolnshire and Norfolk (i.e. the onshore western margin of the Southern North Sea Basin). These are described in more detail below.

The only other Permian or Mesozoic reservoir considered to have storage potential is the Portland Sand, which occurs at sufficient depth in a small area of the Wessex Basin. The Lower Greensand, which is at sufficient depth beneath part of the northern half of the Isle of Wight, can appropriately be neglected because of its small area. The Chalk is an important aquifer but it does not have any thick and widespread internal permeability barriers, and its top is at depths of less than 800 m throughout the country.

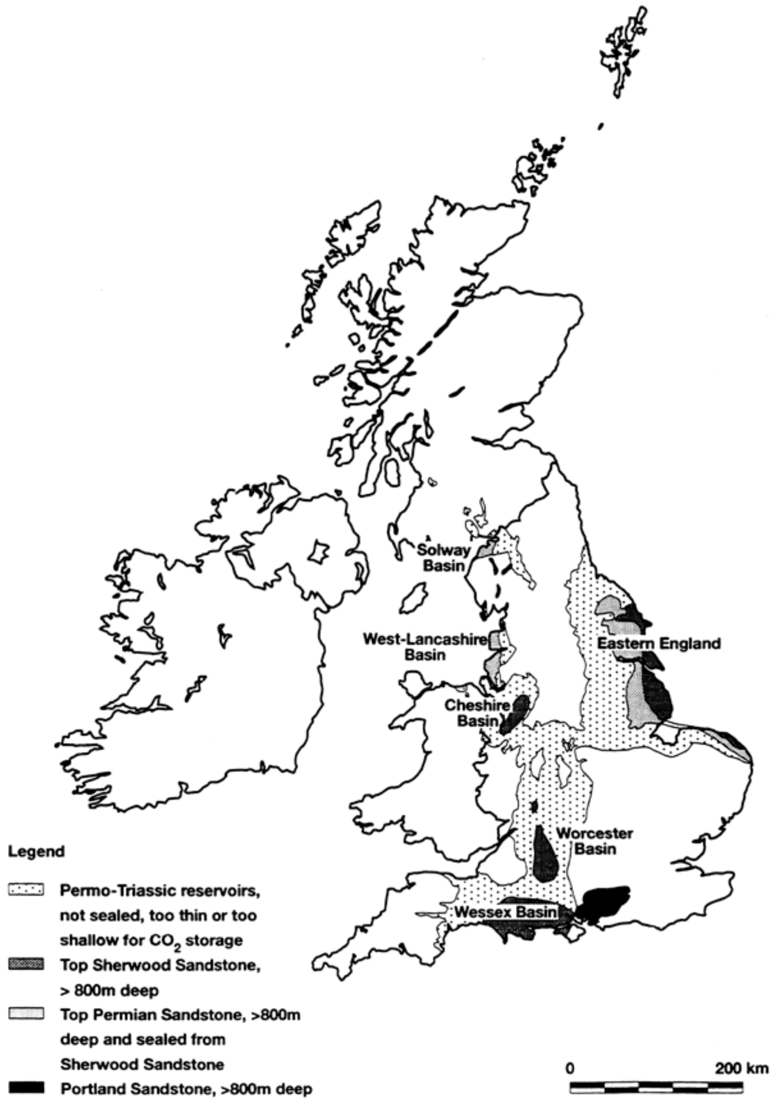

Figure 5-6. Areas of the UK mainland with theoretical CO_2 storage potential

Permian reservoir rocks

Permian sandstones occur at depths of more than 800 m in the Worcester Basin, the Cheshire Basin, parts of west Lancashire, the Solway Basin and in eastern England between North Yorkshire and the Wash.

In the Worcester Basin, thick sandstones known as the Bridgnorth Sandstone occur at depth. They are directly overlain by conglomerates and then sandstones of the Triassic Sherwood Sandstone Group so that these strata probably form a single thick aquifer. Therefore the Bridgnorth Sandstone is likely only to have storage potential as the lower part of a single Permo-Triassic aquifer in this basin – mainly by the mechanisms of residual saturation and dissolution. Any storage potential can be classified as theoretical in the present state of knowledge.

Thick Permian sandstones occur at depth in the Cheshire Basin, but, as in the Worcester Basin, in its southern half they are not sealed from the immediately overlying Sherwood Sandstone. In the northern half of the basin they are overlain by the Manchester Marl, which occurs between the Permian sandstones and the Sherwood Sandstone. The sealing capacity of the Manchester

Marl is not known but in this area the Permian sandstones may have some separate theoretical storage capacity.

In West Lancashire, the Lower Permian sandstones are 715 m thick in the Formby 1 well. They are overlain by a thick sequence of Upper Permian mudstones, the St. Bees Shales, which are likely to form an excellent seal. The thickness of the early Permian Sandstone is poorly known away from this well, but seismic data suggest it is very variable. The sandstones do not crop out in West Lancashire. No major structural or stratigraphic traps have been identified and any potential remains theoretical.

In the Solway Basin, the early Permian Penrith Sandstone is overlain by the St. Bees Shale, which probably seals it. It is up to about 380 m thick in the Silloth 1 well. The top 150 m has an average porosity of about 15% and the lower 230 m about 8%. The downwards decrease in porosity is due to an increase in anhydrite cement (Downing & Gray 1986). There is theoretical potential but at present it cannot be quantified.

In East Yorkshire and Lincolnshire, relatively thin early Permian sands and breccias, known as the Yellow Sands or Basal Permian Sands are sealed at depth by thick overlying Zechstein mudstones and evaporites, and occur at depths >800 m beneath a wide area. Sandstones are very thin or absent in many marginal parts of the basin and they only consistently exceed 30 m in thickness in parts of east Lincolnshire. Porosity may vary between 20 and 25% and permeability may be over 100 mD where the sandstone is clean., in East Lincolnshire this is not always the case, as proved by the Cleethorpes geothermal well. Again, there may be a lack of large closed structures suitable for CO_2 injection in the basal Permian Sand in eastern England, so any storage capacity is theoretical at present.

Early Permian Sandstones are known to be a useful aquifer around the part of the margin of the Ulster basins. Its distribution is not known precisely and it is impersistent in places. It may be confined to the Lough Neagh/Larne Basin. The lack of data on its distribution means that any CO_2 storage potential is classified as theoretical.

Triassic reservoir rocks

The British Triassic is divided into three broad groups. At the base is the Sherwood Sandstone Group, which is overlain by the Mercia Mudstone Group and then the Penarth Group. Neither the Mercia Mudstone nor the Penarth groups have significant reservoir potential on a regional scale.

The Sherwood Sandstone is by far the most important Triassic reservoir in the UK. It occurs in all the Mesozoic basins. It consists of a thick succession of feldspathic sandstones that have excellent reservoir properties at depth. It is sealed by the Mercia Mudstone Group, which conatins significant halites in some basins. It is buried to depths of >800 m beneath a small part of the Central Somerset Basin, large parts of the western Wessex Basin, the southern Worcester Basin, the Cheshire Basin, parts of east Yorkshire, Lincolnshire and Norfolk, and also the Ulster basins in Northern Ireland. It is normally (hydrostatically) pressured throughout the UK.

In East Yorkshire and Lincolnshire the porosity of the Sherwood Sandstone exceeds 20% over much of the area where it is buried to depths >800 m (Figure 5-7). The average permeability is likely to exceed 200 mD over much of this region and the thickness in the Cleethorpes geothermal well near the east coast exceeds 500 m. The Mercia Mudstone Group is likely to form a good seal above the Sherwood Sandstone. However, regional seismic mapping has not identified any major structural closures and the Sherwood Sandstone is used for water supply as far as 15-25 km east of the outcrop (Figure 5-7) so assurance would have to be provided that there would be no updip migration of injected CO_2.

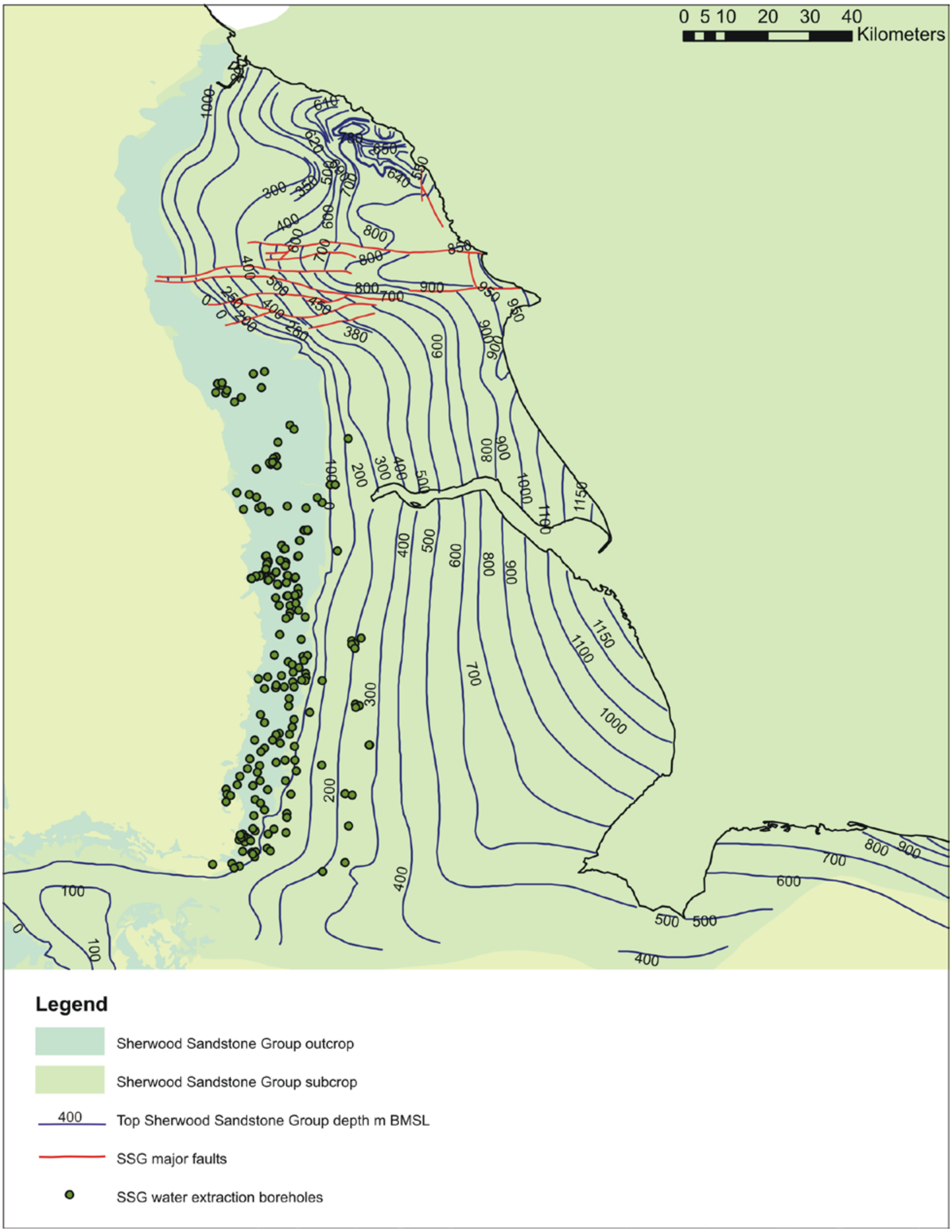

Figure 5-7. Depth to top Sherwood Sandstone Group in eastern England and water extraction boreholes.

The Sherwood Sandstone could have CO_2 storage potential in the centre of the Wessex Basin, providing sufficient quantities can be injected without unacceptable pressure rise, and suitable structural closures exist (these have not been identified on regional seismic interpretations). The Mercia Mudstone is known to form a good seal in the Wytch Farm oil field, which has a Sherwood Sandstone reservoir. There is also theoretical potential in the Worcester Basin and

Cheshire Basins that could repay further study. Potential conflicts of interest with water supply would need to be considered over at least parts of these areas.

The Sherwood Sandstone also occurs at depths >800 m in much of the Lough Neagh-Larne Basin and Rathlin Trough in Northern Ireland. Seal is again provided by the Mercia Mudstone. However, the configuration of the sandstones at depth is highly uncertain: seismic and gravity maps have so far done little to elucidate the situation and consequently any storage potential is theoretical.

Portland Sand

The Portland Sand occurs around the southern and western margin of the London Platform. They thin steadily to the south and southwest. To the south, they eventually pass laterally into the mudstones of the Kimmeridge Clay Formation. To the southwest they pass laterally into the fine-grained limestones of the Portland Stone. Gas and oil discoveries have been made in the Portland Sands near the northern margin of the Weald Basin, proving that they are sealed by the mudstones and anhydrite found in the overlying Purbeck Beds. The Portland Sands are at depths of more than 800 m in the centre of the Weald Basin and in the southern half of the Isle of Wight. Permeability probably averages around 100 mD and the sandstone is essentially clean, with no internal impermeable layers. The Portland sandstone is in hydraulic contact with the Lower Greensand close to the northern margin of the Wessex Basin and thus connected to outcrop. It is normally pressured and forms part of a hydraulic system that is connected to surface rather than being completely sealed.

Lower Greensand

The Lower Greensand is highly porous and permeable, and buried to sufficient depths beneath a small area in the northern Isle of Wight, but again may suffer from limitations imposed by the lack of large closed structures.

5.4.2.4 Cainozoic basins

There is one major Cainozoic basin in the UK onshore area - the London Basin. Neither this nor any of the other areas of Cainozoic strata in the UK contain reservoir rocks that are sufficiently deeply buried or well sealed for CO_2 storage in the UK onshore area.

5.4.2.5 Conclusions

It is concluded that there is some theoretical CO_2 storage capacity in the saline water-bearing reservoir rocks of the UK onshore area, particularly in Permo-Triassic reservoirs. However, the realistic and/or valid potential cannot be quantified at present because detailed maps that allow structural closures to be identified and analysed are not in the public domain.

5.5 CO_2 STORAGE POTENTIAL IN UK OFFSHORE SALINE WATER-BEARING RESERVOIR ROCKS

The UK Continental Shelf is a vast area that can be conveniently divided into the North Sea, to the east of Britain, and the remaining areas to the north, west and south of the UK. The North Sea contains what are effectively two separate sedimentary basins, the Southern North Sea Basin and the Central and Northern North Sea Basin, lying respectively to the south and north of a feature called the mid-North Sea High. These are discussed separately below because their geology differs significantly. The North Sea contains the majority of the UK's oil and gas resources. However, there are also oil and gas fields in production in the Faroes-Shetland Basin to the north of Scotland, and the East Irish Sea Basin to the west of England (Figure 5-8).

Hydrocarbons in non-commercial quantities have also been found in the English Channel and St George's Channel.

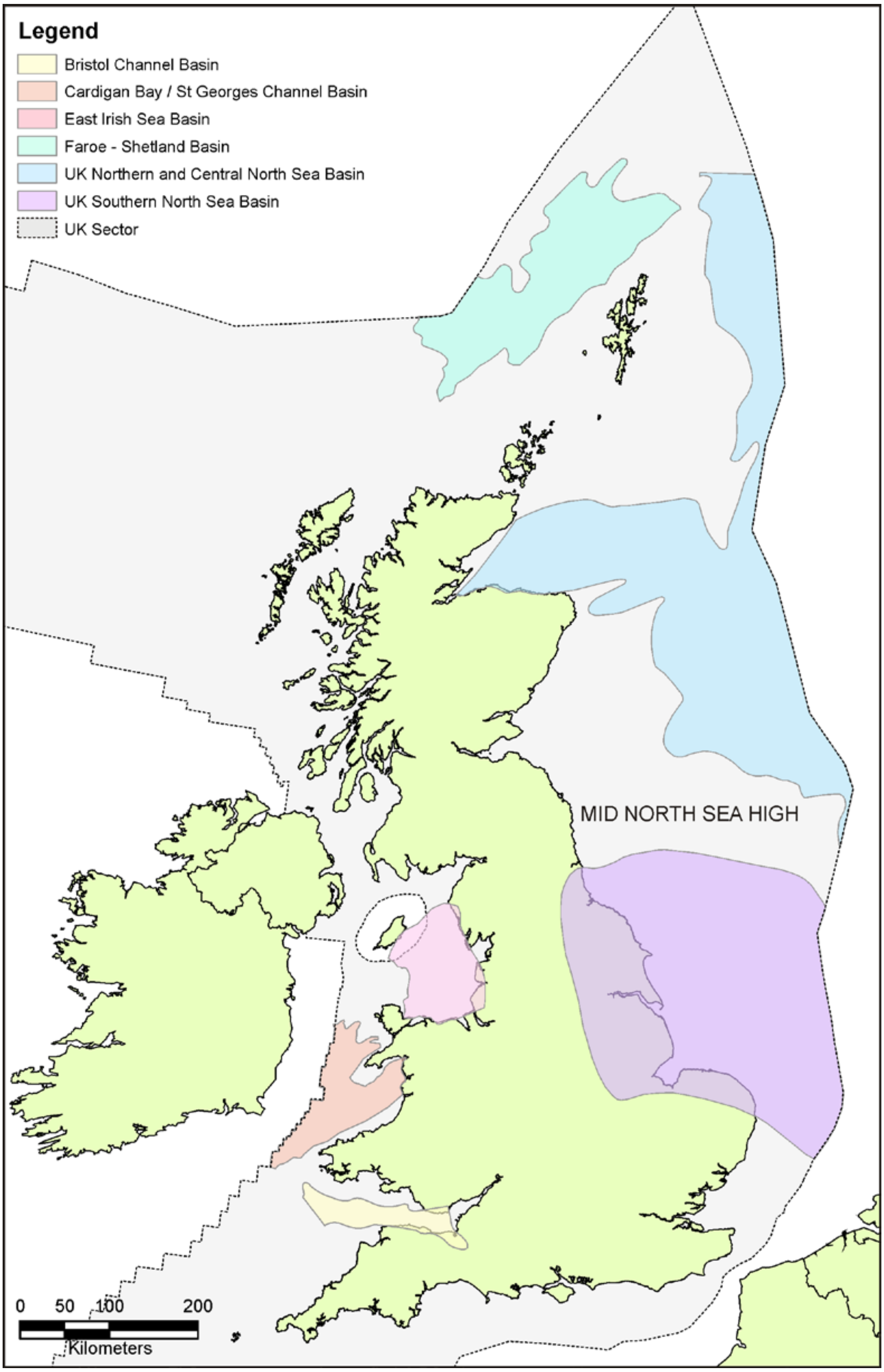

Figure 5-8. Major sedimentary basins on the UK Continental Shelf considered in this study.

5.5.1 The Southern North Sea Basin

The Southern North Sea Basin is close to many of the UK's major industrial sources of CO_2, which comprise mainly power stations and integrated steel plants (Figure 2-2). Thus it is well placed for storing CO_2. The summary below is based on a fuller analysis of it storage capacity in Holloway et al. (*in press*).

There are five major reservoir formations in the UK sector of the Southern North Sea (Figure 5-9):

- Sandstones within the Carboniferous succession
- The Leman Sandstone Formation
- The Bunter Sandstone Formation
- The Spilsby Sandstone Formation
- The Chalk

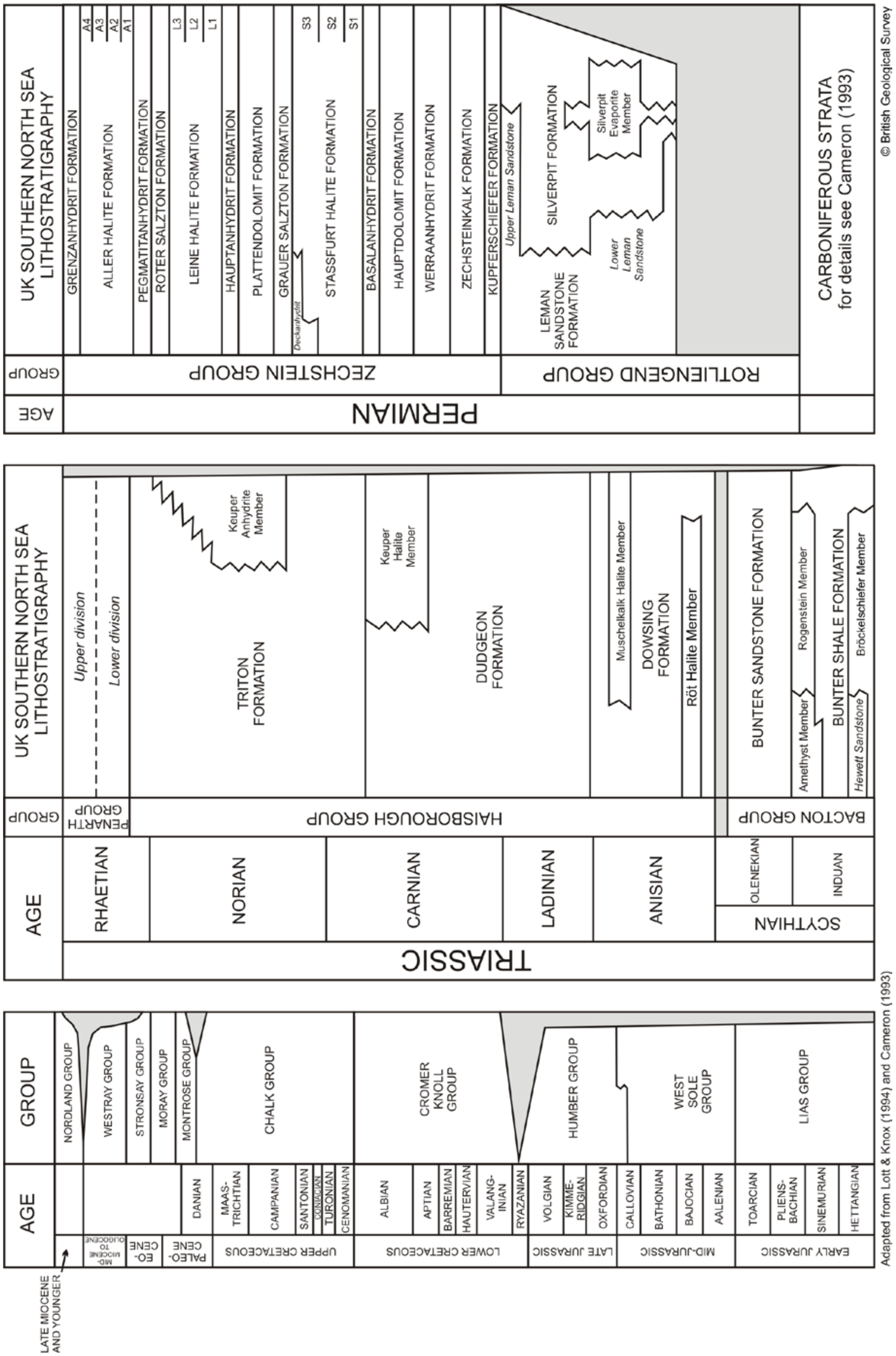

Figure 5-9. Stratigraphy of the Southern North Sea Basin, showing the 5 major reservoir horizons.

The Carboniferous sandstones are very well known locally (i.e. in the gas fields that have Carboniferous reservoirs), but not enough is known at present about their regional distribution, thickness, reservoir characteristics and structure to make a regional analysis of their CO_2 aquifer storage potential and they are only briefly considered here.

The Leman Sandstone Formation is the most important gas reservoir in the Southern North Sea. However, in the gas fields, where detailed information is available, and presumably the remainder of the area east of the East Midlands Shelf, it is divided into many relatively small compartments by internal permeability barriers, most of which are thought to be faults. These barriers severely impede or prevent fluid flow over production timescales (decades). This means that if CO_2 were injected into a water-bearing compartment of the Leman Sandstone Formation, the pore fluid pressure in that compartment would rise rapidly and possibly prevent significant safe injection. Therefore the Leman Sandstone Formation is not thought likely to be a good reservoir for aquifer storage of CO_2, at least in the eastern part of the UK sector of the Southern North Sea.

The Bunter Sandstone Formation is thought likely to have the best aquifer storage potential amongst the reservoir rocks of the Southern North Sea - because there are indications that compartmentalisation may be less severe than in the Leman Sandstone Formation:

- There are no indications of compartmentalisation in the (few) Bunter Sandstone gas fields.
- Pressure communication within the Esmond, Forbes and Gordon fields is known to be good (Ketter 1991).
- The Little Dotty and Hewett Bunter Sandstone reservoirs, which are approximately one kilometre apart, share a common underlying aquifer (Cooke-Yarborough & Smith 2003).
- Water invasion has occurred in all the above five fields, to varying degrees.

All these factors suggest that it might be possible to displace significant amounts of water from the pore space of the Bunter Sandstone Formation by CO_2 injection. Nevertheless, there are potential permeability barriers within the formation in various parts of the Southern North Sea Basin, because in places faults (which may act as intra-reservoir seals) are clearly imaged on seismic.

There are a number of very large domes in the Bunter Sandstone (Figure 5-10), which form very large potential traps for buoyant fluids such as CO_2. However, it is difficult to demonstrate unequivocally (a) that they will not leak and (b) that significant masses of CO_2 can be injected into them. Both these factors render the calculations of CO_2 storage capacity in the Bunter sandstone of the Southern North Sea highly uncertain. Although the Bunter Sandstone is, in regional terms, sealed by the overlying Haisborough Group mudstones and halites, there are crestal faults on many of the domes and it is uncertain whether, or at what pore fluid pressure, these might leak.

To estimate the CO_2 storage capacity of the Bunter Sandstone Formation, structural closures were identified from small-scale maps. The volume of the closures was calculated and the rounded average porosity of all core samples in the Bunter Sandstone (18%) was calculated. The reservoir temperature was calculated assuming a geothermal gradient of 30°C/km. The reservoir pressure was assumed to be hydrostatic. CO_2 density was calculated from an equation of state. It was assumed that 40% CO_2 saturation of the pore space could be achieved in all structures. The storage capacity was then calculated in tonnes of CO_2 using the formula:

CO_2 storage capacity (tonnes) = total pore volume x density of CO_2 x 0.4.

The maximum potential CO_2 storage capacity of the Bunter Sandstone of the UK sector of the Southern North Sea is estimated by this methodology to be approximately 14.25 Gigatonnes (Gt = 10^9 tonnes). The five largest domes might each be able to store more than 1 Gt CO_2.

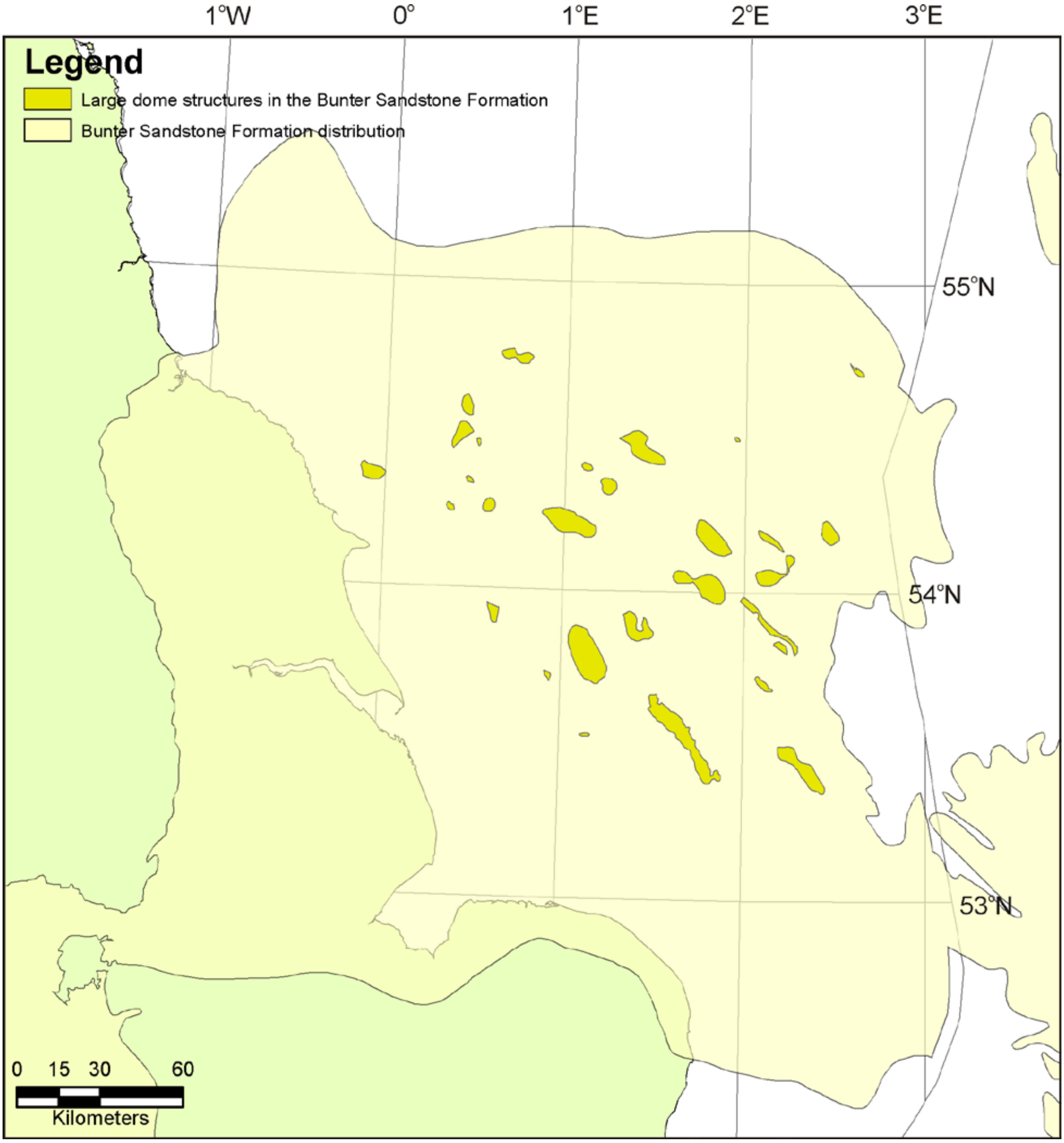

Figure 5-10. Map showing location largest domes in the Bunter Sandstone Formation

Note that the maximum storage capacity could only be achieved if none of the domes leak and it is found to be possible to fill them all with CO_2 to their spill points. The integrity and injectivity of individual structures cannot be estimated from the data available for the study. If 3D seismic data was available and licensed, and well test data was available, it could provide a much more detailed view of the potential of an individual structure but it still would not be able to provide any guarantees about either injectivity or integrity. This could only be proved or disproved by (very expensive) field injection tests.

The Spilsby Sandstone, which occurs in the western part of the basin in the area south of the Humber Estuary, and the Chalk Group, which occurs almost throughout the basin, have good and fair reservoir properties respectively. They are too shallow for CO_2 storage above several of the salt domes that form the major structural closures in the Southern North Sea. They may also be poorly sealed compared to the deeper reservoir formations as there are no halite units above them. Their CO_2 storage capacity has not been quantified to date.

5.5.1.1 CONCLUSIONS

CO_2 storage in the Bunter Sandstone Formation aquifer in the Southern North Sea has great potential but at present is also associated with great uncertainty, both in terms of geology and regulation. It is recommended that (a) detailed modelling of large-scale CO_2 injection and (b) detailed geological studies of individual storage prospects within the Bunter Sandstone are undertaken. If CO_2 storage was initiated in the gas fields of the Southern North Sea, it might be possible to test the integrity of adjacent saline water-bearing structures at the same time.

5.5.2 The Northern and Central North Sea Basin

This basin consists of a central deep area of grabens, with areas of thinner strata known as platforms on either side. In the UK sector the graben are connected: the Central and Viking Grabens straddle the median line and the Witch Ground Graben occurs in the outer part of the Moray Firth. Formations older than the Upper Cretaceous Chalk are present in the grabens and the Inner Moray Firth Basin, but largely absent from the East Shetland Platform, Fladen Ground Spur and Central Platform. The pre-Upper Cretaceous strata in the grabens are compartmentalised and overpressured to varying degrees (Moss et al. 2003), and thus are unlikely to form good, large aquifer CO_2 storage sites, even though it may be possible to inject some CO_2 into reservoir compartments that are only slightly overpressured. The (normally pressured) pre-Upper Cretaceous strata in the Inner Moray Firth Basin may have some realistic potential however.

Post-Upper Cretaceous strata (particularly Palaeocene and Eocene fan sandstones) in the centre of the basin may have good potential. However, on the Platform areas these may be too shallow to have reliable long-term seals. The only hydrocarbon fields on the East Shetland Platform and Fladen Ground Spur at depths of <1km are heavy oil accumulations. The lighter hydrocarbons from these have been lost, probably mainly as a result of biodegradation but some of these heavy oil fields appear to have gas chimneys above them, indicating that lighter hydrocarbons (particularly gases) may have escaped.

It is noteworthy that the oil and gas fields in the Palaeocene and Eocene fans are, with one exception, always in the youngest sandstone (Moss et al. 2003). This suggests that, at least in the long term, the thinner mudstones that occur between these sands, like the thin shales within the Utsira Sand at the Sleipner CO_2 injection project (Chadwick et al. 2001), do not form good seals.

No structure contour maps of the top of the Palaeocene and younger fan sandstones were available for the study, although distribution maps were available. In the absence of any evidence of the volume of structural and stratigraphic traps on the fan system, the CO_2 storage capacity of the Palaeocene and Eocene reservoirs was crudely estimated by assuming that the volume of structural closure per unit area is the same as that of the Utsira Sand, a Pliocene fan system in the centre of the same basin. This indicated that their theoretical CO_2 storage capacity is likely to be in excess of 3 Gt CO_2 in structural traps alone. If the potential for CO_2 dissolution and trapping as a residual CO_2 saturation is taken into account, the potential would be much larger.

5.5.3 The East Irish Sea Basin

In the East Irish Sea Basin, the main saline water-bearing reservoir rock is the Sherwood Sandstone Group, the upper part of which is known as the Ormskirk Sandstone Formation. It contains oil and gas fields but is largely a saline aquifer (Figure 5-11). It demonstrates the required characteristics for CO_2 storage i.e. apparently closed structures, high porosity and permeability, and it is overlain by the Mercia Mudstone Group, which provides an effective seal. Its CO_2 storage potential was estimated using a structure contour map (British Geological Survey 1994) to map apparent structural closures and assuming a porosity of 15% and that a maximum CO_2 saturation of 40% could be achieved in these closures. Using this method, the CO_2 storage potential within the non-hydrocarbon-bearing closed structures of the saline aquifer is estimated at up to 630 million tonnes (Kirk, *in press*). However, an important caveat is that the apparent structural closures occur intermingled with the oil and gas fields and thus at some time may have lain along the migration path of oil and gas. The question of why they don't contain oil and gas then arises – one possible answer is that buoyant fluids may leak from them. The potential for storage by dissolution and residual saturation, and in small unmapped structural closures was not investigated but could increase the potential substantially.

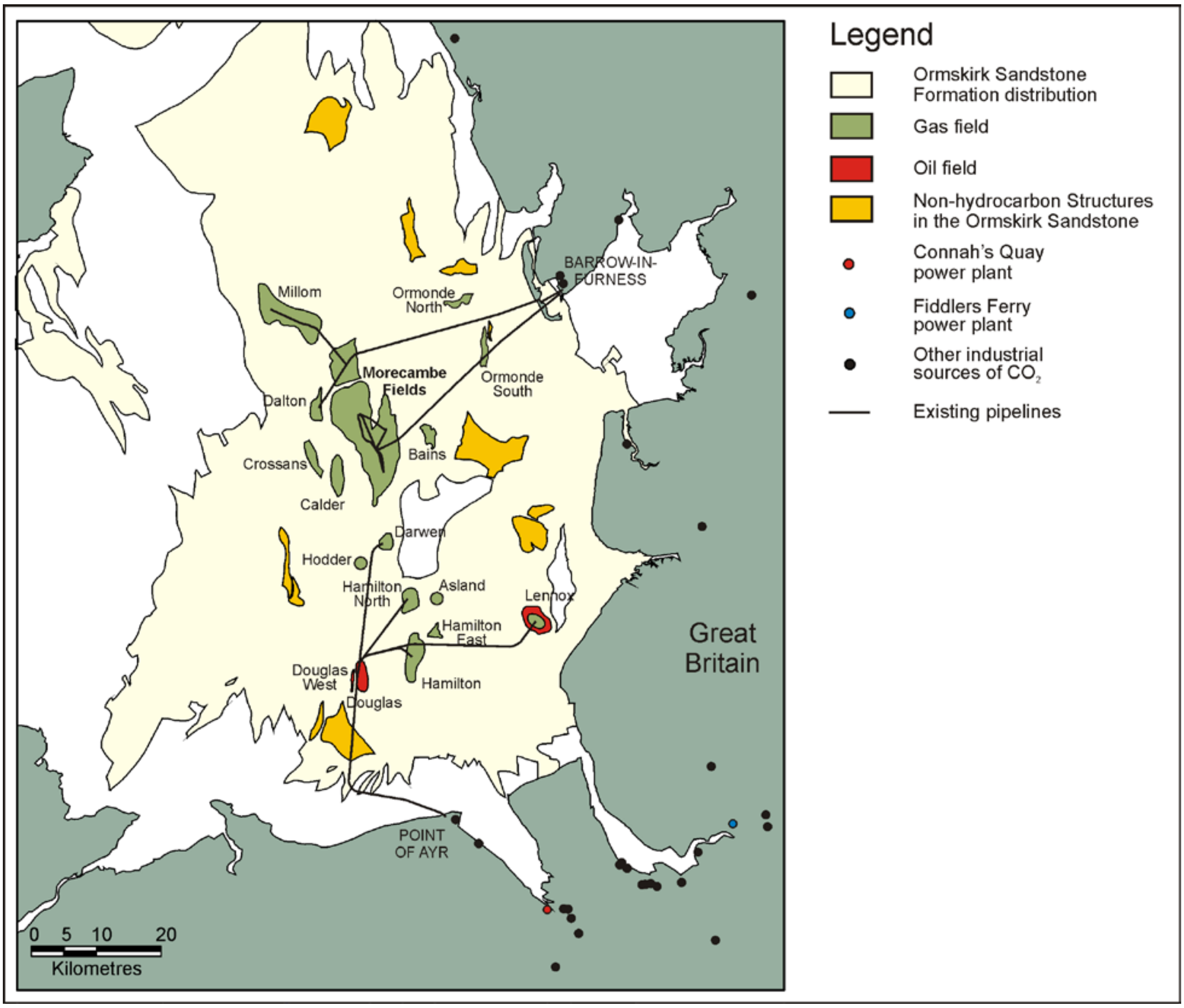

Figure 5-11. Map showing distribution of oil and gas fields, aquifer closures and distribution of Ormskirk Sandstone Formation in the East Irish Sea

5.5.4 The St George's Channel Basin

Geological investigations demonstrated that there might be potential for a geological CO_2 storage site in the St George's Channel Basin, off the NW coast of Pembrokeshire (Figure 5-8).

The basal Cainozoic sandstone sequence in a broad anticline around wells 106/24-1 and 106/24a-2B represents the best prospect for a CO_2 storage reservoir in the St George's Channel Basin. This prospect was investigated as part of the Valleys case-study in the CO2store project (DTI 2006). A map in Tappin et al. (1994) demonstrates that there is three-way dip closure against the St George's fault, which has been intruded by a salt wall: optimistically, salt is considered likely to help seal the fault plane. The crest of this structure lies at a depth of about 550 m and the sandstone reservoir rocks are overlain by a succession of mudstones, silty mudstones and lignite beds. It is envisaged that the CO_2 would be injected into the reservoir via wells located on the flank of the structure.

The main risks are thought to be:

1. The reservoir consists of relatively thin fluvial sands that occur near the base of the Cainozoic succession. The distribution of these sands in 3 dimensions is unknown. Consequently there is a risk that they may be thin, of limited lateral extent, or even absent on the flank of the structure where the proposed injection wells would be sited. If the sands were of limited lateral extent, injection might result in an unacceptable pressure rise in the reservoir, which might result in the need to re-drill the injection wells at an alternative location or abandon the project altogether.
2. The strength and permeability of the cap rocks above the reservoir is not known, but their permeability can reasonably be assumed to be low.
3. The integrity of the storage site relies on an effective seal along the St George's Fault.

The Dragon gas discovery in Jurassic sandstones in the St George's Channel Basin may also represent a potential CO_2 storage site, once developed and depleted. It has the advantage that it has the proven capability to retain buoyant fluids for millions of years. However, information about the size and other characteristics of this reservoir is proprietary and was not available for this study.

5.5.5 The Bristol Channel Basin

Geological investigations of the Bristol Channel indicated no clear CO_2 storage potential. Seismic interpretations suggest that there are not likely to be any large structural closures in this basin. Moreover, the potential reservoir sands all appear to be unsuitable. Cretaceous reservoir sands are too shallow for CO_2 storage, and the Sherwood Sandstone (at least in the nearest borehole, at Burton Row, Brent Knoll, Somerset) has very poor porosity.

6 Conclusions

It is helpful to consider the CO_2 storage capacity of the UK and its Continental Shelf in terms of a resource pyramid that divides the total resource into three categories: *theoretical* resources, *realistic* (quantifiable) CO_2 storage potential and (clearly) *valid* CO_2 storage potential (Bradshaw et al. (*in press*). These categories are a convenient and practical way to classify a continuum of potential in which increasing levels of confidence can be placed.

The *theoretical* resource is very large because the UK Continental Shelf is very large and contains many sedimentary basins that contain potentially useful saline water-bearing reservoir rocks. However, the large parts of the UK Continental Shelf that are remote from land areas and at present do not contain identified oil and gas resources have theoretical CO_2 storage potential that is never likely to be realised. Quantifying this potential should be a low priority because of the high costs involved and because most of it will prove to be unrealistic. Moreover it is already clear that the theoretical potential is sufficient for the UK's needs for the next few decades (see below).

The potential becomes somewhat more realistic in the non-hydrocarbon-bearing basins closer to shore, and significant, quantifiable and realistic in the hydrocarbon-bearing basins, particularly in the North Sea and East Irish Sea Basins. The CO_2 storage capacity in the UK's gas fields can be considered to be *realistic*, and close to the valid category and the storage capacity in the UK's oil fields can be considered to be within the *valid* category.

The prime sites for geological CO_2 storage in the UK are considered to be the offshore oil and gas fields. Their realistic CO_2 storage capacity is estimated to be in excess of 7.5 Gt CO_2, of which the oilfield capacity (approximately 1.175 Gt) can be considered to fall into the valid category. There is a window of opportunity, open between now and 2030, to exploit these fields before the production wells are plugged and the infrastructure removed.

The realistic CO_2 storage capacity of the saline water-bearing parts of the Bunter Sandstone Formation in the Southern North Sea Basin is *up to* 14.25 Gt, but could be significantly less depending on how well-sealed the Bunter Sandstone proves to be. The realistic CO_2 storage capacity in structural and stratigraphic traps in the saline water-bearing parts of the Ormskirk Sandstone Formation is *up to* 0.63 Gt CO_2 – and this figure excludes any storage by dissolution and residual saturation. These two reservoirs are the only reservoirs that have been sufficiently well studied to realistically assess their CO_2 storage capacity. A further 3 Gt of potential capacity tentatively identified in the early Cainozoic sandstones of the Northern and Central North Sea Basin is not considered to be sufficiently well-defined to be included in the "realistic" category. Thus the total presently quantified realistic storage capacity of the UK and its Continental Shelf is >7.5 Gt CO_2, and could be up to 22GT CO_2. This compares to total UK CO_2 emissions of 0.575 Gt CO_2 annually, of which approximately 0.132 Gt comes from the 20 largest UK power stations. Thus the quantified realistic CO_2 storage capacity appears sufficient for the UK's medium-term needs.

Therefore the challenges for studies of CO_2 storage capacity in the UK are perhaps not to estimate the total theoretical CO_2 storage capacity, as this is not a particularly meaningful number, but rather to:

1. Upgrade selected parts of the theoretical storage capacity into quantified realistic storage capacity.
2. Upgrade parts of the realistic CO_2 storage capacity into the valid storage capacity category.

Given that the Bunter Sandstone Formation and the Ormskirk Sandstone Formation contain only a small fraction of the pore space in saline water-bearing reservoir rocks in the UK, there is ample opportunity to firm up much more potential storage capacity. In particular, further analysis of the CO_2 storage capacity of the Northern and Central North Sea Basin (including the Inner Moray Firth Basin) would certainly increase the tentatively identified 3Gt of CO_2 storage potential (see below). Further analysis of the storage capacity of the saline water-bearing reservoir rocks of the East Irish Sea Basin would also likely upgrade its realistic storage potential.

7 Recommendations

It is recommended that further analysis of the CO_2 storage capacity of selected parts of the UK be undertaken, starting with the hydrocarbon-bearing basins and moving on to the nearshore non-hydrocarbon bearing basins that are close to the major sources of CO_2. A prioritised list of potential studies is given below:

1. Realistic CO_2 storage potential of the saline water-bearing reservoir rocks of the Northern and Central North Sea basin, including the Inner Moray Firth basin. These have excellent theoretical potential.
2. Realistic CO_2 storage potential of the saline water-bearing reservoir rocks of the East Irish Sea Basin. A more detailed analysis including numerical simulation of the potential for storage by dissolution and residual saturation is recommended.
3. A detailed study, using 3D seismic surveys and numerical simulation of CO_2 injection, of the large domes in the Bunter Sandstone of the Southern North Sea Basin would refine estimates of their storage capacity.
4. A detailed, seismically-based study of those parts of the UK landmass that are considered to have theoretical potential, to identify realistic potential.
5. Numerical simulations of CO_2 injection into generic Southern North Sea and East Irish Sea gas fields would result in a more precise estimation of UKCS gas field storage capacity.

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Appendix 1 Oil field data

Useful basic data for the UK's offshore oil fields.

Key to table: Figures in purple are averages. STOIIP: Stock tank oil initially in place. URR: Ultimately Recoverable Reserves. FVF: Formation Volume Factor. P: Pressure. T: Temperature. Bbl: Barrels

Name	Area	Water depth	STOIIP 10^6 bbl	URR oil 10^6 bbl	FVF	URR oil reservoir condition 10^6 m^3	P bar	T°C	CO_2 density reservoir conditions kg m^{-3}
Alba	C/NNS	138		461	*1.50*	109.8	453	*111*	*760*
Alwyn North (Brent East)	C/NNS	126	223.4	102.6	1.55	25.3	453	112	757
Alwyn North (Brent North)	C/NNS	126	44.05	20.14	1.85	5.9	444	107	765
Alwyn North (Brent NW)	C/NNS	126	45.94	25.8	2	8.2	452	113	753
Andrew	C/NNS	117	304	140	1.52	33.8	256	110	556
Angus	C/NNS	71	18.5		*1.50*		172	*111*	*361*
Arbroath	C/NNS	93		102	1.33	21.6	256	118	524
Argyll	C/NNS	79	218		*1.50*		*378*	*111*	*703*
Arkwright	C/NNS	95	73	25	1.456	5.8	255	121	511
Auk	C/NNS	82	529	93	1.154	17.1	280	102	628
Balmoral	C/NNS	147	197	110	1.26	22.0	218	97.2	538
Banff	C/NNS	100	304	79	1.31	16.4	216	31	897
Beatrice	C/NNS	46	480	146	1.09	25.3	201	80	596
Beauly	C/NNS	146		3	*1.50*	0.7	*378*	*111*	*703*
Beinn	C/NNS	99		23	*1.50*	5.4	*378*	*111*	*703*
Beryl	C/NNS	119	2322	960	1.6	244.1	338	97	715
Birch	C/NNS	127	75	34	2.4	13.0	514	132	741
Bittern	C/NNS	93		110	*1.50*	26.2	*378*	*111*	*703*

Blake	C/NNS	100		71	*1.50*	16.9	*378*	*111*	*703*
Blenheim	C/NNS	148		23	*1.50*	5.6	*378*	*111*	*703*
Brae Central	C/NNS	107	244	70	1.77	19.7	487	119	758
Brae South	C/NNS	112	795	320	1.73	88.0	491	123	750
Brae West (Balder)	C/NNS	106	116	36	1.16	6.6	174	63	651
Brae West (Flugga)	C/NNS	106	76	24	1.15	4.4	182	63	670
Brent (Brent + Statfjord)	C/NNS	140	5015	1980.68	1.9	598.0	407	99.5	763
Brimmond	C/NNS	94	14.8	1.4	*1.50*	0.3	197	*111*	*426*
Broom	C/NNS	145			*1.50*		*378*	*111*	*703*
Buchan	C/NNS	111	466	90	1.205	17.2	517	106	811
Buckland	C/NNS	111		33	*1.50*	7.9	*378*	*111*	*703*
Buzzard	C/NNS				*1.50*		*378*	*111*	*703*
Captain	C/NNS	104		347	*1.50*		***378***	***111***	***703***
Carnoustie	C/NNS	93		1	*1.50*	0.2	*378*	*111*	*703*
Chanter - Galley Sst	C/NNS	144	3.1	6	1.54	1.4	427	122	709
Chanter - Piper Sst	C/NNS	144	3.1	6	1.54	1.4	427	122	709
Claymore Carboniferous	C/NNS	110	68.1	3.4	1.153	0.6	270	79	717
Claymore Permian	C/NNS	110	10.9	4.9	1.236	1.0	270	79	717
Claymore Main Jurassic	C/NNS	110	1002.6	337.5	1.097	58.8	261	77	716
Claymore Cretaceous	C/NNS	110	357.1	164.2	1.230	32.1	281	88	690
Clyde	C/NNS	81	408	154	1.29	31.6	445	147	654
Cook	C/NNS	94		19	*1.50*		*378*	*111*	*703*
Cormorant	C/NNS	161	1568	623	1.285	127.2	333	91	733
Curlew B	C/NNS	93	24	6	1.5	1.4	503	121	763
Curlew D	C/NNS				*1.50*		*378*	*111*	*703*
Curlew D South	C/NNS	93		2	1.9	0.6	502	122	760
Cyrus	C/NNS	113	82	23.5	1.19	4.4	236	112	510
Dauntless	C/NNS	91		13	*1.50*	3.1	***378***	***111***	***703***
Deveron	C/NNS	162	41	20	1.12	3.6	345	104	696
Don	C/NNS	164		24	1.36	5.2	503	129	742
Donan	C/NNS				*1.50*	0.0	***378***	***111***	***703***
Dunbar (Brent Fm)	C/NNS	145	561	161	2.85	72.9	570	128	782
Dunbar (Statfjord & U	C/NNS	145	129	25	2.4	9.5	575	130	780

Lunde)									
Duncan	C/NNS		49		*1.50*		***378***	***111***	***703***
Dunlin	C/NNS	150	827	363	1.13	65.2	415	99	771
Egret	C/NNS	91	17	8	*1.50*	1.9	866	171	815
Eider	C/NNS	158	204	85	1.1	14.9	346	107	686
Fergus	C/NNS	70	16.3	11.3	1.102	2.0	390	108	722
Fife	C/NNS	72			1.10	0.0	390	108	722
Flora	C/NNS	70	69	13	1.13	2.3	396	*111*	*718*
Forties	C/NNS	106	4196	2545	1.22	493.4	222	96	552
Fulmar	C/NNS	81	822	567	1.43	128.8	393	140	628
Galley	C/NNS	150		373	*1.50*	88.9	*378*	*111*	*703*
Gannet A	C/NNS	95		69	*1.50*	16.5	***378***	***111***	***703***
Gannet C	C/NNS	95		90	*1.50*	21.5	***378***	***111***	***703***
Gannet D	C/NNS	95		233	*1.50*	55.4	*378*	*111*	*703*
Gannet E	C/NNS	95		173	*1.50*	41.1	*378*	*111*	*703*
Gannet F	C/NNS	95		143	*1.50*	34.0	*378*	*111*	*703*
Gannet G	C/NNS	95		98	*1.50*	23.2	*378*	*111*	*703*
Glamis	C/NNS	147	31.4	19	*1.50*	4.5	315	119	609
Gryphon	C/NNS	112		878	*1.50*	209.2	*378*	*111*	*703*
Guillemot W & NW	C/NNS	88		300	*1.50*	71.5	*378*	*111*	*703*
Hamish	C/NNS	140	7	3.8	1.34	0.8	242	79	680
Hannay	C/NNS	120		7	*1.50*	1.8	*378*	*111*	*703*
Harding	C/NNS	109	322	200	1.11	35.3	178	60	683
Harding C	C/NNS				*1.50*		*378*	*111*	*703*
Harding S	C/NNS				*1.50*		*378*	*111*	*703*
Heather	C/NNS	145	464	146	1.49	34.6	341	108	678
Heron	C/NNS	90	86	478	*1.50*	114.0	888	177	812
Highlander	C/NNS	128		63	1.20	12.0	293	93	682
Hudson	C/NNS	157		882	*1.51*	211.6	*378*	*111*	*703*
Hutton	C/NNS	148	550	190	1.12	33.8	434	107	759
Innes	C/NNS		19		*1.50*		*378*	*111*	*703*
Iona	C/NNS	145.4		8	*1.50*	1.9	*378*	*111*	*703*
Ivanhoe Main Piper Sands	C/NNS	137	57.8	31.22	1.22	6.0	242	79	680
Ivanhoe Supra	C/NNS	137	37.4	11.23	1.22	2.2	242	79	680
Janice	C/NNS	80		517	*1.50*	123.2	*378*	*111*	*703*
Keith	C/NNS	123.1		11	*1.50*	2.5	*378*	*111*	*703*
Kingfisher Brae Unit 2	C/NNS	105	104.00	30.00	2.46	11.7	500	121	761
Kittiwake	C/NNS	85	173.00	70	1.20	13.3	450	118	738
Kyle	C/NNS	90		32	*1.50*	7.6	*378*	*111*	*703*

Larch (trees)	C/NNS	126.5		11	*1.50*	2.6	*378*	*111*	*703*
Leadon	C/NNS	120		89	*1.50*	21.3	*378*	*111*	*703*
Leven	C/NNS	81.08		6	*1.50*	1.4	*378*	*111*	*703*
Lyell	C/NNS	150		30	*1.50*	7.0	*378*	*111*	*703*
MacCulloch	C/NNS	150	200	60-90	1.20	17.1	191	79	578
Machar	C/NNS	84.12	123	1103	*1.50*	262.8	262	107	578
Magnus	C/NNS	186	1665	665	1.43	151.1	459	116	750
Mallard	C/NNS	90.83		19	*1.50*	4.4	*378*	*111*	*703*
Maureen	C/NNS	94	398.00	217.4	1.29	44.6	261	119	530
Medwin	C/NNS	75.13		1	*1.50*	0.3	*378*	*111*	*703*
Miller	C/NNS	105.6		300.0	1.97	93.9	500	121	761
Monan	C/NNS	92.96	9.00	7.28	*1.50*	1.7	290	148	484
Montrose	C/NNS	91.14	236.00	98.00	1.51	23.5	258	125	502
Mungo	C/NNS	86.96	155.00	187.4	*1.50*	44.7	287	123	556
Murchison (UK)	C/NNS	156.1	790.00	340.0	1.31	70.9	434	110	750
Nelson	C/NNS	84.73	790.00	435.0	1.36	93.8	229	106	521
Ness	C/NNS	113.1		40.50	*1.50*	9.7	*378*	*111*	*703*
Nevis	C/NNS	107.6		87.60	*1.50*	20.9	*378*	*111*	*703*
Ninian	C/NNS	140	2920.00	1185	1.20	226.0	447	102	784
Ninian Columba terraces	C/NNS	140		71.10	*1.50*	16.9	*378*	*111*	*703*
NW. Hutton	C/NNS	148		127.0	*1.50*	30.3	513	118	777
Orion	C/NNS	71.63			*1.50*	1.8	*378*	*111*	*703*
Osprey	C/NNS	160	158.00	60.00	1.09	10.4	414	101	763
Pelican	C/NNS	153		102.1	*1.50*	24.3	*378*	*111*	*703*
Petronella	C/NNS	134		36	*1.50*	8.7	***378***	***111***	***703***
Pierce	C/NNS	85	387.00	107.9	*1.50*	25.7	***378***	***111***	***703***
Piper	C/NNS	145	1400.00	1085	1.26	217.7	255	79	698
Renee	C/NNS	148.4		8	*1.50*	2.0	*378*	*111*	*703*
Rob Roy	C/NNS	137	143.00	109.90	1.37	24.0	242	79	680
Ross	C/NNS	110		55.50	1.20	10.6	*378*	*111*	*703*
Rubie	C/NNS	149.1		8	*1.50*	1.8	*378*	*111*	*703*
Saltire	C/NNS	145	224.00	93.00	1.20	17.7	*378*	*111*	*703*
Scapa	C/NNS	117	206.00	120.0	1.16	22.2	233	85	633
Scott	C/NNS	140	946.00	441.0	1.54	108.2	593	100	862
Skua	C/NNS		27.00	22	*1.50*	5.3	648	153	763
Staffa	C/NNS		30.5	5.5	1.99	1.7	535	136	743
Statfjord (UK)	C/NNS	145		590	*1.50*	140.7	***378***	***111***	***703***
Stirling	C/NNS	147	44.8	3	*1.50*	0.7	251	108	555

Strathspey (Banks)	C/NNS	136	95	20	2.20	7.0	442	104	773
Strathspey (Brent)	C/NNS	136	101	57.7	1.88	17.2	404	100	760
Tartan (downthrown)	C/NNS	140		48	1.52	11.6	400	116	705
Tartan (upthrown)	C/NNS	140		68	1.85	20.0	321	102	679
Teal	C/NNS	69		327	*1.50*	78.0	*378*	*111*	*703*
Telford	C/NNS	143		443	*1.50*	105.5	*378*	*111*	*703*
Tern	C/NNS	167	452.00	302.0	1.13	54.2	247	93	616
Thelma	C/NNS	135	52.00	11.00	2.58	4.5	459	126	721
Thelma SE	C/NNS	135	194.00	30.00	1.79	8.5	479	126	734
Thistle	C/NNS	160	824.00	404.0	1.18	75.8	418	104	757
Tiffany	C/NNS	125	156.00	71	1.57	18.7	514	135	733
Toni	C/NNS	133	121.00	48.00	2.20	16.8	483	125	739
Douglas	EISB	30	202	99.82	1.075	17.0	77.56	30	685
Lennox	EISB	30	184	75.82	1.3	15.6	111.7	30	795
Douglas West	EISB	34							
Foinaven	WOS	496	233	42	*1.50*	10.0	*378*	*111*	*702.57*
Schiehallion	WOS	375	543	425	*1.50*	101.3	*378*	*111*	*702.57*
Loyal	WOS	474	100	78	*1.50*	18.6	*378*	*111*	*702.57*
Clair	WOS	138	250000						