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Defining simple and comprehensive assessment units for CO_2 storage in saline formations beneath the UK North Sea and continental shelf

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Abstract:

In the UK, by far the largest CO_2 storage opportunities lie offshore. The North Sea in particular has a long and complex geological history, with potential reservoirs geographically widespread and occurring at multiple stratigraphic levels. Diverse storage estimates have been made, using a range of working methods, and yielding different values, e.g. SCCS (2009) [1]; Bentham (2006) [2]. Consequently the UK Storage Appraisal Project (UKSAP), commissioned and funded by the Energy Technologies Institute (ETI), is undertaking the most comprehensive assessment to date, using abundant legacy seismic and borehole data. This study has a remit to use best current practice, consistent between locations, to calculate the CO_2 storage capacity of the entire UK Continental Shelf (UKCS) within saline aquifers and hydrocarbon fields. The potential storage formations have been subdivided into units for assessment, and filtered to remove units with only a small estimated storage capacity to concentrate resources on more viable units. The size of potential storage units approximate to a power law distribution, similar to that of hydrocarbon fields, with a large number of small units and a small number of large units.

Keywords: Carbon storage, sequestration, North Sea

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1. Introduction

The UKSAP has the remit to assess the CO_2 storage capacity of the entire UK Continental Shelf within saline

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aquifers and hydrocarbon fields. Onshore capacities are believed to be small and prone to adverse public reaction regardless of technical merit. The study is ongoing, and this paper presents only preliminary methodology and results from a portion of the study, and only for saline formations. The estimate will be extended to the entire study area and refined to provide a fully risked, probabilistic estimate of the total storage capacity of the entire UK continental shelf, with the exception of the area west of the Shetland Isles which is regarded as too remote from potential CO_2 sources. This paper concentrates upon the portion of the study undertaken by the University of Edinburgh, namely the pre-Cenozoic of the Northern and Central North Sea, including the Moray Firth and Wytch Ground Graben (Fig. 1). The first task undertaken was to define which of the geological units within the study area were candidates for CO_2 storage, i.e. would be described as saline formations or saline aquifers in the now conventional terminology. In all cases, the smallest stratigraphic units used (formations and members) are defined by the British Geological Survey (BGS) and published by the UK Offshore Operators Association (UKOOA), description of the pre-Cenozoic of the Northern and Central North Sea are included in references [3, 4, and 5]. Formations and members with low potential-reservoir content (sandstones and limestones), i.e. those that are mud-dominated with only thin reservoir (metres thickness or less), were rejected at this stage.

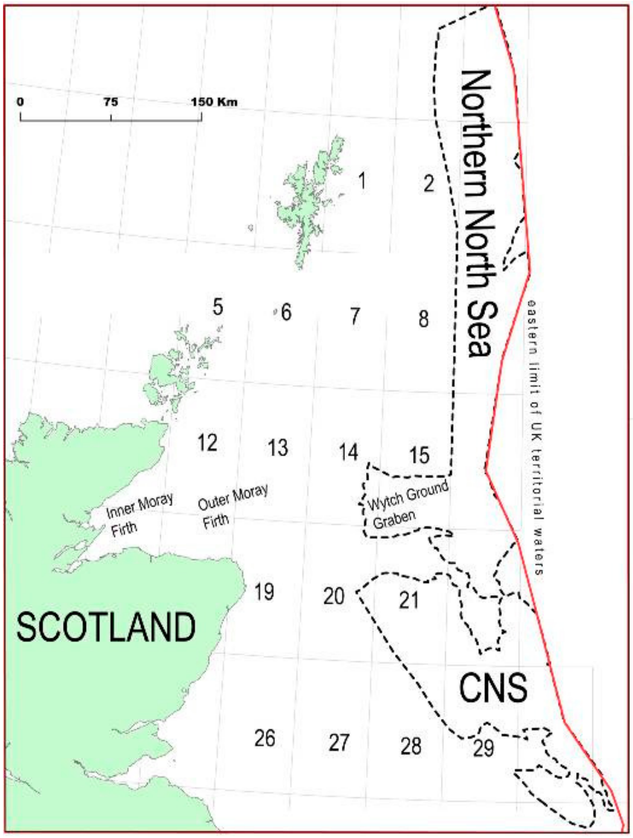

Figure 1 – Location map of the UK Northern and Central North Sea. Also shown is the area within which variations in overpressure have been used to define units of assessment (dashed line). CNS = Central North Sea. Numbers refer to areas of the UKCS termed ‘quadrants’.

Each saline formation was then divided into spatially defined ‘units of assessment’, each of which can be studied individually to produce a probabilistic estimate of ultimate storage capacity and security of storage. For each unit, data were collected in a database, with 60 data entries required for each unit, along with a reference source for the data and an expression of the confidence in the data. Note that depleted and depleting hydrocarbon fields are present in some of the aquifers. These fields sometimes represent areas of local, anomalously low pressure (depending on the production history of the field). These fields are assessed independently in this project, storage volumes for hydrocarbon fields are calculated using the ‘volume-for-volume’ replacement method (NETL, 2006 [6]).

The units of assessment for saline formations fall into two clear categories: those in which the unit-wide build-up of pressure is likely to be the factor limiting the theoretical storage potential, and those units in which this is not the case as pressure can dissipate to the open ocean or other sink. Note that the unit-wide build-up of pressure is distinct from the build-up of pressure close to an injecting borehole, which depends upon many factors other than the geology of the unit, many of which (e.g. injection rate) are potentially controllable. In the case that unit-wide pressure build-up is the factor determining the theoretical storage potential, then the working definition of an assessment unit is: *"a volume of reservoir which acts as a single pressure compartment, such that the pressure build up around an injection well can potentially dissipate within the unit, but not beyond it"*. Note that there is no implication that the storage potential of the entire assessment unit can be accessed from a single borehole. Each unit of assessment is regarded as separate to, and distinct from, underlying and overlying units despite the possibility of (normally unquantifiable) vertical pressure connection from unit to unit.

Four principal categories of saline aquifer storage unit have been identified, which require different approaches to define units of assessment, described below.

1.1 **Overpressured reservoirs**, the units are sometimes close to rock fracture point, e.g. the Upper Jurassic Fulmar Formation. Storage assessment units have been defined by laterally dividing stratigraphic units using pressure cells within the Upper Jurassic sediments compiled by GeoPressure Technology in their North Sea Central Graben and North Sea Viking Pressure Studies (Figure 1). The units are generally at their maximum burial depths at present day, and are not located in areas of structural inversion.

In the Northern and Central North Sea areas, the assumption has been made that that the lateral cell boundaries are mostly faults and are hence approximately vertical. The faults are assumed to penetrate from the base-Cretaceous unconformity to basement in this study, the oldest stratigraphic unit of interest being of Devonian age. The assumption has been made that these faults effectively subdivide not only the Upper Jurassic, where they were defined, but also the entire Triassic-Jurassic sediment package which is overpressured, at least in the more axial portions of the study area. There is insufficient pressure data available for the majority of the Jurassic-Triassic sediments to test this assumption. The underlying Devonian – Permian sediments are hydrostatically pressured, and are hence assumed to be not compartmentalised by these faults, see discussion below. CO_2 storage in highly-overpressured units will be limited by the small (or potentially zero) permissible increase in fluid pressure before risk of caprock fracture or re-activation of existing faults. The most probable leakage point is assumed to be the structural highest point of the system, where buoyant pressure from the injected CO_2 is at a maximum.

1.2 **Hydrostatially pressured reservoirs that are known to be compartmentalised** from production of contained hydrocarbon fields, e.g. the Leman Sandstone Formation in the Southern North Sea. It is not known how compartmentalised these formations are outside their contained hydrocarbon fields, so the assumption has been made that the entire formation is divided into compartments of the same size as the average compartment in the contained hydrocarbon fields. Pressure-space storage capacity estimation methods can also be used for this category of reservoirs.

1.3 **Hydrostatically pressured reservoirs that are not thought to be compartmentalised** because there is no evidence of compartmentalisation in their contained hydrocarbon fields. This is applicable to many of the post-rift units in the area. The units fall into 2 categories: units with identifiable structural closures i.e. potential traps; and units that lack identifiable traps. This classification partly reflects the state of knowledge of a formation, and not just the geology.

The Bunter Sandstone Formation in the Southern North Sea is an example of an open saline formation that crops out both on land and the sea bed. It does contain identifiable structural closures, that are known from a previous study (Bentham, 2006 [2]). The Chalk formations of the Northern and Central North Sea are an example of open saline aquifers where structural closures are not generally known, except for the large ones close to the median line visible on the regional-scale map of Surlky et al., 2003 [7]).

These open saline aquifers cannot be subdivided using pressure data, but require more arbitrary subdivision so that laterally variable parameters e.g. porosity can be adequately quantified where data are available. In the case of the Upper Cretaceous Chalk formations of the Central and Northern North Sea, subdivision follows 'watersheds' in the topography of the top surface that are analogous to hydrological watersheds in a landscape (Figure 2). Because CO_2 is buoyant in the subsurface, the watersheds are the loci of low-points in the top surfaces, not high points as in the landscape analogy. Because the topography of the Chalk units is of small amplitude [7] the 'watersheds' are not particularly well defined but do provide a way of subdividing otherwise large and relatively uniform formations.

Subdividing the open saline aquifers that include identifiable structural closures is equally challenging and is still the subject of on-going discussion.

In both (2) and (3), the area of any unit above 800m burial depth is regarded as having no storage potential due to the low density of CO_2 under ambient conditions. These zones can act as a leak-off pathway for excess pressure induced by injection to the more deeply buried section of the aquifer, provided that any water leak-off into the sea is deemed to be acceptable. If the aquifer outcrops on land, then water leak-off is unlikely to be acceptable and saline water displacement or pressure changes must be either avoided, or carefully predicted and managed.

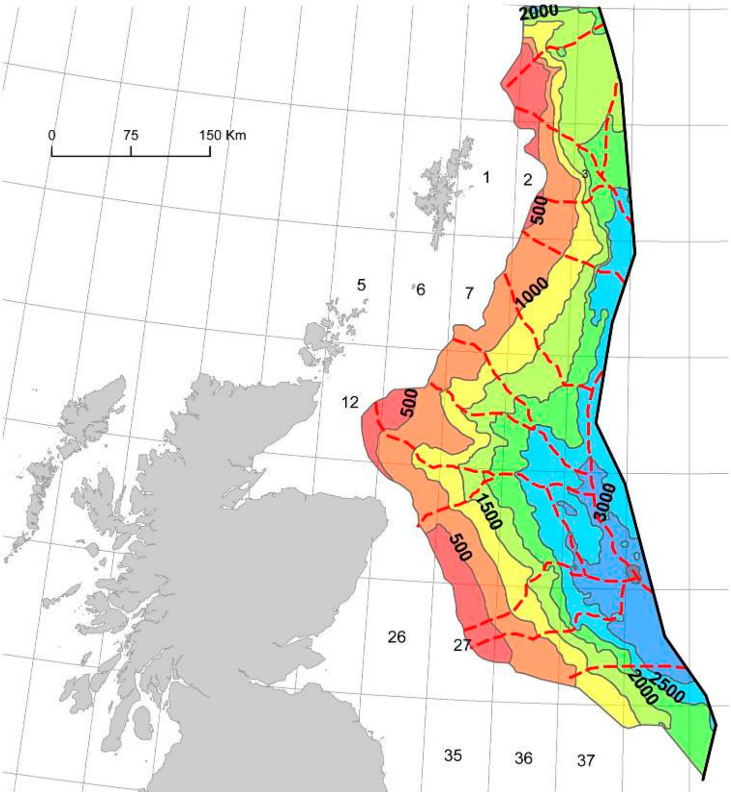

Figure 2 – The Top Cretaceous surface (redrawn from Surly et al., 2003 [7]; depth contours in 500 m intervals) showing the 'watershed' method of defining units of assessment (red lines). The Upper Cretaceous units outcrop on the sea floor to the west of the map (from BGS mapping), and a significant percentage of the area is above 800m depth. Note that the majority of the units have no structural closure, and as such any injected CO_2 would migrate towards the seabed outcrop, although capillary trapping, local structural trapping and dissolution may well prevent it from reaching the outcrop.

1.4 **Reservoirs with spatially variable overpressure** can vary from high overpressure in deeply buried sections to more shallow buried hydrostatically pressured units. These may have at least nominal connections to the surface, e.g. the Palaeocene Mey Sandstone Member of the Lista Formation. Pressure is dynamically conducted from the deeply buried sections by slow fluid migration towards the hydrostatically pressured sections. These units can be considered to be zoned, with a three-fold division. The deep and shallow sections are comparable to (1) and (3) above, respectively. There is also an intermediate depth zone of overpressure that is effectively a buffer between the other two zones. Storage capacity within the deep and shallow zones will be limited as described in previous sections. This intermediate zone, typically 1-3km depth is anticipated to have the highest storage capacity with the lowest leakage risk.

2. Pre-Cenozoic of the Central and Northern North Sea: Capacity Filtering

As a result of applying the above definitions to a section of the study (the pre-Cenozoic of the Central and Northern North Sea), a total of 1215 units were defined. Given this large number of units, a decision was made to apply a filter to the units to ensure that resources were concentrated upon units that were most likely to make viable real-world storage units. The simplest filtering process that could be devised was to make a first-pass estimate of storage capacity, and to filter out all units with less than a threshold value. Storage capacities were hence estimated using the methods of the NETL [6], using data from literature sources. The areal extent of stratigraphic units is taken from pre-existing mapping by the BGS (Richards et al, 1993 [3]; Cameron, 1993 [4]; Johnson & Lott, 1993 [5]), based primarily on archives of borehole data. The same references have specimen vertical profiles through the formations, from which thickness and net:gross ratio were estimated. Porosity was taken from a wide variety of literature sources; in the absence of a published porosity, a deliberately high value of 25 % was used. By using a high value of porosity, the estimated storage capacity would be high, so that units would tend to pass the filter (and hence be subjected to a more rigorous scrutiny at a later stage of the project) rather than be erroneously rejected at this stage. At this stage in the project, only limited time was spent on searching for porosity data, as this is a time consuming process. During the later stages of the project, more porosity data have been located, allowing for refinement of the storage estimates. A constant storage efficiency (i.e. the proportion of the water-filled portion of the formation that can be filled with CO_2) was taken as 2 %. Again, this value was chosen to be high relative to values used in other studies, so as to avoid erroneously rejecting units at this stage. The results of this initial estimate of storage capacity are shown in Figure 3.

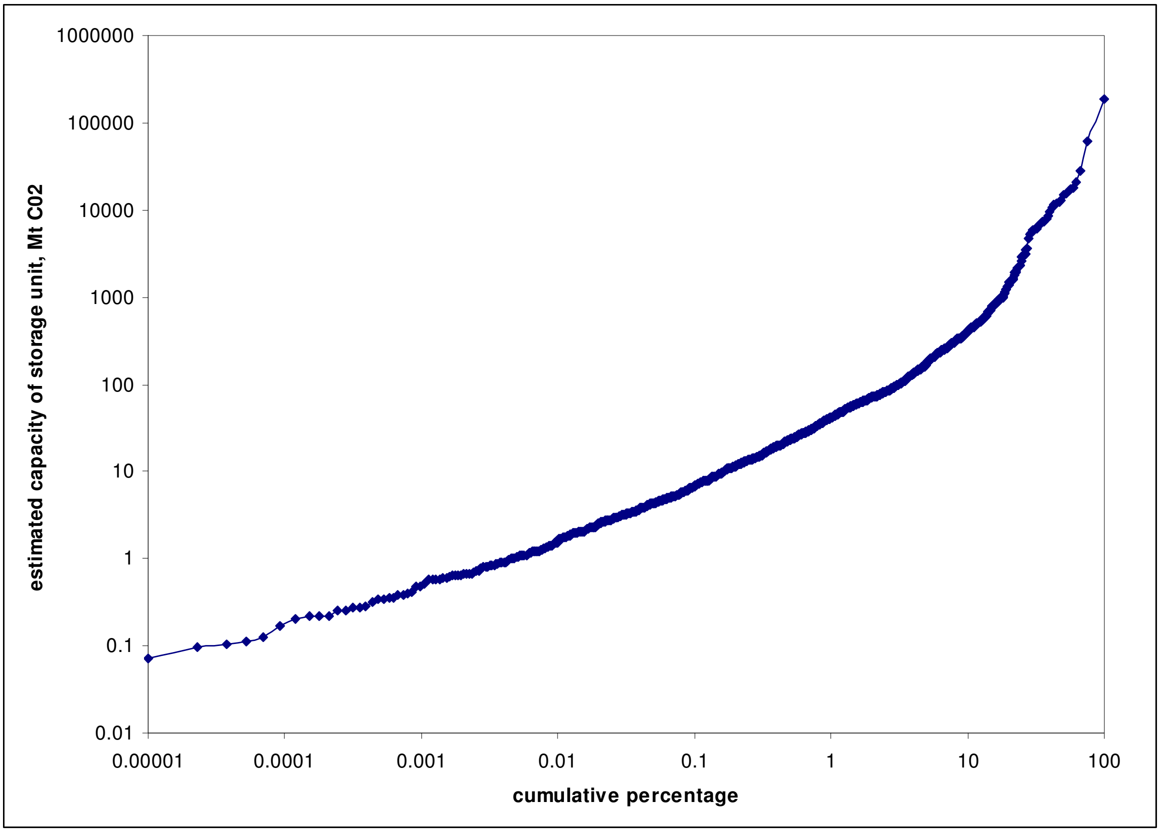

Figure 3 – Distribution of estimated storage capacity, calculated for the filtering exercise on all 1215 units of assessment in the pre-Cenozoic of the Northern and Central North Sea. Note the very long tail to the data with very low storage capacities which make only a very small contribution to the total. At this stage, there are more 320 units with capacities < 10 Mt CO_2, and 630 units with capacities < 50 Mt CO_2. Many of the very small units are artefacts of the method of overlaying shape files from 2 sources within a GIS, where small discrepancies between the files exist.

A filter was now applied at 50 Mt estimated storage capacity, i.e. all units with a first-pass estimate of less than 50 Mt were rejected, and not considered further in the study. This rejected only 1.2 % of the total storage capacity of the study area (Figure 3), but substantially reduced the work load of the project with 485 assessment units remaining. The total number of units further decreased as understanding of the geological nature of the units increased; and 233 units were actually entered into the database. The reasons for the reduction in unit number included:

- The thick sand-dominated Auk (Permian) and Buchan (Devonian) formations were initially divided into around 100 units each, on the understanding that they would be cut by the same faults that define the Jurassic pressure cells, and would hence be compartmentalised. Field data shows that these sands are in fact hydrostatically pressured, and there is no evidence that they are compartmentalised. Furthermore, the data distribution for these sands is such that many units of assessment would have no well penetrations, and hence no direct data. The decision was taken to amalgamate the units into a small number of larger units.

- Removal of duplication, where formations only have reservoir potential within members that are entered separately.

- Re-applying the 50 Mt filter once better data were available. Typically, porosity, thickness and / or net:gross data have been refined, where initially only a single value for an entire formation was used, or where 25 % was initially assumed for porosity but where published data are now available.

- Re-evaluating the lateral extent of the formations to reconcile the formation extant shape-files with wells penetrations.

- Re-evaluating reservoir potential based on increased understanding of the geology of the units. After further analysis some formations which had initially been included as potential reservoirs were deemed unsuitable for CO_2 storage due to inadequate permeability and porosity.

3. Initial results and discussion

Figure 4 illustrates cumulative static storage capacity for the 233 units of assessment remaining within the pre-Cenozoic of the UK Northern and Central North Sea. The results are based on a constant storage efficiency of 2% and do not, at this stage, include an assessment of the likelihood of safe storage, i.e. of seal integrity or the probability of leakage. Hence the total capacity figures illustrated in Figure 4 should not be considered as a realistic estimate for the total capacity in the areas studied.

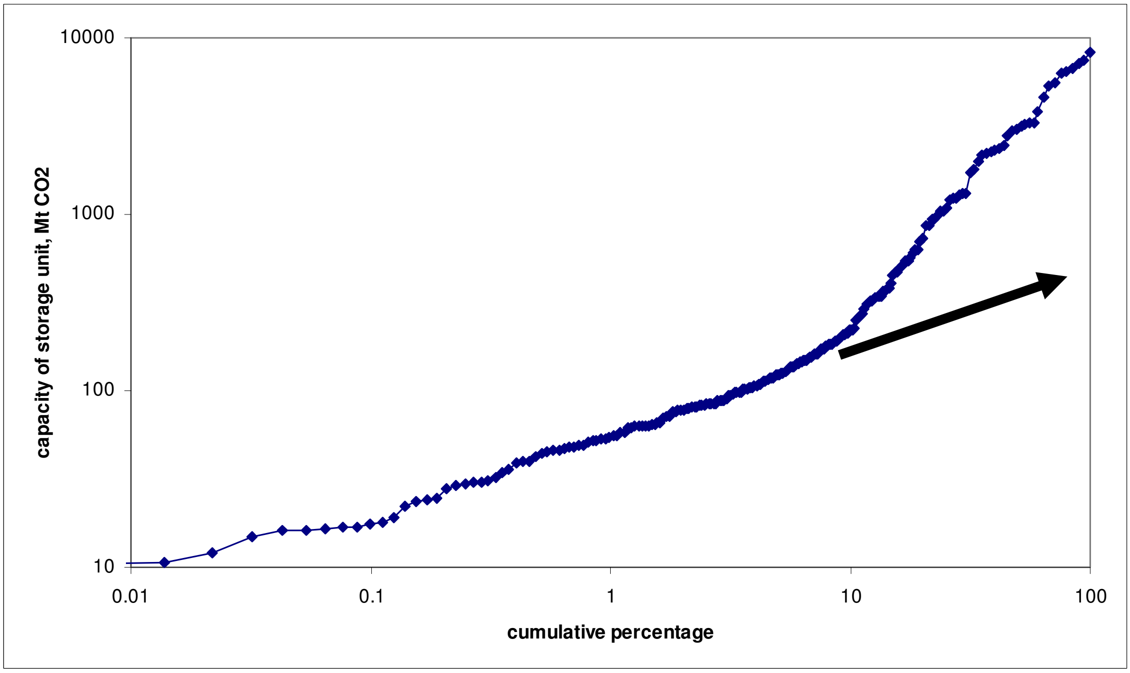

Figure 4 – The distribution of estimated storage capacity in the 233 units remaining after screening the units illustrated in Fig. 3, assuming a uniform static storage efficiency of 2 % as before. The arrow illustrates the extrapolation of the data trend for < 10 % up to 100 %, see text.

There are still a small number of units with storage capacities below 50 Mt despite the filtering. As above, this is mostly due to locating data where previously only estimates had been available. Re-applying the 50 Mt filter at this stage would reduce the number of units by 16 %, while neglecting only 0.8 % of potential storage capacity. As the majority of work has now been completed for these units there is little incentive to remove them from the database.

The size of storage capacities approximates to a power-law distribution, i.e. is approximately linear in Figure 4. This distribution is comparable with the distribution of hydrocarbon accumulations such as illustrated for the UK North Sea by Selley, his Fig 10.5 [8]. There is however an inflection point in the data in Fig. 4 at about 10 % cumulative capacity. Whether this reflects geological reality or is an artefact of the method used to define storage units is now discussed.

3.1 Hypothesis 1: Unit size distribution controlled by methodology

As described above, by necessity more than one method has been used to define storage units in the study, and the size distribution therefore contains units that may not be comparable. For the units that are believed to be pressure cells (case 1 above), then the distribution reflects mostly geological factors, i.e. the distribution of porefluid pressure within the subsurface, as controlled by barriers to porefluid flow such as sealing faults, lateral changes in sedimentary facies or diagenetic barriers. However, the definition of even these units includes a degree of expert judgement, as in many cases lateral changes in pressure are gradational and division into units is arbitrary (also case 4 above). In some cases, an arbitrary cut-off in pressure difference is used, below which two slightly different pressure gradients would still be regarded as a single pressure cell. In the case of the pre-Cenozoic of the Northern and Central North Sea, this pressure cell method applies largely to the Jurassic and Triassic units within the deeper, more axial portions of the Central and Viking Graben. Where pressure data are sparse, or all the data are approximately hydrostatic (cases 2- 4 above), then the saline formation must be left undivided, or more arbitrary divisions made, as with the Cretaceous Chalk units (Fig 2). This results in large estimated storage potentials (of the order of a gigatonne of CO_2) for units which may cover thousands of square kilometres. In the pre-Cenozoic of the Northern and Central North Sea, this applies largely to the Cretaceous and pre-Triassic units and to all the stratigraphy within the Moray Firth / Wytch Ground Graben.

It is possible that the change in gradient reflects the difficulty of subdividing hydropressured units using the legacy data available to this study, i.e. that in reality, the large saline formations are in fact compartmentalised by unknown faults or other barriers, for which no evidence is available. It might be conjectured that, could such units be subdivided effectively, the largest unit would have an estimated storage capacity of 500 Mt (see Fig 4 for the extrapolation).

3.2 Hypothesis 2: Unit size distribution controlled by geology

However it is also possible that the inflection of the data shown in Figure 4 reflect the geology of the North Sea. The most recent rifting event in the area was predominantly Upper Jurassic [9], so that (with the exception of areas that have been reactivated such as the Moray Firth [10]) the post-Jurassic sediments are largely unfaulted. Inspection of the saline formations with estimated CO_2 storage potential of high volume (> 500 Mt), it is clear that many are indeed part of the post-rift sequence. In these cases, the very large storage volumes are not artefacts, unless unknown sedimentological or diagenetic barriers exist, for which there is no evidence. However, a significant proportion of the large units are pre-Triassic, but either lie outside of the axial areas of the Central and Viking Graben where pressure data are available, or are hydrostatically pressured. In these cases, the very large units may be artefacts of lack of data, as the pre-Triassic sequence is cut by the faults involved in late Jurassic rifting. Whether these faults are sealing is largely unknown. As some of the faults cut very thick (> 500 m) sandstones with minimal shale content, it seems unlikely that clay-smearing has occurred along the fault planes. The degree to which quartz cementation may have sealed fault planes within quartz-dominated sandstones can only be the subject of speculation.

In conclusion, it seems probable that the saline formations with large estimated CO_2 storage capacity (> 500 Mt) contain both artefacts of the methods of defining the storage units, and genuine large geological units that lack internal known subdivision. At least some large saline formations may have significant barriers to fluid flow that are currently unknown due to a lack of suitable data.

4. Further Work

The largest uncertainty in the storage capacity estimate is the storage efficiency, which is currently an order-of-magnitude estimate. The factor which determines storage efficiency, in any unit that is not in fluid communication with the surface, is the maximum pressure increase that the reservoir or seal rock can tolerate without fracturing, since fractures might act as conduits for the escape of the CO_2. It is intended to calculate the static storage efficiency for all relevant storage units.

For potential storage units that are connected directly to the surface, and hence from which porewater can escape, preventing the long-term build-up of pressure, then unit-wide pressure build-up is not a limiting factor. For these units, a storage efficiency can probably only be established by dynamic modelling. To prevent the necessity of modelling every open, saline formation within the North Sea, a series of more generic numerical models will be run to determine the sensitivity of the storage efficiency to the physical properties and geometry of the saline formation, for example the average angle of dip. With this knowledge, it should be possible to ascribe an efficiency factor, or range of factors, to each individual saline formation. The results will be published at a future date.

A significant part of the project is assessing the reliability of each storage unit for safe, long-term CO_2 storage. This involves examination of the nature of the primary seal; faulting intensity and magnitude within the unit; the risk of lateral migration of the CO_2 to the lateral boundaries of the unit; the age and number of wells; the potential for formation damage; and the operational risk. The aim is to provide a probabilistic and risked total storage capacity for the UKCS. Again, the results will be published at a future date.

5. Conclusions

Large geological units must be subdivided if accurate estimates of CO_2 storage capacity are to be made, otherwise very large and potentially variable units must be characterised by single data values or ranges. Unsurprisingly, the size distribution of potential CO_2 storage units depends upon the methods used to define such units. However, in an area with complex and variable geology such as the North Sea, a single method of subdivision is not practical, so that multiple methods must be employed. For the pre-Cenozoic of the Northern and Central North Sea, the (preliminary) size of the resulting units approximately follows a power law distribution; however an inflection in the distribution could be either the result of the differing methodologies used to subdivide formations, or more probably, genuine geological differences between formations, to the extent that current data define.

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