The occurrence of faults in the Bunter Sandstone Formation of the UK sector of the Southern North Sea and the potential impact on storage capacity.

M. S. Bentham[a]1, A. Green[b] and D. Gammer[b]

[a] British Geological Survey, Kingsley Dunham Centre, Keyworth, NG12 5GG, UK
[b] The Energy Technologies Institute, Holywell Building, Holywell Way, Loughborough, LE11 3UZ, UK

Abstract

The Triassic Bunter Sandstone Formation of the Southern North Sea is believed to have significant potential to store CO_2 for climate change mitigation [1]. It has fair to good reservoir properties and a seal is provided by the mudstones of the Triassic Haisborough Group. It has been folded into domes and periclines (henceforth Bunter domes) by the post depositional late Triassic to Tertiary movement of the underlying evaporites of the Zechstein Group. These domes have been identified as targets for CO_2 storage as they are very large and at least some of them have the ability to retain buoyant fluids, demonstrated by the presence of gas fields in some domes [2], [3], [4], [5] (though the majority of the formation is saline water-bearing). However, faults have been identified within the Haisborough Group cap rock directly above a number of the Bunter domes. The faults are thought to have formed as result of extensional stresses exerted during dome formation. They may have an impact on storage site security, as they could act as migration pathways for CO_2 out of the storage site and therefore limit the number of Bunter domes that could be utilised for storage of CO_2. This study considers the occurrence of faults in the cap rock above the Bunter domes and the potential impact on static capacity estimates.

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Keywords: Bunter Sandstone Formation; Static Capacity; Faulting; CCS

1. Introduction

It has been shown that Bunter Sandstone Formation has fair to good reservoir properties [1], [6]. It is overlain by the Haisborough Group which forms a proven seal over several gas fields discovered in the Bunter Sandstone Formation. In addition, the Bunter Sandstone Formation has been folded by post-depositional halokinesis of the underlying Zechstein Group which is made up of dominantly evaporitic strata. As a result the formation consists of numerous 4-way dip-closed anticlines (Bunter domes) which could potentially trap and retain buoyant fluids such as CO_2. All of these factors make it an attractive prospect worth considering for storing CO_2.Where the pore space of the Bunter domes is not filled by gas it is filled by highly saline pore fluid.

However, in many cases the effectiveness of the Haisborough Group caprock could be compromised by the presence of faults in the crests of the Bunter domes. The faults are thought to have been formed as a result of extensional stresses exerted during the formation of the domes during the underlying movement of the Zechstein Group salts. The faults in the Bunter domes may pose a risk to containment of CO_2 as they may compromise the caprock and may create a migration pathways out of the Bunter Sandstone Formation reservoir into overlying strata and, in a worst case scenario, the seabed.

The UK Storage Appraisal Project (UKSAP), commissioned and funded by the Energy Technologies Institute, [7] identified several Bunter domes [7] which may have potential to store CO_2. As part of UKSAP the storage capacities of these Bunter domes were calculated and a number of Features Events and Processes (FEPs)

* Corresponding author. Tel.: ++ 44 (0)115 9363048; fax: ++44 (0)115 9363200.
E-mail address: mbrook@bgs.ac.uk.

related to security of storage in the domes were assessed. This risk assessment identified that many of the Bunter domes have faults in their crests, of varying severity, density and throw. The aims of this study are to understand how many of the Bunter domes are faulted, how significant the faulting is and the impact faults may have on storage capacity estimates for the Bunter Sandstone Formation.

2. Methodology

UKSAP [7] assessed the storage potential of the Bunter Sandstone Formation by:

- Mapping the location of the Bunter domes using a combination of 3D seismic data and well data.
- Using a combination of well data and published data to assess the reservoir properties of the Bunter Sandstone Formation.
- Calculating the storage capacity of the Bunter domes using the UKSAP methodology [7].
- Qualitatively risking the individual Bunter domes using a FEP methodology [7].

Bunter domes with a crestal depth of less than 800 m were excluded from the analysis.

Due to the qualitative nature of the fault risk assessment the risks were not weighted or carried through to the storage capacity calculations in the UKSAP capacity estimates. This paper investigates the potential impact of faulting on storage capacity and future utilisation of the Bunter domes. It considers the storage capacity estimates for each Bunter dome in the light of the fault risk assessment in order to calculate theoretical storage capacities associated with severity of faulting.

2.1 Mapping of the Bunter Sandstone Formation

The Bunter Sandstone Formation in the UK sector of the Southern North Sea was mapped using a combination of depth surfaces acquired from PGS (interpreted by PGS on the Southern North Sea Megamerge 3D seismic survey and gridded at 1000 m x 1000 m) and IHS well data (IHS EDIN database). No structural data outside the domes (e.g. the location of faults and salt walls) were available. The map of the top Bunter Sandstone Formation was used to identify closed structures with the potential for storing CO_2 (Bunter domes, Fig 1). UKSAP identified 29 Bunter domes with crests below the cut-off depth of 800 m. It should be recognised that this may not be an exhaustive count, additional Bunter domes may exist outside the limits of the project data.

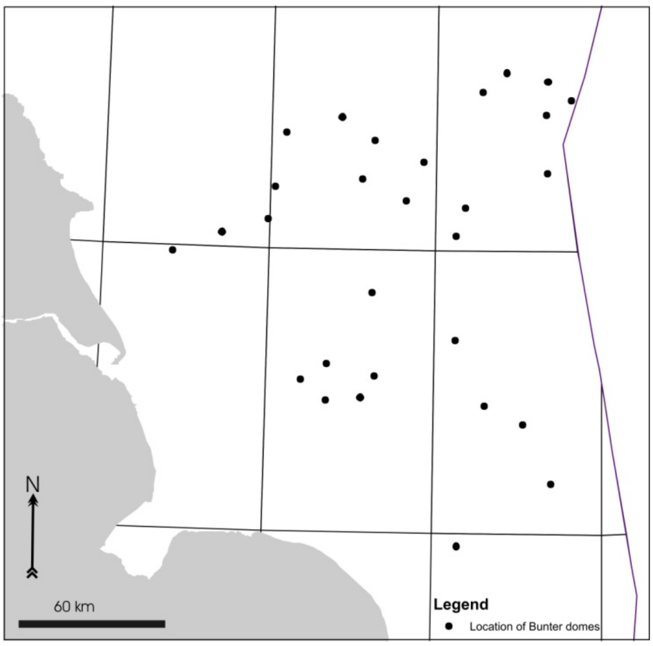

Fig 1. Centroids of the UK SAP mapped Bunter domes in the Southern North Sea

2.2 Fault Assessment

As part of the UKSAP assessment the security of storage (or risk) was assessed for all of the Bunter domes. A Features, Events and Processes (FEP) approach was used for this initial site screening [8]. Risk categories included containment issues (susceptibility to upward or lateral movement of CO_2 out of the storage volume) and operational issues (susceptibility to change in achievable storage capacity or injection rate) [7]. This paper focuses on the risk of faults to containment.

Faulting was qualitatively assessed for each mapped Bunter dome using 3D seismic data derived from the PGS 3D Seismic Mega Merge, with 100 m line spacing. A series of seismic inlines and crosslines cutting through the identified Bunter domes were visually examined by an assessor for the presence or absence of faults in the reservoir (Bunter Sandstone Formation) and the caprock (Haisborough Group). The severity of faulting was categorised and recorded according to the pre-agreed set of criteria listed in Table 1. Examples are shown in Figure 2.

Table 1. Criteria provided to the assessors for assessing faulting in the UK SAP project.

	Classification		
FEP	Low	Medium	High
Fault density	No faults, recorded comment based on resolution of data	< 10 resolved faults per unit	10 resolved faults per unit
Throw and fault seal	None (comment on resolution of data source)	Estimated offset less than caprock/inter-reservoir shale (note timing of faulting versus expected consolidation)	Estimated offset greater than caprock thickness. Potential for clay smear to be noted if information available
Vertical extent	Resolved fault displacement limited to reservoir and seal (comment on resolution based on data source)	Resolved fault terminates in overburden / reservoir deeper than 800 m	Resolved fault greater displacement/conduit to shallower than 800 m.

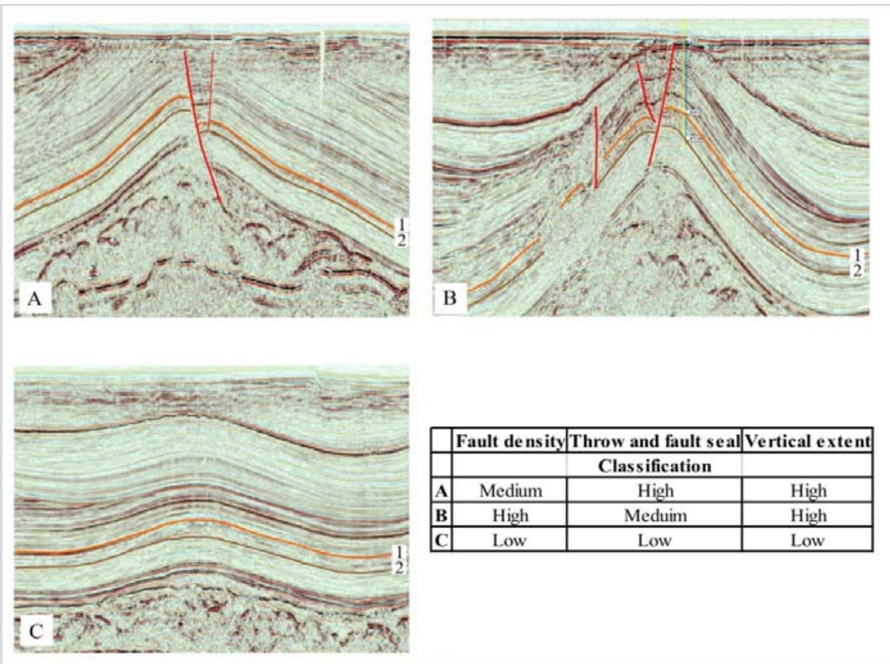

Fig 2. Examples of faulting styles in the crests of the Bunter domes and the associated risk classifications. Where [1] is the top of the Bunter Sandstone Formation reservoir unit and [2] is the base of the Bunter Sandstone Formation reservoir unit. Data courtesy of WesternGeco.

In addition to the classification of low to high described in Table 1 the assessor also assigned a confidence value to the assessment of low, medium or high based on the perceived quality of the data used in the assessment. Several of the Bunter domes were not fully covered by seismic from the PGS Megamerge and in such cases the risk of faulting was described as unknown.

It should also be noted that 3D seismic survey used had a resolution of 1 line per 100 m. This may not be sufficient to image all the potential faults as some may be present between the lines available to this study, additionally faults may be present in the crests of the Bunter domes that are not seismically resolvable.

2.3 Storage Capacity

The static CO_2 storage capacity of the Bunter Domes was calculated using the methodology developed in the Energy Technology Institute UK Storage Appraisal Project [7]. The P50 theoretical storage capacity results from this study for the Bunter Domes are shown in Figure 3. The total P50 theoretical storage capacity of the 29 Bunter Domes was estimated by UK SAP to be 4600 Mt (million tonnes). Of these closures, 17 were assessed to have a static capacity of over 50 Mt each.

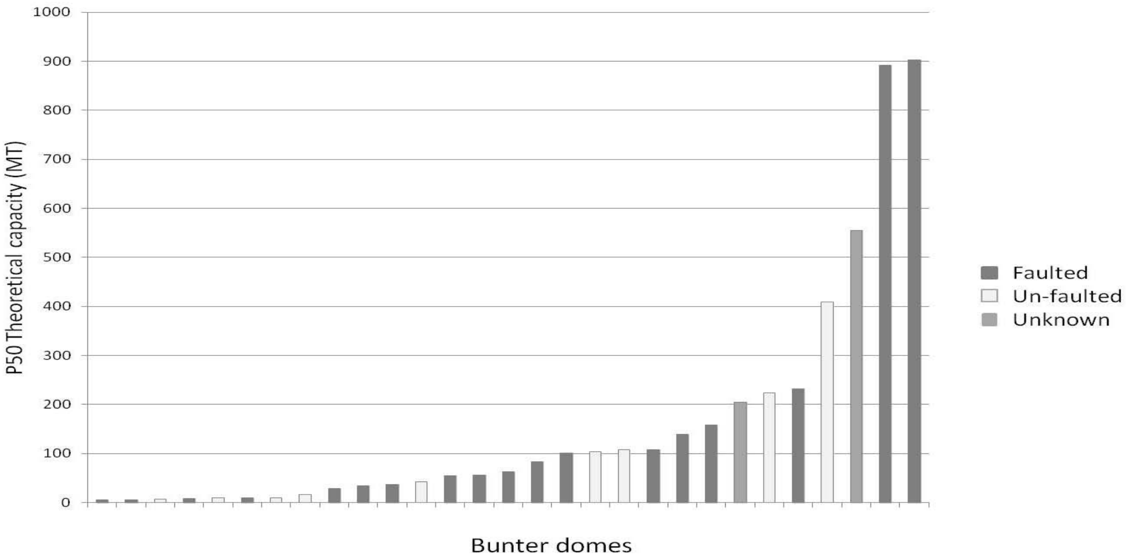

Fig 3. P50 Theoretical static capacity of the Bunter Domes in the Southern North Sea and presence of faulting.

3. Occurrence of faulting

Within the limits of the data resolution, of the 29 Bunter domes identified in the mapping exercise and analysed in the risk assessment, 19 show evidence of crestal faulting, 10 appear to be un-faulted and 1 could not be assessed due to lack of seismic coverage (Fig. 4). The throw and fault seal and vertical extent analysed each represent a specific risk described below.

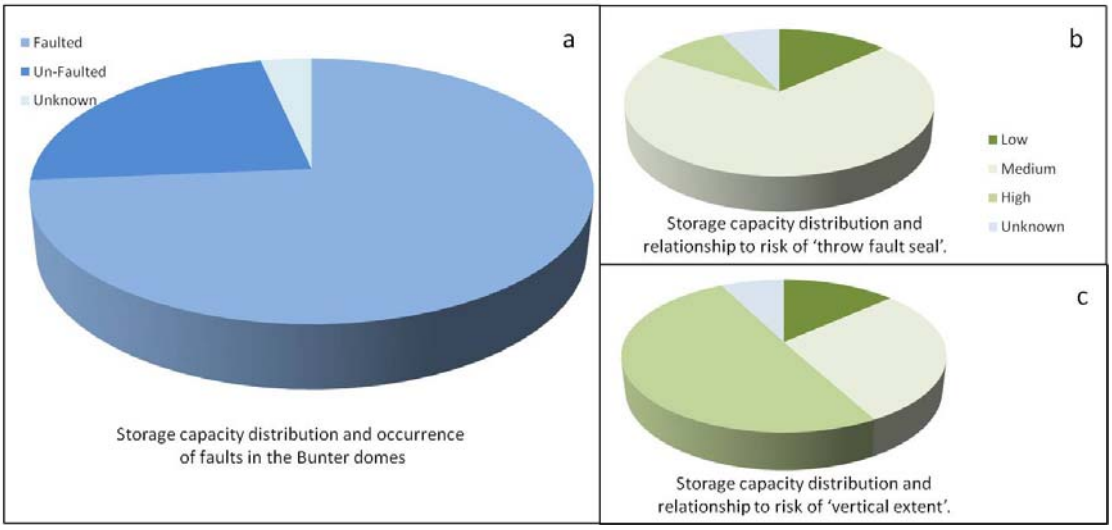

Fig 4. Capacity distribution, occurrence of faults and relationship to fault risk categories in the Bunter domes in the UK sector of the Southern North Sea.

3.1 Throw and fault seal

The presence of a fault does not in itself mean that there would be an impact on security of storage. If the offset of a fault is less than the thickness of the caprock the likelihood of providing a migration pathway through the caprock is lower. In comparison faults that have offsets greater than the thickness of the caprock have an increased risk of CO_2 migrating out of the reservoir as it increases the chance that the reservoir or caprock will be juxtaposed against geological horizons that are non-sealing. This is reflected by the 'throw and fault seal' risk criterion. The severity of offset of the faults observed in the crest of the domes was captured in the risk assessment by a ranking of low to high in the 'throw and fault seal' field. Bunter domes with faults ranked low in 'throw and fault seal' have faults which exhibit no offset on the fault plane on the seismic data, these faults can be considered the lowest risk. Domes categorised as medium in "throw and fault seal" have faults which have an offset of less than the thickness of the caprock. In the high risk category domes have faults with offsets greater than the caprock and it is in this scenario that the caprock is most likely to be compromised. Also, no information was available of the sealing capacity for the faults above Bunter domes. No information was available to this project in terms of fault rock composition. The presence of low permeability fault rock such as shale gouge or smear would reduce the risk of CO_2 migration along the fault plane. In total, 15 Bunter Domes were categorised to have a medium risk in 'throw and fault seal' and only 4 were described as high risk (Table 2).

3.2 Vertical extent

Migration of CO_2 via faults to depths shallower than 800 m is classified as a risk due to the properties of CO_2. In normal geothermal and pressure regimes CO_2 below 800 m is likely to be in its highly dense phase, above approximately this depth (depending on the exact pressure and temperature) the migrating CO_2 may undergo a phase change due to the decreasing pressure and temperature and become gaseous. The CO_2 would then expand and migrate faster, this could cause a more serious leakage of CO_2 depending on the surrounding geology. As a result, faults which terminate below 800 m depth are considered to be a lower risk than faults which extend above 800 m depth. This is captured in the 'vertical extent' FEP. This risk factor was categorised as low, medium or high. Bunter domes classified as low in 'vertical extent' have faults whose extent is limited to within the reservoir or caprock and below 800 m depth. Faults terminating in the overburden at depths > 800 m are considered medium risk. Faults extending into the overburden to depths shallower than 800 m are considered high risk. Of the 29 Bunter domes identified, 1 is low risk in terms of vertical extent, 5 are considered to be medium risk and 11 are considered to be high risk (Table 2). Again the presence of sealing low permeability fault rocks would reduce this risk. There are only 3 Bunter domes which have high risk for both Throw & fault seal and Vertical extent.

Table 2. Fault risk distribution in the Bunter domes.

Risk Criteria	Throw and fault seal	Vertical extent
Low	0	1
Medium	15	5
High	4	12
Unknown	0	1

4. Impacts of faults on static capacity

Of the 29 Bunter domes assessed by UKSAP, 9 were unfaulted with an estimated P50 theoretical storage capacity of 1050 Mt. If a minimum P50 capacity cut-off, of 50 Mt is also applied, this reduces the number of suitable domes to 4, but these provide the vast majority of the potential unfaulted capacity. The total estimated theoretical capacity for unfaulted Bunter domes with a P50 theoretical storage capacity >50 Mt is 980 Mt.

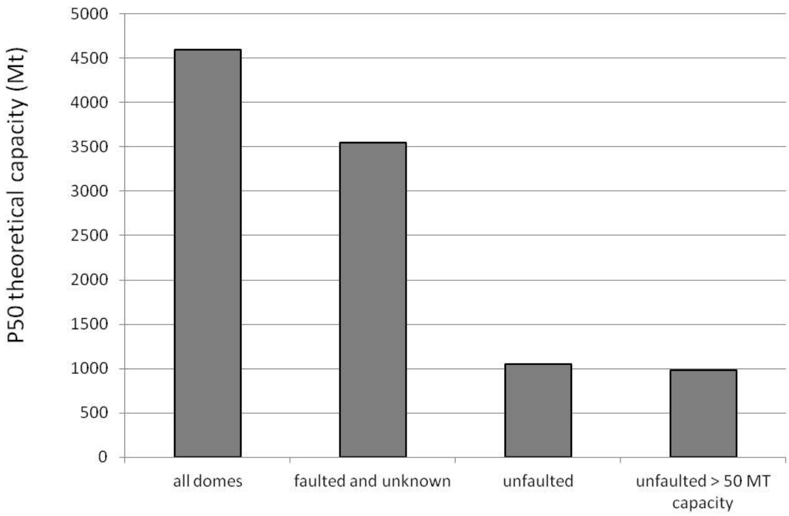

Fig 5. Distribution of storage capacity and faulting in the Bunter domes

Discounting potential storage sites in the Bunter Sandstone Formation due to the presence of faulting in the caprock without considering the potential for fault sealing and the caprock properties would have a significant impact on the availability of pore space for CO_2 storage in the UK sector of the Southern North Sea.

The Haisborough Group, which directly overlies the Bunter Sandstone Formation and forms its primary seal, consists of a series of mudstones and evaporites up to 420 m thick. It is divided into three formations. The lowermost, the Dowsing Dolomite Formation, consists mostly of red silty mudstones. However, over much of its distribution [9] it also includes the Röt Halite Member which likely improves the seal for the Bunter Sandstone Formation, and below that, the Solling Claystone which rests immediately above the Bunter Sandstone Formation. The Dudgeon Saliferous Formation overlies the Dowsing Dolomite Formation and consists of thick, predominantly green mudstones up to 100m thick. The Keuper Halite forms the boundary between the Dudgeon Saliferous Formation and the overlying Triton Anhydritic Formation. The Triton Anhydritic Formation consists of a monotonous sequence of red mudstone with a few layers of anhydrite that form the Keuper Anhydritic Member. Unsurprisingly given the lithologies found in the Haisborough Group, in the UKSAP project the caprock risk (excluding faults) was ranked as low for all the Bunter domes.

The nature of the faults cutting the Haisborough Group is poorly known as there is little if any core from this formation in the UK sector. It is possible that faults cutting through the Haisborough Group evaporites have been ‘sealed’ as a result of creep of the evaporitic formations within the group. The mudstones and shales of the Haisborough Group may also play a role in the of sealing faults due to the likely presence of shale gouge on the fault plane formed during movement of the fault. As a result of these potential mechanisms many of the faults above the Bunter domes may act as barriers to fluid flow and reduce the risk of CO_2 migrating out of the reservoir. Circumstantial evidence from seismic data is available over the Bunter Sandstone Formation gas fields and shows faults in the caprock similar to those in Bunter domes. These have retained gas over millennia, suggesting some crestal faults are in fact sealed. For example in the Little Dotty gas field gas is trapped in a faulted anticline [5]. The faults associated with this field must have been sufficiently sealing to allow gas to accumulate. It is likely that in reality, there is a combination of both sealing and non-sealing faults in the study area. However, no data are available as to the sealing properties of faults in the Bunter Sandstone Formation.

5. Discussion

Given the promising reservoir characteristics of the Bunter Sandstone Formation, the proven caprock of the Haisborough Group and the presence of numerous domes, the Bunter Sandstone Formation presents an attractive prospect for CO_2 storage. Of the capacity identified in UKSAP, 980 Mt is unfaulted, and these domes are likely to be favored for licensing for the initial roll out of CCS in the UK. To put this figure into perspective, this would provide sufficient capacity for all UK CO_2 emissions which are likely to be captured up to the late 2030s.

As the number of 'perfect' un-faulted Bunter domes may be limited, as is highlighted by this study, the importance of understanding the sealing capacity of faults is key to fuller utilisation of the potential storage space contained in the Bunter domes. Further work is under way to more fully understand the scale of this risk. Due to the presence of evaporites and mudstones in the Haisborough Group the faults within the cap rock may be 'self sealing' and may therefore not pose a risk to storage integrity. Faulting is present in the cap rock above several Bunter gas fields, supporting the theory that some faults may have self-sealed, however this process is not fully understood. If CCS is fully implemented in the UK it is likely that we will have to consider less than perfect storage sites after the initial 'perfect / low hanging fruits' have been exploited. If such storage sites are to be licensed further research is needed on the behaviour and sealing capacity of faults within the cap rock and overburden.

6. Conclusion

The P50 theoretical storage capacity of all the Bunter domes was estimated by UKSAP to be 4600 Mt CO_2. There are limited numbers of domes in the Bunter Sandstone Formation which have no crestal faulting in the reservoir or caprock (only 9 were identified in the UKSAP project). These represent a capacity of 1050 Mt and are likely to promising candidates for use during initial roll out of CCS in the UK. For those domes with faults, many are likely to be sealing, but further work is required so the risk of CO_2 migration due to faulting can be properly assessed, understood and potentially mitigated to maximise the utilisation of the storage capacity of Bunter domes UK sector of the Southern North Sea.

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