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Retention capacity of seals from hydrocarbon field analogues for appraisal of saline aquifers

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ABSTRACT

Saline aquifers have very large potential as stores for carbon dioxide, but the seals are untested. The effectiveness of typical sealing lithologies can be assessed using natural hydrocarbon reservoirs. The heights of the hydrocarbon columns in many natural reservoirs are limited by a spill point or by the limited thickness of the reservoir; however, amongst the remaining reservoirs the range of calculated limiting porethroat radii correspond with measured literature values worldwide. This suggests that capillary leakage is the limiting factor in the retention of hydrocarbons in many natural accumulations, and is at least potentially the limiting factor in CO_2 storage. The distribution of limiting porethroat radii for oil and gas fields of the UK North Sea could be used with caution as a generic input for statistical assessment of a prospective CO_2 storage location at an early stage of investigation, before measured site-specific data is available. The calculated limiting porethroat radii show only a weak decrease with burial depth and no correlation to the degree of faulting of the seal. There is a strong correlation with seal lithology; calculated radii for halite seals are significantly smaller than for the majority of shale seals. There is no difference between the calculated limiting porethroat radii for fields with at least some degree of fault sealing, compared to those with no reported fault sealing.

1. Introduction

CO_2 storage in saline aquifers involves the utilisation of a seal which was not previously retaining buoyant fluids. In the case of a halite seal then there may be high confidence in the ability of the seal to retain the CO_2, however in the case of a shale (or mudrock) seal there is likely to be less confidence in the seal performance (e.g. Wilkinson et al., 2013). In many cases it may be possible to build confidence in the performance of a seal where the same stratigraphic unit acts as a seal at some other geographical location, in a known hydrocarbon field. For example Heinemann et al. (2012) suggested that the seal to the high capacity Bunter Sandstone aquifer in the UK southern North Sea would be effective as the same strata act as seals in several gas fields. Where a direct analogue is not available, the recommendations of Chadwick et al. (2008) provide some guidance: the seal is at least 20–100 m thick; laterally continuous; with no or only small faults and with a much higher capillary entry pressure than it is expected to have to hold. While the thickness, lateral continuity and faulting intensity may be assessed using existing well logs or seismic sections, the capillary entry pressure (which in terms of rock properties equates to the limiting porethroat radius i.e. the smallest radii of the porethroats which form the leakage pathways of least resistance) may prove to be more challenging. The method of Krushin (1997), which correlates porethroat size with the percentage of quartz in the mudrock, can be used provided that there are core (or possibly cuttings) samples available, however the data show sufficient scatter to impart significant uncertainty into any result.

In addition, although the recommendations of Chadwick et al. (2008) suggest that faulted caprocks should be avoided, there are many cases of hydrocarbon fields that are at least partly sealed by faults, so that a faulted caprock still has the potential to retain buoyant fluids, presumably including CO_2. Many seals of hydrocarbon fields show faulting at a scale resolvable by seismic imaging, and may be rejected during initial screening of storage sites in favour of unfaulted areas. However, given the likely future utilisation of aquifer porespace for multiple, competing, purposes (compressed air energy storage; hydrogen storage; methane gas storage; carbon storage), then competition for subsurface storage may dictate that faulted seals must be assessed for useability.

The approach adopted here is to study hydrocarbon fields, for which published data are available, to draw generic conclusions about seals to aid in de-risking the appraisal of a seal of untested performance. The calculated limiting porethroat dimensions could

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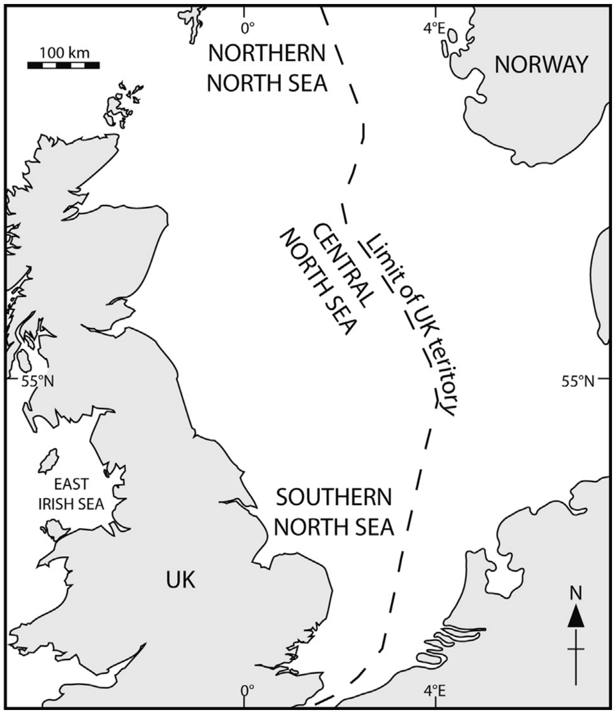

Fig. 1. Location map.

be used, for example, as input for probabilistic assessment of a prospective CO_2 storage location, for example by a Monte Carlo approach. The method is essentially the reverse of the calculations presented here, where by the capillary entry pressure of CO_2 under reservoir conditions (pressure, temperature and porewater salinity) is calculated, and this pressure used to determine a limiting (maximum) column height of CO_2 that can be retained under the seal, again under reservoir conditions. In this study, 140 individual reservoirs within oil and gas fields of the UK North Sea (Fig. 1) were studied, as data is available in a fairly uniform format in Gluyas and Hichens (2003) and Abbotts (1991). The studied fields include clastic, carbonate and evaporite seals. Limiting porethroat radii are calculated (see the discussion for an explanation of the physical significance of this parameter), as being of substantially more utility than capillary entry pressures which depend upon factors other than the rock geometry, such as the properties of the fluids in the reservoir. Geological controls on the porethroat radii are then sought, to assist the assessment of an untested seal. In particular, the role of faulting on the apparent pore throat radii is examined, on the assumption that fracturing associated with faulting would reduce the performance of a seal.

2. Methods

The limiting porethroat radius of the seal for each hydrocarbon field is calculated using the following method. The buoyancy pressure exerted on a seal by the underlying column of hydrocarbon is equated to the capillary entry pressure of the seal, allowing the effective porethroat radius to be calculated (Eq. (1); symbols are in Table 1).

$$r_{\text{pt}} = 2\sigma_{\text{hydrocarbon-brine}}\cos\theta/(\rho_{\text{water}} - \rho_{\text{hydrocarbon}})gh_{\text{c}} \quad (1)$$

where a reservoir has both an oil and a gas charge, the total buoyancy pressure is taken to be the sum of the pressures due to both the oil and gas, but the interfacial tension of gas–water is used as the gas phase will be in contact with the seal at the field crest where buoyancy pressure is highest. The density of water under reservoir conditions is calculated using the equations of Danesh (2007) as a function of pressure, temperature and salinity. The density of hydrocarbon gas is calculated using the method of Naylor et al. (2010) from the gas expansion factor and specific gravity. Gas fields that lacked these key data were excluded from the results. The density of oil under standard conditions is derived from the API gravity. The density under reservoir conditions may be significantly different, partly due to compression but more significantly due to the presence of dissolved gas: formation volume factors for the fields range from 1.0 to 3.0 m^3/Sm^3, i.e. the oil shrinks upon production to the surface due to the exsolution of dissolved gas. The density of the oil under reservoir conditions is calculated using simple mass balance (Eq. (2)).

Table 1
Symbols.

FVF	formation volume factor
g	acceleration due to gravity
GOR	gas–oil ratio
h_c	height of hydrocarbon column
r_{pt}	porethroat radius
ρ_x	density of phase x
σ	interfacial tension between two fluids
θ	contact angle between two fluids measured at an interface

$$\rho_{\text{oil, reservoir}} = \frac{\rho_{\text{oil, surface}} \pm \rho_{\text{gas, surface}}.\text{GOR}}{\text{FVF}} \quad (2)$$

For gas fields, the interfacial tension (IFT) between the gas and water is estimated as a function of reservoir pressure using a polynomial fit to experimental data for methane from Ren et al. (2000) and Tian et al. (1997) at 298, 373 and 473 K (Fig. 2). For intermediate temperatures, linear interpolation is used. For oil fields, the IFT between the oil and water is calculated using the interfacial tension of water and air and the interfacial tension between air and oil from Eq. (3) (Adam, 1957).

$$\sigma_{\text{oil-brine}} = \sigma_{\text{water-air}} - \sigma_{\text{oil-air}} \quad (3)$$

IFT for oil–air is determined as a function of temperature using the equation of Baker and Swerdloff (1956), and corrected for dissolved gas using the equation of Abdul-Majeed and Abu A.L-Soof (2000). The IFT of water–air is calculated as a function of temperature using a linear equation fitted to the data of Speight (2005). The contact angles for both oil and gas in a water-wet system are assumed to be zero, after Naylor et al. (2010). This assumption has been widely made within the petroleum industry; see Stone (1970) and McCaffery (1972).

Fields that are filled to spill point or have no detectable lower hydrocarbon–water contact were excluded from further analysis, as the seal performance is not the factor that is controlling the height of the hydrocarbon column, and consequently the calculated limiting porethroat radius of the seal will not be the true physical value. This step is an important one in this analysis, and fields with ambiguous data were omitted from further consideration rather than include fields where the hydrocarbon height may not be limited by seal performance. The hydrocarbon fields were then classified according to their geological characteristics, to investigate any geological controls on seal performance. Data categories were: the degree of faulting of the seal; present day depth of the field crest; and the presence or absence of fault sealing in the field. The degree of faulting of the seal was assessed using published cross-sections of the fields from Gluyas and Hichens (2003); the sections are either interpreted in seismic sections or diagrams drawn from interpreted sections. The degree of faulting of the seal was assessed in 3 categories: no/small faults where any faults were restricted to the reservoir and did not penetrate the seal; 'medium' where the faults penetrated the immediate seal but not the overburden; and