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Geological reservoir characterization of a CO_2 storage site: The Utsira Sand, Sleipner, northern North Sea

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Abstract

The paper aims to draw some generic conclusions on reservoir characterization based on the Sleipner operation where CO_2 is being injected into the Utsira Sand. Regional mapping and petrophysical characterization of the reservoir, based on 2D seismic and well data, enable gross storage potential to be evaluated. Site-specific injection studies, and longer-term migration prediction, require precision depth mapping based on 3D seismic data and detailed knowledge of reservoir stratigraphy. Stratigraphical and structural permeability barriers, difficult to detect prior to CO_2 injection, can radically affect CO_2 migration within the aquifer.

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1. Introduction

The world's first industrial-scale CO_2 storage operation has been in operation at the Sleipner field in the North Sea since 1996. CO_2 is being injected at a depth of about 1000 m into the Utsira Sand, a major, regional saline aquifer. At the time of writing more than 5 Mt of CO_2 have been injected, with a projected final target of about 20 Mt. The Sleipner sequestration operation is the focus of the SACS (Saline Aquifer CO_2 Storage) project, whose aims include monitoring and modelling the fate of the injected CO_2 and regional characterization of the Utsira reservoir and its caprock. This paper describes some of the results of the investigations

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and draws out some generic aspects of geological reservoir characterization that are particularly applicable to CO_2 injection into aquifers of regional extent with low structural relief.

2. Properties of the Utsira Sand reservoir

2.1. Regional structure and stratigraphy

The Utsira Sand [1] comprises a basinally restricted deposit of Mio-Pliocene age extending for more than 400 km from north to south and between 50 and 100 km from east to west (Figs. 1 and 2). Its eastern and western limits are defined by stratigraphical onlap, to the southwest it passes laterally into finer-grained sediments, and to the north it occupies a narrow, deepening channel. Locally, particularly in the north, depositional patterns are quite complex with some isolated depocentres, and lesser areas of non-deposition within the main depocentre.

Internally the Utsira Sand comprises stacked overlapping 'mounds' of very low relief, interpreted as individual fan-lobes and commonly separated by thin intra-reservoir mudstone or shaly horizons. It is interpreted as a composite low-stand fan, deposited by mass flows in a marine environment with water-depths of 100 m or more.

The top Utsira Sand surface (Fig. 2a) generally varies quite smoothly in the depth range 550–1500 m, and is around 800–900 m near Sleipner. Isopachs of the reservoir sand define two main depocentres (Fig. 2b), one in the south, around Sleipner, where thicknesses locally exceed 300 m, and another some 200 km to the north with thicknesses approaching 200 m.

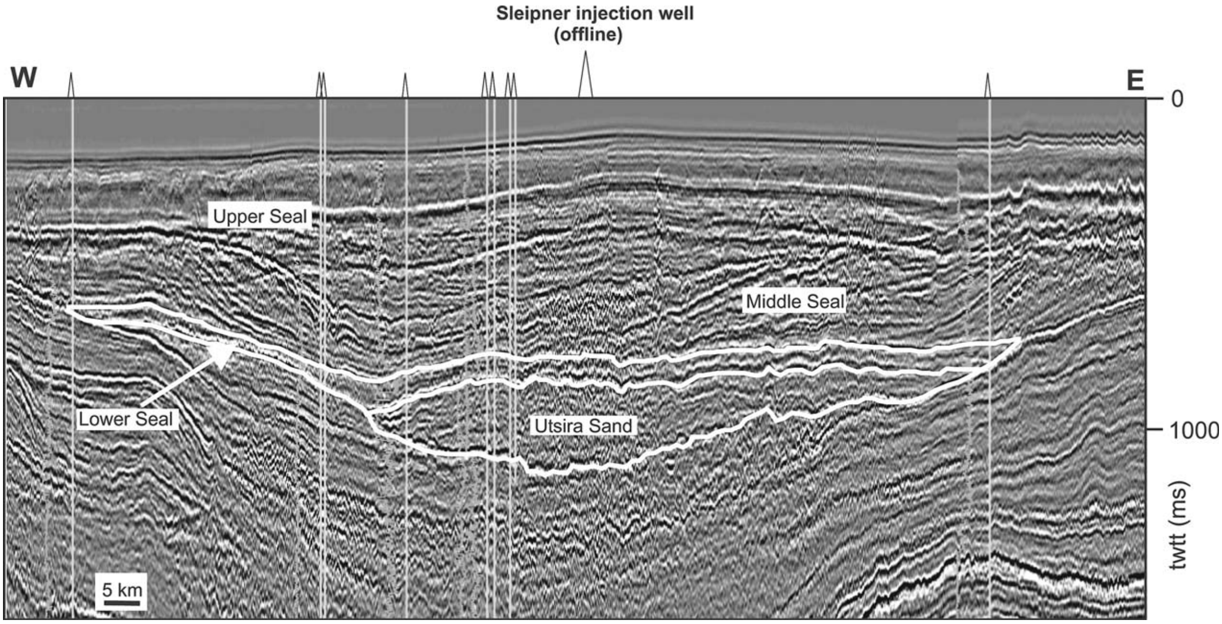

Fig. 1. Regional seismic line across the North Sea Basin illustrating the Utsira Sand and the caprock succession. [Seismic data courtesy of Schlumberger Ltd.]

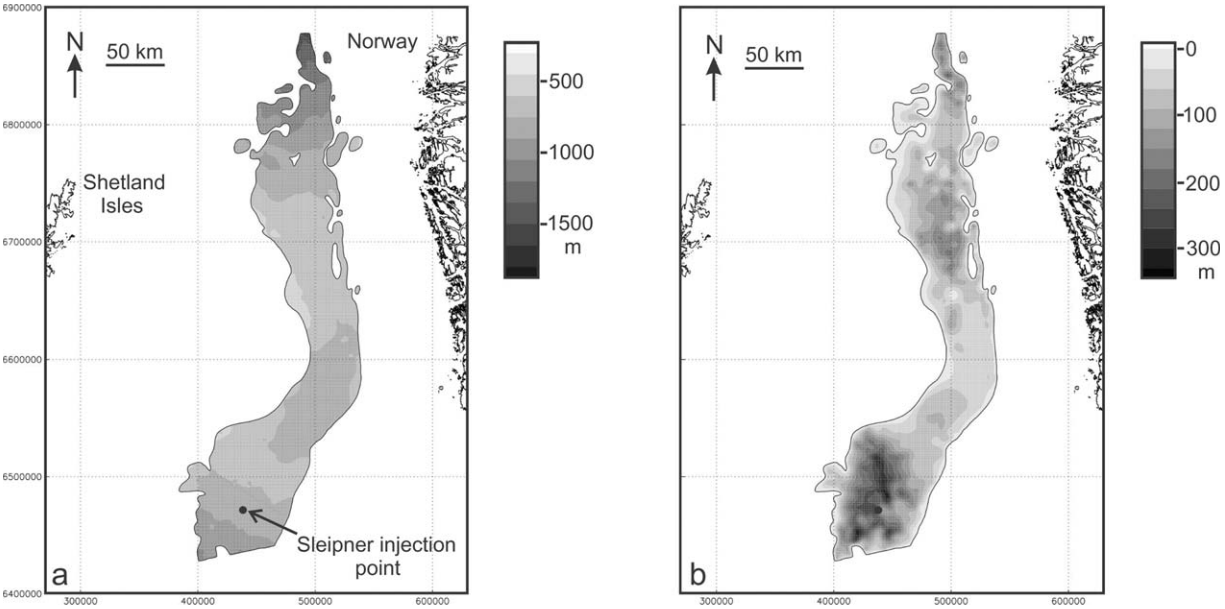

Fig. 2. Maps of the Utsira Sand: (a) depth to top reservoir (b) reservoir thickness (isopach).

The regional reservoir maps were constructed from about 16,000 line km of 2D seismic data, and information from 132 wells penetrating the reservoir unit. They are ideal for strategic planning, but are less useful for specific site selection. The spatial resolution of the reservoir topography is severely limited by the grid spacing of the 2D seismic data, typically 5–10 km. For aquifers with low structural relief, the much higher spatial resolution provided by 3D seismic data is required to plan specific injection scenarios (see below). Similarly the large spacing of the wells combined with the lack of core material from which to derive measurements of the physical properties of the rocks, limits the ability to construct a detailed reservoir model.

2.2. Structural and stratigraphical detail around the injection point

Around Sleipner, some 770 km^2 of 3D seismic data were interpreted. The top of the Utsira Sand dips generally to the south, but in detail it is gently undulatary with small domes and valleys. The Sleipner CO_2 injection point is located beneath a small domal feature that rises about 12 m above the surrounding area (Fig. 3a).

The base of the Utsira Sand is structurally more complex, and is characterized by the presence of numerous mounds, interpreted as mud diapirs. These are commonly about 100 m high and are mapped as isolated, circular domes typically 1–2 km in diameter, or irregular, elongated bodies with varying orientations, up to 10 km long. The mud diapirism is associated with local, predominantly reverse, faulting that cuts the base of the Utsira Sand, but does not appear to affect the upper parts of the reservoir or its caprock [2].

On geophysical logs the Utsira Sand characteristically shows a sharp top and base (Fig. 3b), with the proportion of clean sand in the reservoir unit varying generally between 0.7 and 1.0.

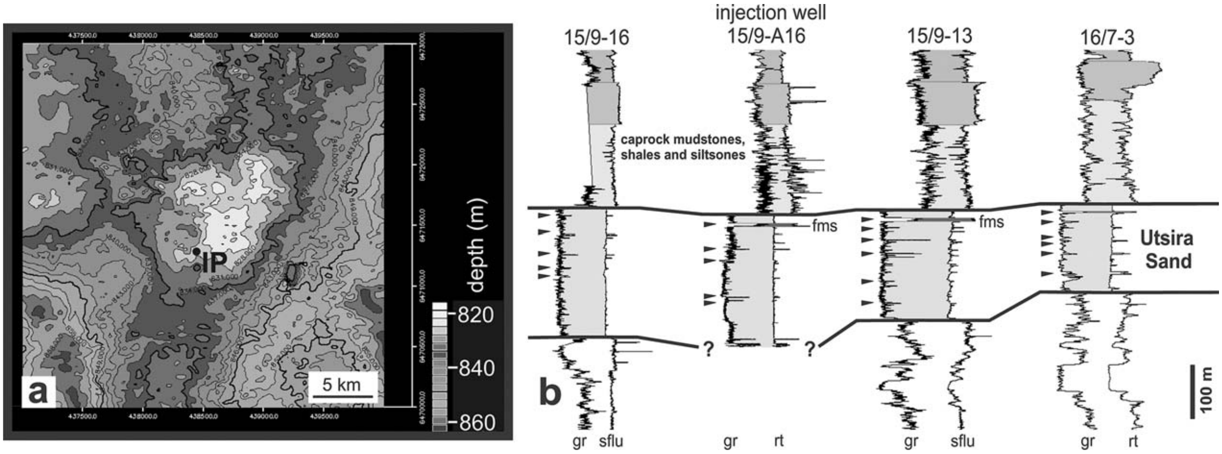

Fig. 3. (a) Depth to top Utsira Sand around the injection point (IP). (b) Geophysical log correlation panel from Sleipner wells. Note thin intra-reservoir shales (arrowed) and the 'five-metre shale' (fms) beneath uppermost unit of the Utsira Sand.

The shale fraction mostly comprises a number of thin mudstone or shale beds (typically about 1 m thick), which show as peaks on the gamma-ray, sonic and neutron density logs, and also on some induction and resistivity logs (Fig. 3b). In the Sleipner area, a thicker shale, some 5 m thick (here termed the 'five-metre shale') separates the uppermost sand unit from the main reservoir beneath (Fig. 3b). The shale layers constitute important permeability barriers within the reservoir sand, and have proved to have a significant effect on CO_2 migration through, and entrapment within, the reservoir. The structural and stratigraphical detail, which the geophysical data has revealed around the injection point, is essential to understanding and predicting the long-term behaviour of the CO_2 plume (see below).

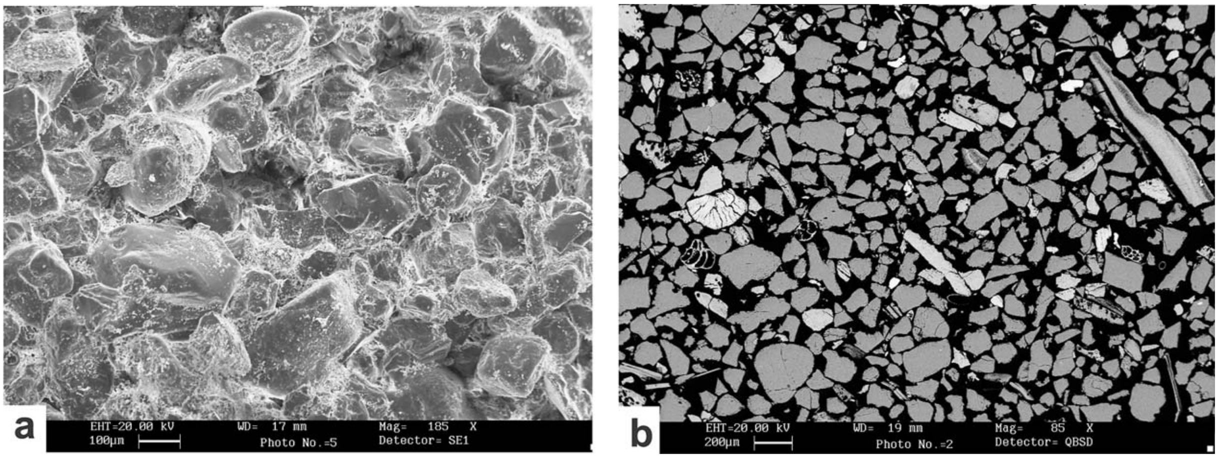

Fig. 4. SEM images of the Utsira Sand (a) reflected light (b) transmitted light.

Table 1
Generalized properties of the Utsira Sand from core and cuttings. Mineral percentages based on whole-rock XRD analysis

Grain size	Porosity	Permeability	Sand/shale ratio	Mineral (%)					
				Quartz	Calcite	K-feldspar	Albite	Aragonite	Mica and others
Fine (medium)	35–40% (27–42%)	1–3 Darcy	0.7–1.0 (0.5–1.0)	75	3	13	3	3	3

2.3. Physical properties

Macroscopic and microscopic analysis of core and cuttings samples of the Utsira Sand show a largely uncemented fine-grained sand, with medium and occasional coarse grains (Fig. 4). The grains are predominantly angular to sub-angular and consist primarily of quartz with some feldspar and shell fragments (Table 1). Sheet silicates are present in small amounts (a few percent). Porosity estimates of the Utsira Sand core based on microscopy range generally from 27 to 31%, locally up to 42%. Laboratory experiments on the core give porosities from 35 to 42.5%. These results are broadly consistent with regional porosity estimates, based on geophysical logs, which are quite uniform, in the range 35–40% over much of the reservoir.

3. Properties of the Utsira caprocks

The caprock succession overlying the Utsira reservoir is several hundred metres thick, and can be divided into three main units (Fig. 1). The Lower Seal, formerly known as the Shale Drape [3], forms a shaly basin-restricted unit some 50–100 m thick. Above this, the Middle Seal mostly comprises prograding sediment wedges of Pliocene age, dominantly shaly in the basin centre, but coarsening into a sandier facies both upwards and towards the basin margins. The Upper Seal is of Quaternary age, mostly glacio-marine clays and glacial tills.

The seismic, geophysical log and cuttings data enable many caprock properties to be characterized and mapped on a broad scale. Specific knowledge of mechanical and transport properties, however, requires core material and a detailed testing programme. To this end, a caprock core was acquired at Sleipner in 2002 and is currently undergoing detailed analysis; the results, however, are as yet unavailable.

The Lower Seal extends more than 50 km west and 40 km east beyond the area currently occupied by the CO_2 injected at Sleipner [3] and forms the primary sealing unit. This is well beyond the predicted final migration distance of the total volume of injected CO_2 [4]. Cuttings samples from wells in the vicinity of Sleipner comprise dominantly grey clay silts or silty clays. Most are massive (Fig. 5a), although some show a weak sedimentary fabric (Fig. 5b). XRD analysis (Fig. 5c) typically reveals quartz, undifferentiated mica, kaolinite, K-feldspar, calcite, smectite, albite, chlorite, pyrite and gypsum together with traces of drilling mud contamination (Table 2). The clay particle-size fraction is generally dominated by illite with minor kaolinite and traces of chlorite and smectite.

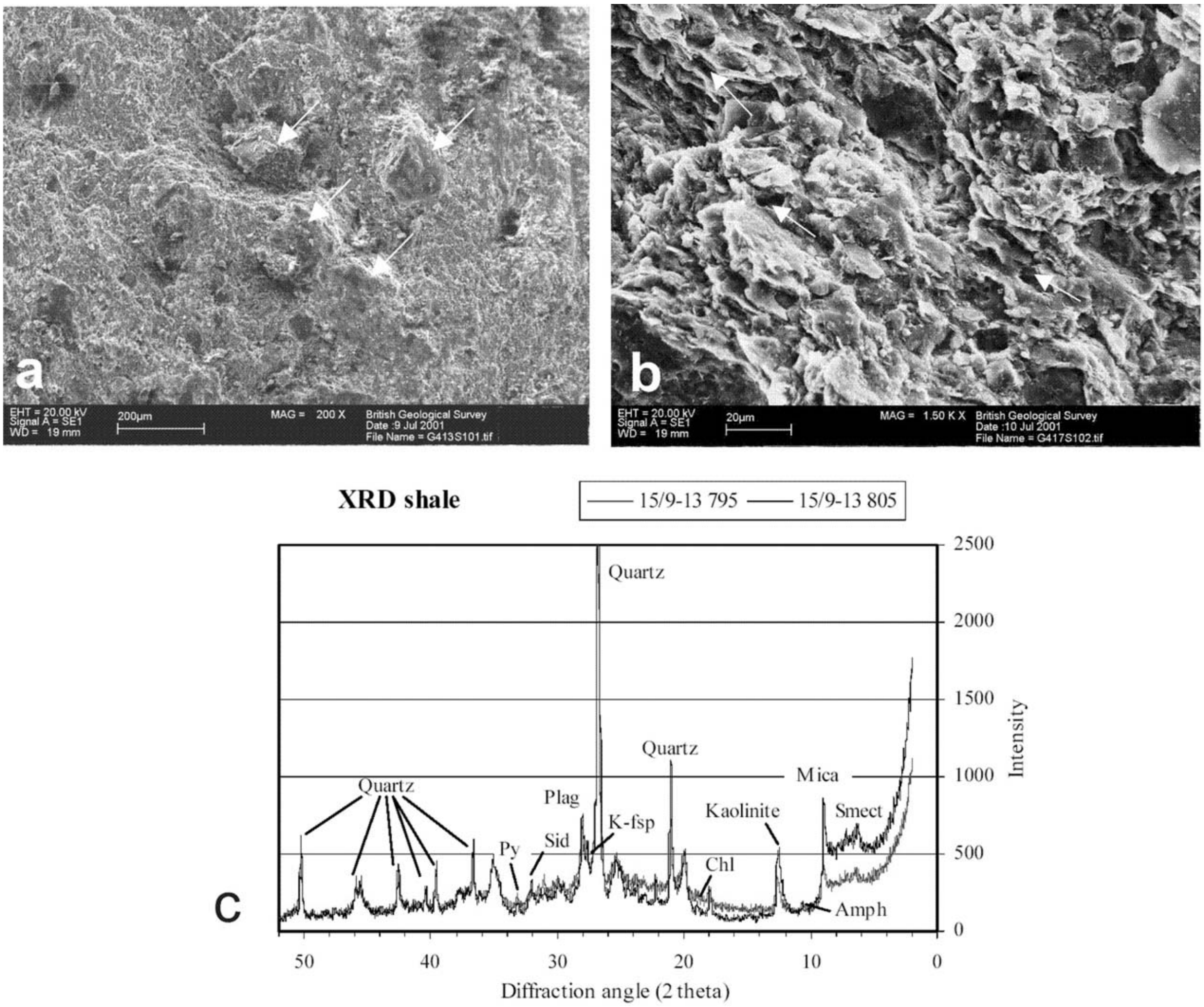

Fig. 5. Utsira caprock cuttings material. (a) SEM image of massive mudrock with a number of rounded fine-grained quartz grains (arrowed). (b) High magnification detail of laminated mudrock showing tightly packed platelets with preferred orientation. Micropores (arrowed) are a few microns in diameter and appear to be poorly connected. (c) X-ray diffraction traces from two samples.

Table 2
Generalized properties of Utsira caprocks, based on analysis of cuttings

Sand (>63 µm)	Silt (2–63 µm)	Clay (<2 µm)	Mineral (%)													CEC meq/100g	TOC (%)
			Quartz	k-spar	Alb	Calc	Mica	Kaol	Smect	Chlor	Pyr	Gyp	Hal	sylv	bar		
0–5%	40–60%	45–55%	30	5	2	3	30	14	3	1	1	1	2	1	5	6.0–20.2	0.68–1.28

The cuttings samples are classified as non-organic mudshales and mudstones according to the Krushin classification [5]. Although the presence of small quantities of smectite may invalidate its predictions, XRD-determined quartz contents suggest displacement pore throat diameters in the range 14–40 nm. Such displacement pore throat diameters predict capillary entry pressures of between about 2 and 5.5 MPa [5], capable of trapping a CO_2 column several hundred metres high. In addition, the predominant clay fabric with limited grain support resembles type ‘A’ or type ‘B’ seals [6], stated to be capable of supporting a column of 35° API oil greater than 150 m in height. Empirically, therefore, and bearing in mind the current lack of measurements on core material, the caprock cuttings suggest the presence of an effective seal at Sleipner, with capillary leakage of CO_2 unlikely to occur.

Seismic stratigraphy plays a key role in mapping caprock efficacy by enabling potentially sandy units, such as prograding foreset strata to be mapped. Seismic amplitude anomalies, or ‘bright-spots’, are also evident in the caprock succession. These indicate localized occurrences of sandy strata, probably gas-filled, and perhaps indicative of conduits for gas migration.

4. Effective storage capacity

Assessment of the total reservoir storage potential is required to devise a long-term injection strategy. The total pore volume of the Utsira Sand, based on the isopach map (Fig. 2b) and regional assessments of porosity and shale volume, is about 6×10^{11} m^3.

For a reservoir with relatively low structural relief such as the Utsira Sand, the total pore volume of the reservoir cannot necessarily be utilized. A simple, but perhaps more realistic measure of effective storage is the pore volume enclosed within structural and stratigraphical traps, wherein CO_2 can be expected to accumulate in the long-term. The 3D seismic mapping around Sleipner indicates that only 0.3% of the available porosity is actually situated within structural closures at the top of the reservoir. Given that CO_2 migrating from a small number of injection wells is unlikely to encounter all of the small traps, a more realistic estimate of the pore-space within closed structures around Sleipner is just 0.11% of the total pore-volume. A simple extrapolation of these figures over the entire Utsira Sand gives an approximate storage volume in traps of just 6.6×10^8 m^3.

On the other hand, trapping of CO_2 beneath intra-reservoir shale beds may significantly increase realizable storage volumes. The time-lapse seismic data (Fig. 6a) failed to resolve individual shale beds prior to CO_2 injection (see below), but subsequent to injection the data clearly show how the bulk of the injected CO_2 is currently being trapped beneath the intra-reservoir shales. This has the effect of markedly decreasing migration distances in the short-term. Simple buoyancy-driven migration simulation shows that ~4.2 Mt of CO_2 trapped wholly at the top of the reservoir would ultimately migrate 6 km or so from the injection point (Fig. 7). This compares with the observed 2001 CO_2 plume (4.3 Mt in situ) whose areal extent or ‘footprint’, lay entirely within 1.3 km of the injection point (Fig. 7). The intra-reservoir shales are, therefore, providing a mechanism for delaying CO_2 dispersal in the short-term (tens of years). This effect would be particularly useful when it is necessary to avoid contamination of nearby working well infrastructure. Intra-reservoir trapping is also likely to increase effective storage capacity in the longer-term by encouraging dissolution of CO_2 into the groundwater and promoting geochemical

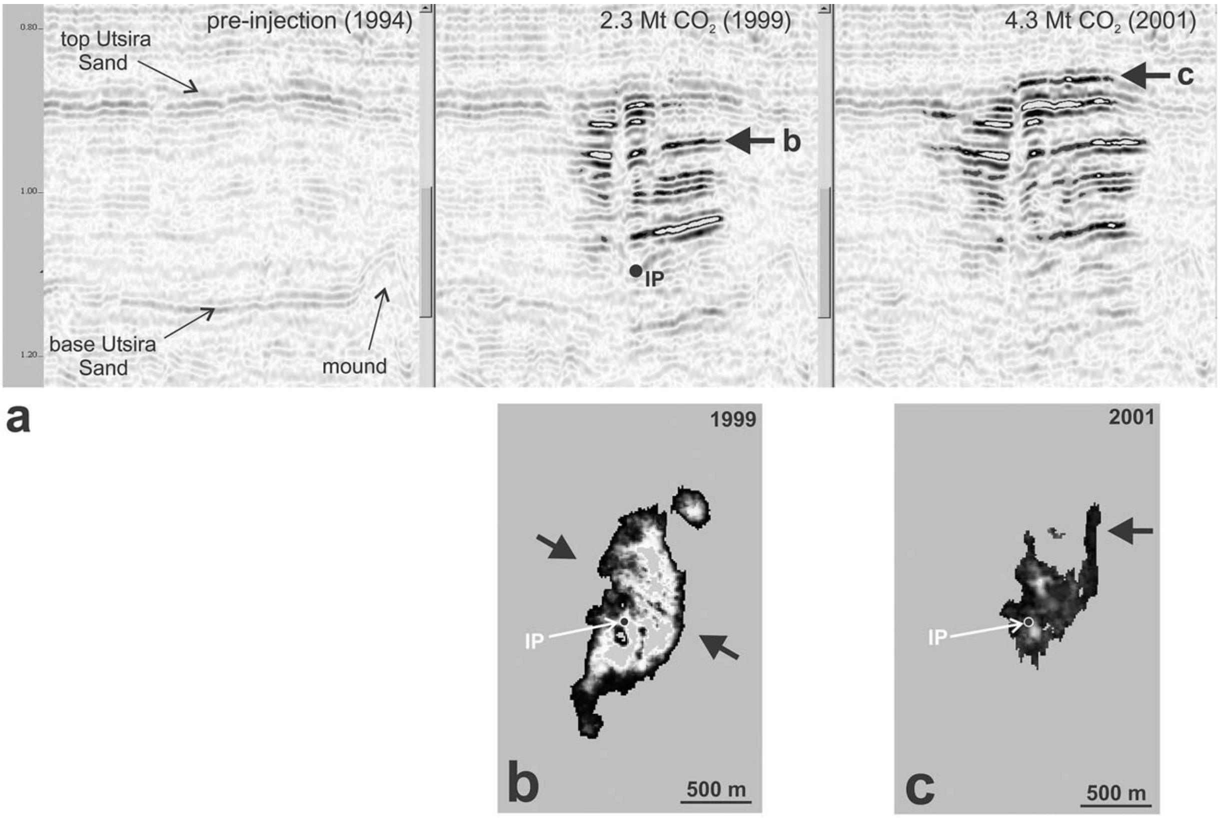

Fig. 6. (a) Time-lapse seismic images showing changes in reflectivity due to injected CO_2. Arrows indicate CO_2 accumulations mapped in (b) and (c). (b) Map of reflection strength on a CO_2 layer in 1999. Possible NW-trending permeability barrier arrowed. (c) Map of reflection strength on top CO_2 layer in 2001. Linear migration along N-trending ridge-like feature arrowed.

reactions leading to chemical 'fixing' [7]. It is clear, therefore, that the assessment of effective storage capacity in an aquifer requires detailed treatment of reservoir structure and stratigraphy.

5. Issues affecting migration of the CO_2 plume

A range of migration models have been constructed taking an injected CO_2 volume of 30 Mm^3 (approximating the expected final injected mass of 20 Mt).

Assuming firstly that the 'five-metre shale' forms an effective long-term trapping horizon, migration simulation predicts that CO_2 would migrate generally in a westerly direction, to reach a maximum distance from the injection site of about 12 km (Fig. 8a). Observations from the 2001 seismic data indicate that CO_2 currently trapped beneath the shale reasonably follows the predicted distribution. An 'anomalous' small outlier of CO_2 to the south of the predicted closure seems principally to be due to complexity of vertical feeder pathways within the plume itself.

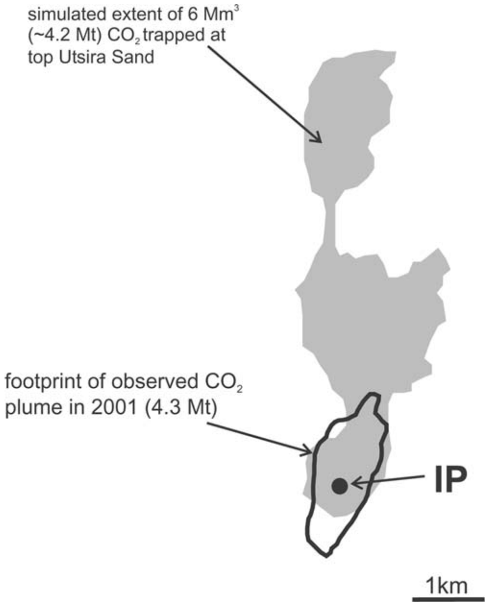

Fig. 7. Simulated lateral extent of 6 mm^3 (~4.2 Mt) of CO_2 assuming trapping only at the top of the Utsira Sand, compared with observed extent in 2001 (with 4.3 Mt of CO_2 in situ).

Because the shale topography is very subdued, however, results are very sensitive to the accuracy of the depth mapping. Changes of dip angle, and errors in the small depth differences between different potential spill points, emphasise the need for precision in the depth conversion.

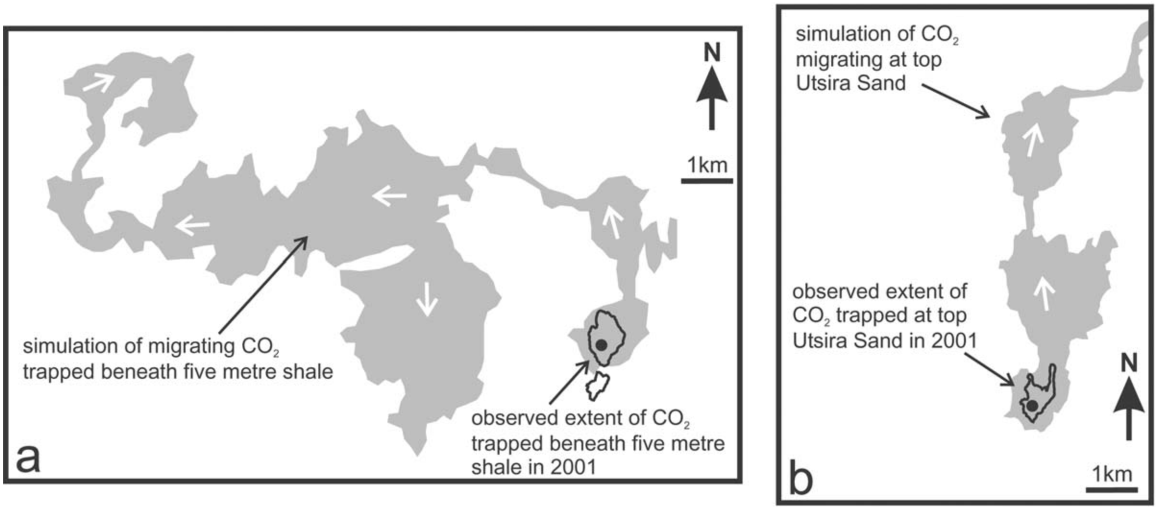

Fig. 8. Simulated longer-term migration distributions for 30 Mm^3 (~20 Mt) of CO_2 compared with observations in 2001 (a) beneath the 'five-metre shale' (b) at top Utsira Sand.

An alternative scenario is that the CO_2 migrates directly to the top of the Utsira Sand. Because the top reservoir has a slight dip discordance with the underlying five-metre shale, the simulation gives quite different results which are less well-constrained (Fig. 8b). Migration is northwards, then northeastwards, until, with 7.4 Mm^3 injected, the CO_2 front moves out of the area of 3D seismic data coverage. Data limitations to the east of the injection point preclude quantitative estimates of migration distributions with CO_2 volumes greater than this. Observations from the 2001 seismic data (Fig. 8b) support the migration simulation, showing the general northward transport with recent alignment along a north-trending linear channel (see below).

In the medium term, the bulk transport direction of CO_2 depends on how much CO_2 is trapped long-term beneath the 5 m thick shale compared with how much is trapped beneath the top of the Utsira Sand. As yet this is uncertain. The time-lapse seismic data indicate that the five-metre shale was breached by CO_2 as early as 1999. Nevertheless the CO_2 layer beneath it had grown considerably by 2001, and may well continue to do so during the injection phase. On cessation of injection, however, it is expected that most of the CO_2 will drain to the top of the Utsira Sand, with lateral migration beneath intra-reservoir barriers becoming less important with time.

In addition to horizontal permeability barriers, represented by the intra-reservoir shales, there is strong evidence that more subtle features are also influential on a finer scale. A NW-trending lineation seen cutting an individual CO_2 layer in 1999 (Fig. 6b) presumably represents a steeply dipping permeability barrier, possibly a small fault. Rapid advance of the CO_2 front along a linear north-trending ridgelike feature seen at the top of the CO_2 plume in 2001 (Fig. 6c) suggests a highly permeable zone, related to structure or perhaps channeling at the top of the Utsira Sand.

It is clear that local permeability heterogeneities, both stratigraphical and structural, can profoundly affect CO_2 distribution and migration within the reservoir. It is perhaps salutary to reflect that most of these features were difficult or impossible to detect on the seismic data prior to CO_2 injection; they only became apparent after being effectively 'illuminated' by the CO_2 stream. The repeat seismic surveys were designed specifically to match the characteristics of the pre-injection data, which was optimized to image deeper production targets. In an ideal situation both pre and post-injection surveys would be tuned to maximize resolution at the injection depth. This would improve understanding of plume development, and reservoir structure, but even so, it is likely that very subtle reservoir features would still remain undetected prior to injection.

The presence of thin, laterally extensive shales within the Utsira Sand, with some sand-on-sand contacts locally, supports a model of the deposition of successive turbiditic sand and thin shale units which locally erode into earlier units, locally producing sand-on-sand contacts which provide potential upward migration pathways for CO_2.

6. Conclusions

Aquifers with low structural relief provide unique problems for the storage of CO_2, specifically because of their lack of a well-defined closure. Reservoir characterization on the regional scale has reasonably straightforward data and interpretive requirements. Two-dimensional seismic coverage and well log data provide an adequate basis for regional structural and physical property mapping which is suitable for strategic planning purposes. For specific site characterization, however, 3D seismic coverage augmented by downhole samples, forms a minimum pre-requisite. Even with very detailed data, however, fine-scale reservoir heterogeneities, capable of seriously affecting CO_2 migration, in the case of Sleipner and perhaps therefore elsewhere, only became evident when illuminated by time-lapse seismic imaging of the CO_2 plume. It is desirable to be able to anticipate and predict these effects, and for this, additional studies such as the development of reservoir depositional models may be helpful. This type of study, and also the necessity for a full caprock sealing evaluation, render core material, from both reservoir and caprock, a desirable pre-requisite.

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