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GEOLOGICAL CHARACTERISATION OF CO_2 STORAGE SITES: LESSONS FROM 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 however 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.

INTRODUCTION

Since 1996 the world's first industrial scale CO_2 storage operation has been in operation at the Sleipner field in the North Sea. CO_2 is being injected into the Utsira Sand, a major, regional saline aquifer. At the time of writing more than 4 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 characterisation of the Utsira reservoir and its caprock. This paper describes some of the results of the investigations and draws out some generic aspects of geological reservoir characterisation which are particularly applicable to CO_2 injection into flat-lying aquifers of regional extent.

PROPERTIES OF THE UTSIRA SAND RESERVOIR

Regional structure

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 (Fig. 1). Its eastern and western limits are defined by stratigraphical lap-out, to the southwest it passes laterally into shaly sediments, and to the north it occupies a narrow, deepening channel.

The top Utsira Sand surface (Fig. 1a) generally varies quite smoothly in the depth range 550 to 1500 m, and is around 800 – 900 m near Sleipner. Isopachs of the reservoir sand define two main depocentres (Fig. 1b), one in the south, around Sleipner, where thicknesses range up to more than 300 m, and another some 200 km to the north.

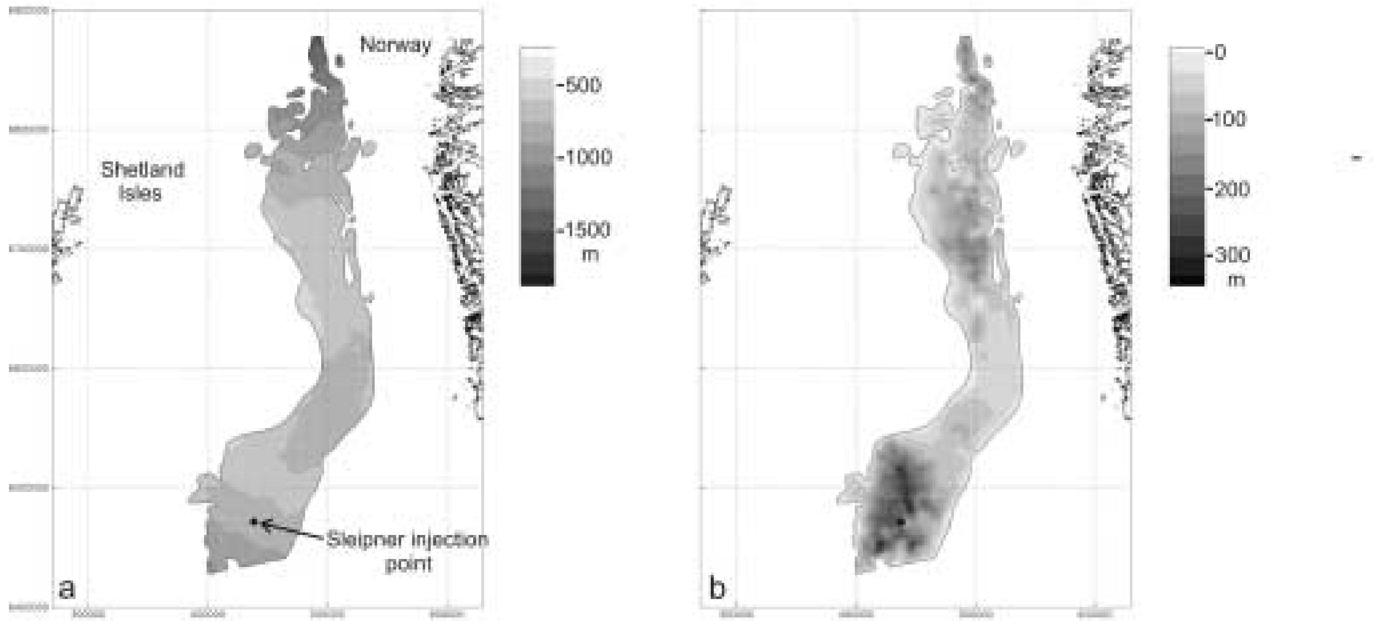

Figure 1: Maps of the Utsira Sand a) depth to top reservoir b) reservoir thickness (isopach)

The regional reservoir maps were constructed from about 16000 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 flat-lying aquifers, the much higher spatial resolution provided by 3D seismic data is required to plan specific injection scenarios (see below).

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 which rises about 12 m above the surrounding area (Fig. 2a).

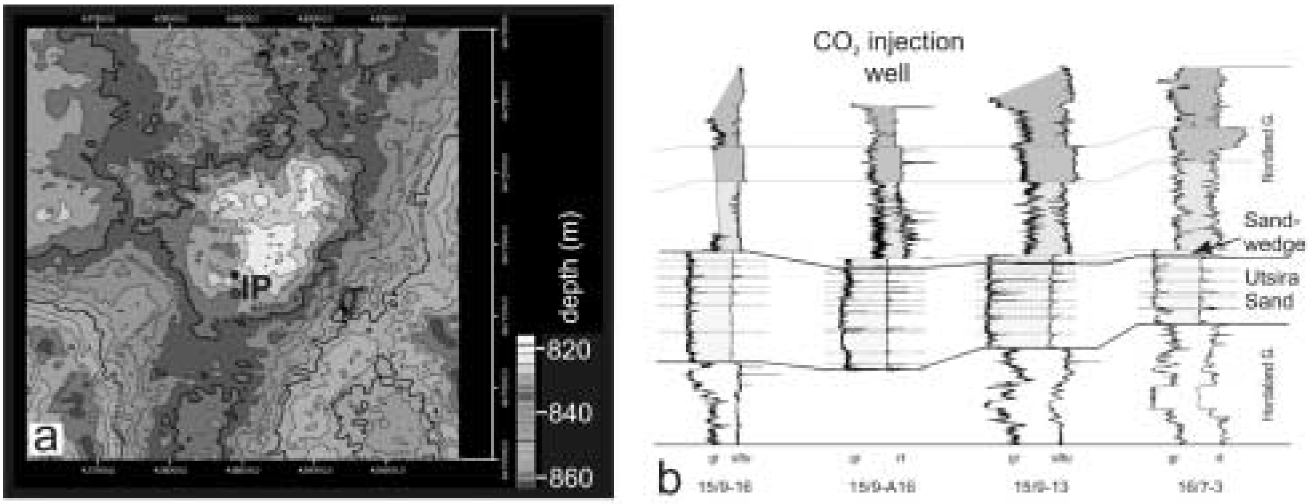

Figure 2: a) Depth to top Utsira Sand around the injection point b) Geophysical log correlation panel from Sleipner wells. Note Sand-wedge above main Utsira Sand and intra-reservoir shales.

On geophysical logs the Utsira Sand characteristically shows a sharp top and base (Fig. 2b). The logs show a number of peaks on the gamma-ray, sonic and neutron density logs, and also on some induction and resistivity logs. These are interpreted as mostly marking thin (~1m thick) layers of shale or clay which constitute important permeability barriers within the reservoir sand.

The base of the Utsira Sand is structurally more complex, and is characterised by the presence of numerous mounds, interpreted as mud diapirs (e.g. Fig. 3a). These are commonly about 100 m high and are mapped as isolated, circular domes typically 1 – 2 km in diameter, or irregular, elongate bodies with varying orientations, up to 10 km long. The mud diapirism is associated with local, predominantly reverse, faulting which cuts the base of the Utsira Sand, but does not appear to affect the Utsira Sand itself or its caprock.

Around and east of the injection point, a unit termed the Sand-wedge lies just above the top of the Utsira Sand, separated from it by a few metres of shale (Fig. 2b).

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).

Physical properties

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

PROPERTIES OF THE UTSIRA CAPROCKS

The caprock succession overlying the Utsira reservoir is several hundred metres thick, and can be divided into three. The lowest part, also known as the ‘Shale Drape’, forms a shaly basin-restricted unit [2]. Above this, a thick Pliocene succession mostly comprises prograding units, dominantly shaly in the basin centre, but coarsening into a sandier facies both upwards and towards the basin margins.The uppermost unit is of Quaternary age, mostly glacio-marine clays and glacial tills.

The ‘Shale Drape’ extends well beyond the area currently occupied by the CO_2 injected at Sleipner and forms the primary sealing unit. Cuttings samples comprise dominantly grey clay silts or silty clays, mostly massive, although some show a weak sedimentary lamination. XRD-determined quartz contents suggest displacement pore throat diameters in the range 14 to 40 nm, which predict capillary entry pressures of between about 2 and 5.5 MPa [3], capable of trapping a CO_2 column several hundred metres high. The predominant clay fabric with limited grain support resembles the type ‘A’ or type ‘B’ seals [4], stated to be capable of supporting a column of 35° API oil greater than 150 m in height. Empirically, therefore, the caprock samples indicate 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.

The seismic, geophysical log and cuttings data enable many caprock properties to be characterised 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 has recently been acquired at Sleipner and core analysis is ongoing.

EFFECTIVE STORAGE CAPACITY

Assessment of the total reservoir storage potential is desirable, so that a long-term strategic injection strategy can be devised. The total pore volume of the Utsira Sand, based on the isopach map (Figure 1b) and regional assessments of porosity and shale volume, is about 6 x 10^{11} m^3.

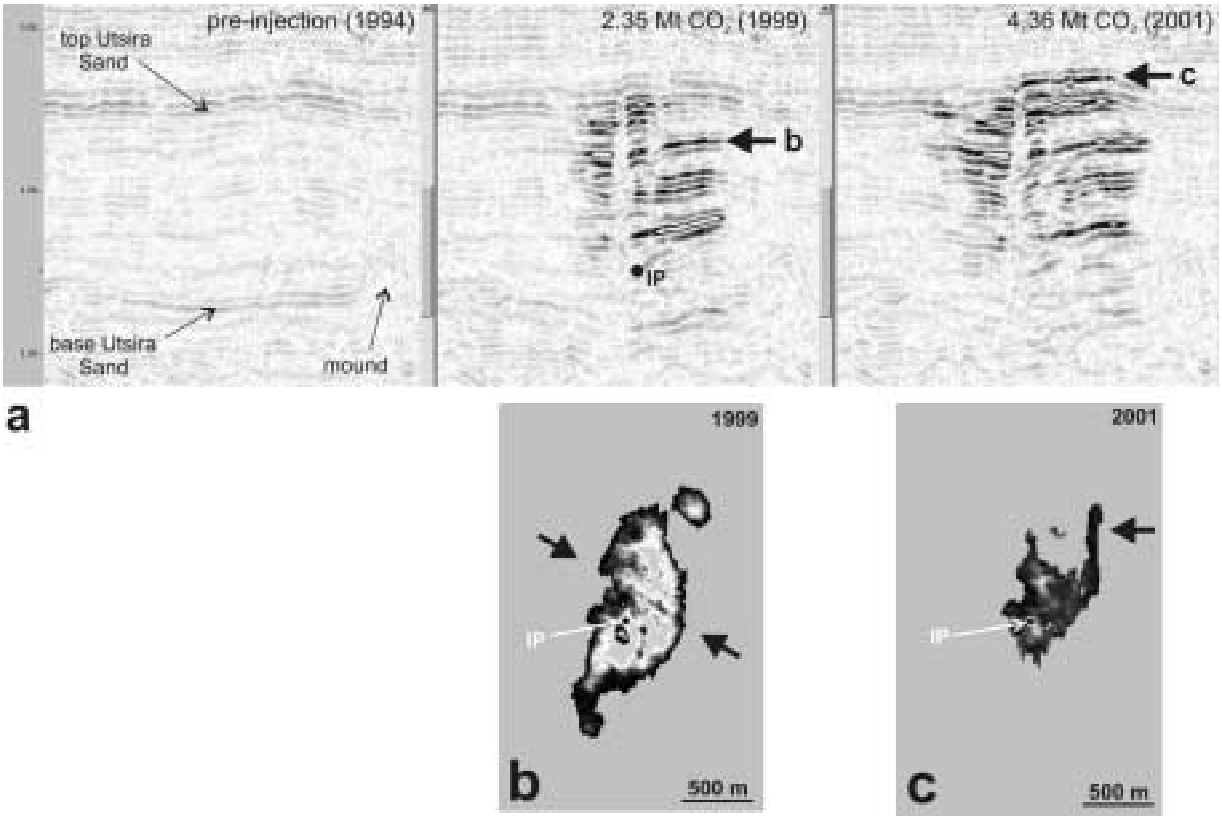

Figure 3: a) Time-lapse seismic images showing changes in reflectivity due to injected CO_2. Arrows indicate CO_2 acccumulations mapped in Figs. b and c. b) Map of reflection strength on a CO_2 layer in 1999. Possible NW-trending permeability barrier arrowed. c) Map of reflection strength on top CO_2 layer in 2001. Linear migration along possible N-trending channel arrowed.

For a relatively flat-lying reservoir such as the Utsira Sand, the total pore volume of the reservoir cannot necessarily be utilised. A simple, perhaps more realistic measure of effective storage is the pore volume enclosed within structural and stratigraphical traps, where CO_2 can be expected to accumulate in the long-term. The 3D mapping around Sleipner indicates that only 0.3% of the available porosity is actually situated within structural closures. 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. Extrapolating these figures over the entire Utsira Sand gives a storage volume in traps of just 6.6 x 10^8 m^3.

On the other hand, trapping of CO_2 beneath intra-reservoir shale beds can significantly increase realisable storage volumes. The time-lapse seismic data (Fig. 3) 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 modelling shows that 2.1 Mt of CO_2 trapped wholly at the top of the reservoir would ultimately migrate more than 4 km from the injection point. This compares with the observed 1999 CO_2 plume (2.35 Mt) whose areal extent or 'footprint', was entirely within 1 km of the injection point (Fig. 4a). By 2001, 4.36 Mt of CO_2 were still confined to within 1.3 km of the injection point, whereas 4.2 Mt trapped wholly at the top Utsira would be expected to reach an ultimate distance of about 9 km (Fig. 4b). 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 adjacent 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 reactions leading to chemical 'fixing' [5].

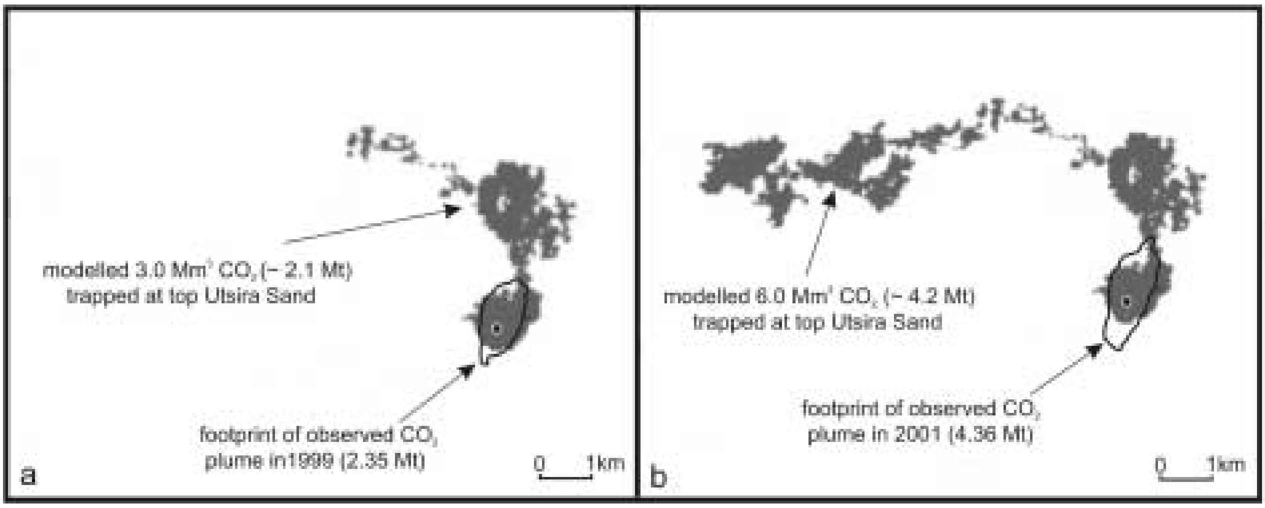

Figure 4: Modelled and observed distributions of CO_2 a) 1999 b) 2001

Trapping of CO_2 in the Sand-wedge, as well as beneath the top of the Utsira Sand, will also increase the overall storage capacity significantly. It is clear therefore that the assessment of effective storage capacity in an aquifer requires detailed treatment of reservoir structure and stratigraphy.

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 to the expected final injected mass of 20 Mt). Assuming migration at the top of the Utsira Sand, the preferred model (Fig. 5a) shows migration generally in a westerly direction, to reach a maximum distance from the injection site of about 12 km. Because the top Utsira 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 emphasises the need for precision in the depth conversion.

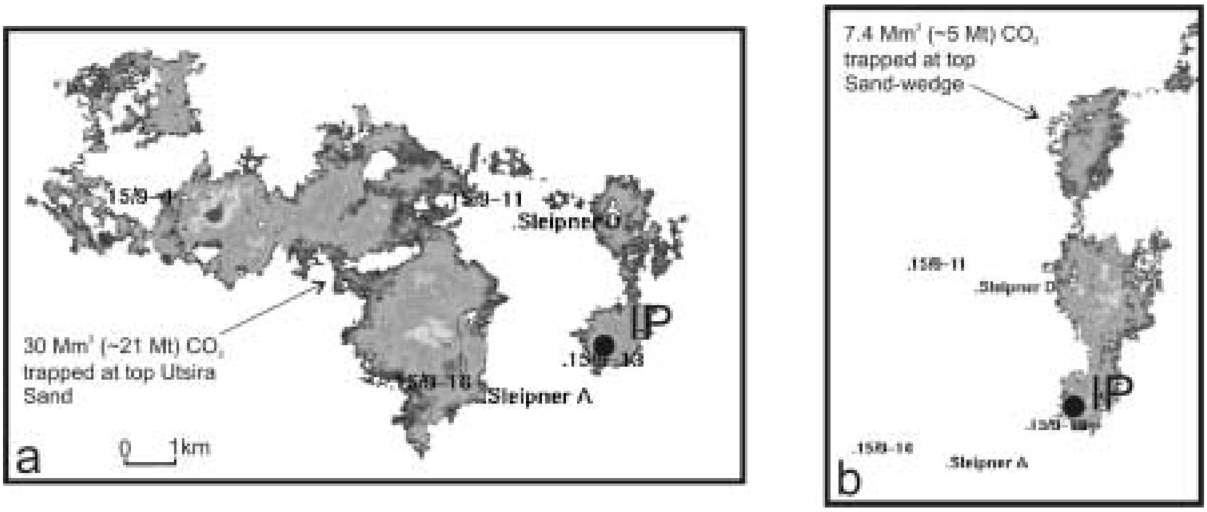

Figure 5: Modelled distributions of CO_2 migration a) at top Utsira Sand b) at top Sand-wedge

An alternative scenario, that the CO_2 leaks into, and migrates along the top of the Sand-wedge, gives less well-constrained results (Fig. 5b). 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.

As discussed above, partitioning of CO_2 between the top Utsira Sand and top Sand-wedge will decrease migration distances in both cases, essentially confining the CO_2 more closely to the injection point.

Horizontal permeability barriers, represented by the intra-reservoir shales, clearly affect CO_2 distribution in the reservoir (Fig. 3a), but 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. 3b) presumably represents a steeply-dipping permeability barrier, possibly a small fault. Rapid advance of the CO_2 front along a linear north-trending feature seen at the top of the CO_2 plume in 2001 (Fig. 3c), suggests a highly permeable zone, perhaps related to channeling at the top of the Sand-wedge.

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.

CONCLUSIONS

Flat-lying aquifers provide unique problems to CO_2 sequestration operations, specifically because of their lack of a well-defined closure. Reservoir characterisation on the regional scale has reasonably straightforward data and interpretive requirements. 2D 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 characterisation 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, only become 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.

REFERENCES

1. Gregersen, U., Michelsen, O. and Sorensen, J.C. (1997). Marine and Petroleum Geology **14**, 893.
2. Chadwick, R.A, Holloway, S., Kirby, G.A., Gregersen, U. and Johannessen, P.N. (2001). In: *Greenhouse Gas Control Technologies. Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies*, pp. 349 – 354, Williams, D., Durie, I., Mcmullan, P., Paulson, C. and Smith, A. (Eds). CSIRO Publishing, Collingwood, Australia.
3. Krushin, J T. (1997). In: *Seals, Traps, and the Petroleum System,* pp. 31 – 47, Surdam, R C. (Ed). AAPG Memoir **67**.
4. Sneider, R.M., Sneider, J.S., Bolger, G.W. and Neasham, J.W. (1997). In: *Seals, Traps, and the Petroleum System,* pp. 1 –12, Surdam, R C. (Ed). AAPG Memoir **67**.
5. Johnson, J.W., Nitao, J.J., Steefel, C.I., and Knauss, K.G. (2001). In: *Proceedings of the First National Conference on Carbon Sequestration, Washington, DC, May 14-17,* 60 p., UCRL-JC-146932.

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