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Storage of CO_2 in saline aquifers – lessons learned from 10 years of injection into the Utsira Formation in the Sleipner area.

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Abstract

The ongoing CO_2 injection at Sleipner has demonstrated that 2/3 of the injected CO_2 has not reached the top of the Utsira Formation, but has instead migrated laterally below imperfect intra-reservoir seals. The CO_2 trapping below the structural spill point in the Utsira Formation is due to local mini traps, capillary flow resistance, and the hydrodynamic drive of the injection. About 40 % of the CO_2 that has entered the pore systems will remain as residually trapped CO_2, whereas an unknown fraction of the remaining CO_2 will migrate towards the top of the reservoir.

Keywords: CO_2 storage; Saline aquifers; Sleipner; Utsira Formation; Capillary trapping.

1. Introduction

Trapping of CO_2 in the subsurface can take place by a number of different mechanisms. These mechanisms are conveniently divided into four classes; structural and stratigraphic trapping, residual trapping, dissolution trapping, and mineral trapping. The relative importance of these mechanisms varies with time (Fig. 1).

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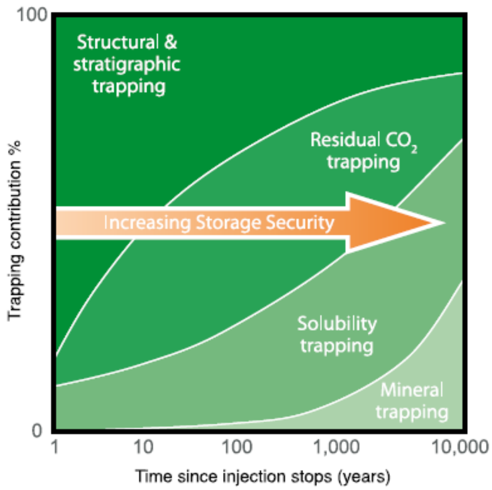

Figure 1 Various mechanisms for trapping of CO_2. From [1].

Structural and stratigraphic trapping refers to trapping beneath a seal, and requires the presence of a structural or stratigraphic trap of the same type as those that result in the presence of mobile hydrocarbon accumulations. Hydrodynamic trapping is sometimes included in this class. The term hydrodynamic trapping is used to describe CO_2 that moves in the subsurface, typically as CO_2 finds its way from an injector to a trap. Residual trapping, on the other hand, refers to the CO_2 that remains in a porous rock after it has been flushed with CO_2. These two trapping classes must predate the next two, which describe gradual transitions to even more stable trapping forms (CO_2 dissolved in water or as a constituent of newly formed rock minerals).

The pore volume in structural and stratigraphic traps is routinely determined in oil and gas companies. The procedures for such determinations are well known, although the estimates are inaccurate, largely because of inaccurate knowledge of the subsurface geology.

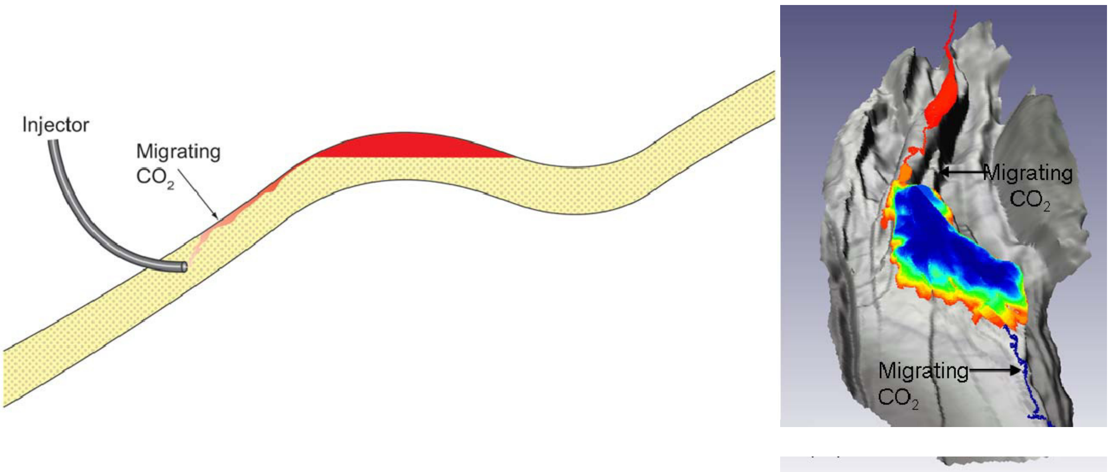

Figure 2 (a) Cross-section and (b) map view of CO_2 that migrates and saturates parts of a rock volume.

The methods for estimates of residual trapping are less well constrained. Such trapping depends on two factors, the irreducible CO_2 saturation in the subsurface, and the pore volume that comes in contact with moving CO_2 (Fig. 2). The volume of residually trapped CO_2 thus depends on the number and distribution of injection wells. Estimation of the volume of water that comes in contact with CO_2 includes significant uncertainties, as it requires accurate knowledge of the width and thickness of the flow path that the CO_2 follows from the injector towards its final destination. Both of these depend on the injection velocity and the capillary entry pressures P_{ce} of the reservoir rock,

$$P_{ce} = 2\gamma / r \qquad (1)$$

where γ is the CO_2-water interfacial tension and r is the radii of pores in the caprock.

An important trapping mechanism that is not explicitly covered by the above mentioned terminology is capillary trapping. This term refers to the case where the buoyancy of the CO_2 is not large enough to overcome the capillary entry pressure of the pore throats, and therefore does not enter into the neighbouring pore (Fig. 3). CO_2 can be stored below or outside structural and stratigraphic closures at high saturations by such trapping.

Fig. 4 shows how a fluid that is injected below a horizontal surface stays or vanishes after injection depending on whether capillary trapping takes place or not. Capillary trapping of a fluid requires that the fluid is not in the wetting phase. The column height that can be trapped by this mechanism is given by

$$h = 2\gamma \cos\theta / rg(\rho_w - \rho_{CO2}) \qquad (2)$$

Here, h is the height of the CO_2 column, θ is the wettability of the reservoir expressed by the contact angle of CO_2 and water against the solid, g is the acceleration of gravity, ρ_w is the density of formation water, and ρ_{CO2} is the density of CO_2. It is presently not clear under what conditions prolonged contact with CO_2 can reduce the CO_2-water interfacial tension, and thereby lead to a reduced capillary storage capacity of CO_2.

About 1 Mt CO_2 has been injected annually into the Utsira Formation above the North Sea Sleipner Field since 1996. Time-lapse seismic data reveals how the CO_2 has moved in the subsurface after injection. The purpose of this paper is to use these data to highlight the importance of capillary trapping of CO_2, and the implications for such trapping on the storage potential of CO_2 in saline aquifers.

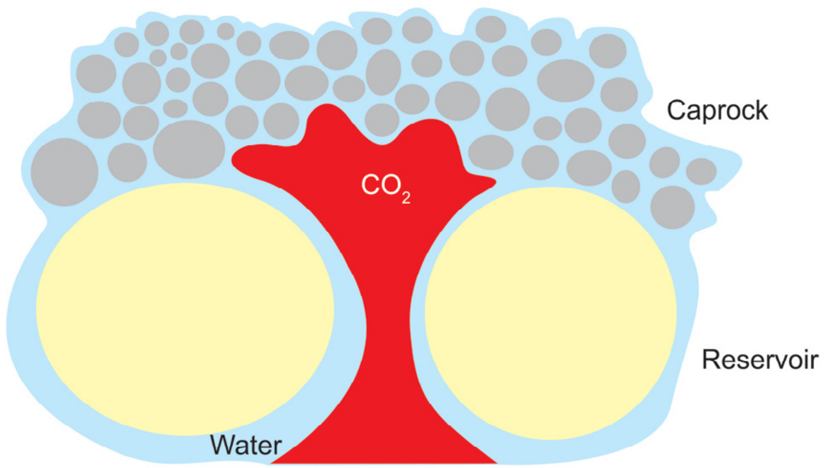

Figure 3 Capillary trapping at pore scale. Breakthrough occurs when the buoyancy results in radius r in the CO_2 stringer that is small enough to allow the CO_2 to invade the caprock pores.

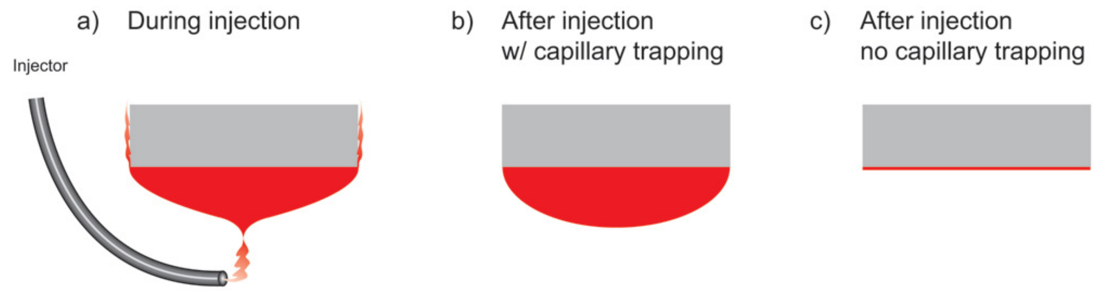

Figure 4 Capillary trapping. (a) CO_2 injection below an impermeable seal. (b) CO_2 distribution after injection with capillary trapping. (c) CO_2 distribution after injection, no capillary trapping. The seal is in grey and the CO_2 is in red.

Figure 5 (a) Location of the Utsira Formation in the North Sea. Colours refer to formation thickness (meters). (b) A west-east cross section of the Sleipner area. This is marked by a black line in (a). Courtesy of Schlumberger.

2. CO_2 distribution and flow paths in the Utsira Formation

The Sleipner fields are situated in the Norwegian North Sea. They produce gas with a high CO_2 content from Jurassic and Tertiary reservoirs. The CO_2 is separated from the hydrocarbons at the Sleipner T platform, and is reinjected into the Utsira Formation of Miocene age. This formation consists of up to almost 300 m thick sandstones with 90 – 98 % sand content, average porosity of 35 – 40 %, net/gross ratio of 0.90 – 0.97 [2], and permeabilities in the 1-8 D range. The formation is a lower shoreface deposit, which was heavily influenced by longshore currents after deposition [3]. Several intraformational shale layers can be identified from well logs in the Utsira Formation. These layers have limited lateral extents and can hardly be correlated between wells. The exception to this is the uppermost 5-6.5 m thick shale layer that separates the uppermost sandy unit from the rest of the Utsira Formation. The CO_2 has migrated into nine discrete layers, numbered from the base (layer 1) to the top (layer 9). The CO_2 in the uppermost sand layer is expected to spill to the north and then to the northeast, whereas the CO_2 in the sand layer below the 5-6.5 m thick shale is expected to spill to the north and then to the northwest.

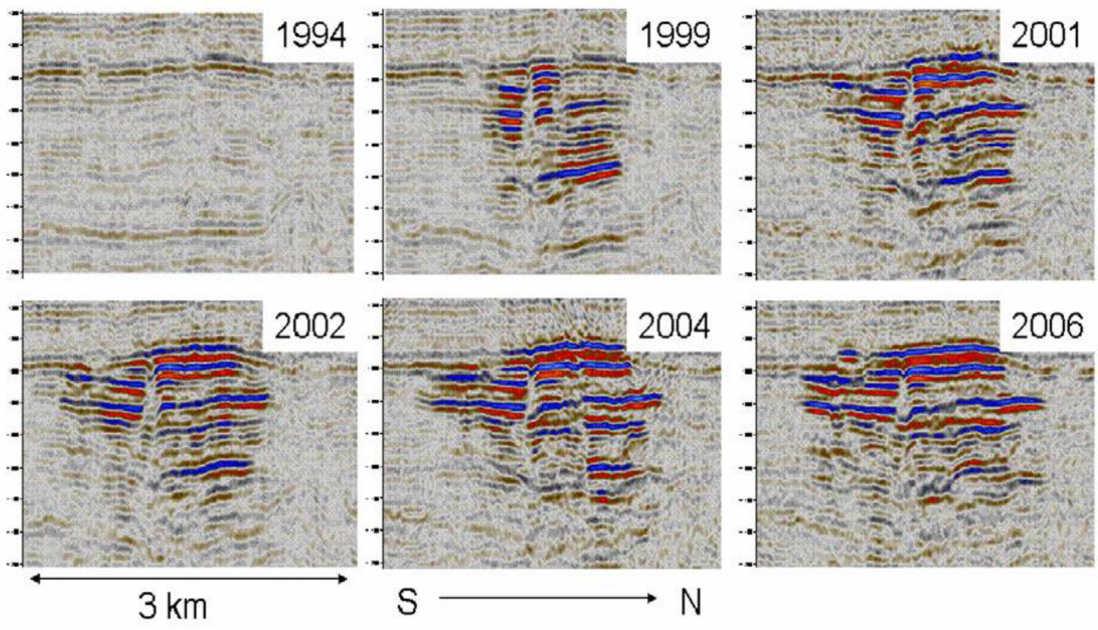

Figure 6 Time lapse seismic data in the Utsira Formation. The bright amplitudes reveal the presence of injected CO_2.

The Sleipner CO_2 injection started in 1996. The first repeat seismic survey (1999) revealed that migrating CO_2 had spread to nine distinct layers – one of these lying above the 5-6.5 m thick shale. The migrating CO_2 appears mainly to have been fed to the different layers from a central vertical feeder, which is expressed as a seismic chimney in the seismic data (Fig. 6) and as a circular feature on the seismic amplitude maps (Fig. 7). This chimney suggests that the continuity of the intraformational shale layers has been broken at the same location in these shale layers. We postulate that the zone of broken shale continuity forms the vertical flow path that the CO_2 has followed on its way to the top of the Utsira Formation. Such a vertical stack of high permeability zones hardly existed by chance prior to injection, just above where the well perforations were later positioned. We find it more likely that it was created by the injection process, possibly because of mechanical instabilities (liquefaction and fluidization) as a response to concentrated vertical CO_2 flow, and probably amplified by local carbonate dissolution and matrix collapse along the flow path.

An injection-made vertical flow path would probably be self-enforcing and locally further increase the vertical permeability and flow velocity. This suggestion is consistent with the observation that the fraction of CO_2 contained in the uppermost two layers increases with time, from about 7 % in 1999 to ca. 33 % in 2006.

The two top layers that could be mapped prior to injection form a gentle structural closure. The topography of the intraformational shales, and thus the deeper CO_2-saturated sandstones, is more uncertain. These layers could not be mapped prior to the injection, and the imaging (in the time domain) of these layers after injection is influenced by the reduced seismic velocities in the gas-saturated layers. These velocity reductions result in a pull-down, and give the false visual expression of a depression close to the injector where the CO_2 concentration is largest.

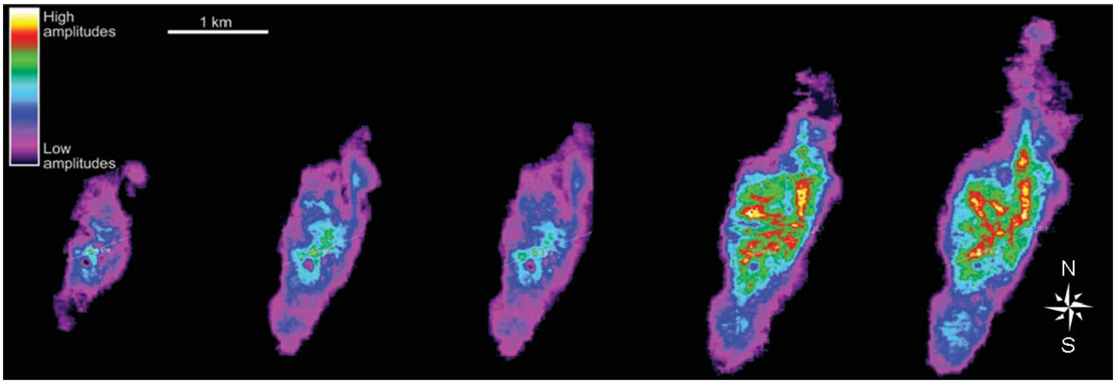

Figure 7 Accumulated total reflection amplitude from all nine layers of the Sleipner CO_2 plume.

The lateral flow of CO_2 into the various layers implies a lateral pressure gradient. As a result, the gas water contact will not be flat during the injection, but instead be deeper close to the vertical feeder [4]. The thickness of the CO_2 column at various locations below the intraformational shales can be constrained from the amplitude variations of the seismic data [5] [6]. Such a conversion of amplitudes to layer thicknesses is the basis for the visualization of the nine layers in Fig. 8. Note that the amplitudes will also be influenced by reflection of seismic energy from shallower layers, and that the reduced seismic reflectivity of the deeper layers close to the feeder (automatically interpreted as reduced layer thicknesses close to the injector in layers 1-3 of Fig. 8) may be due to this effect. As a result, the layer thickness may have been underestimated close to the injector for these layers.

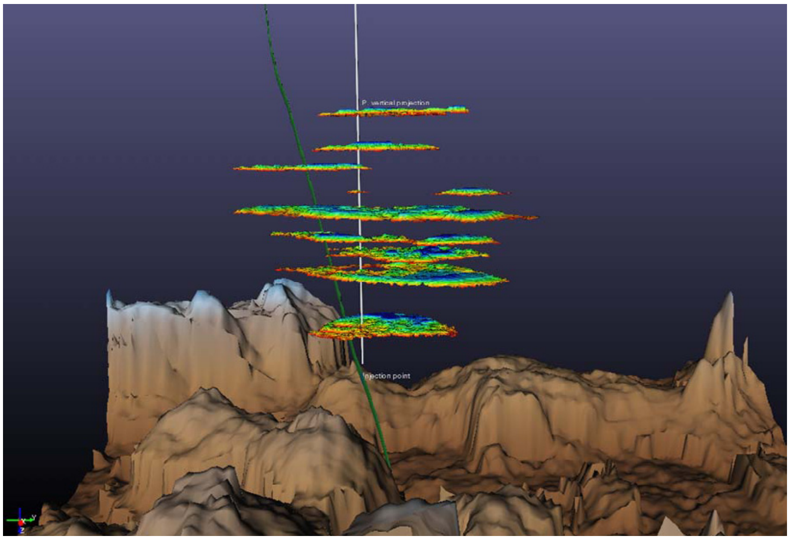

Figure 8 Distribution of bright amplitudes, converted to CO_2 column heights, in the nine CO_2-saturated layers of the Utsira Formation. A flat CO_2-water contact was applied for the construction of this figure. Courtesy of Permedia Inc.

3. Trapping mechanisms

Because the actual shape of the intraformational shales is not accurately known, the mechanisms that provide trapping of the CO_2 in the deeper layers remain elusive. Trapping of CO_2 in these layers is influenced by the topography of the shale layers, the permeability distribution within each sand layer, and the shape of the CO_2-water contact.

The shapes of the shale layers were determined by the shapes of the underlying sands. Each sand layer was deposited with slightly irregular top surfaces, where the top of each sand layer would be offset relative to the top of the underlying layers. As a result, the top surface of each individual sand layer would differ slightly, and result in different drainage directions for injected CO_2. These directions could later have been modified by folding, which would results in common drainage patterns for all the sand layers. Such folding can not be resolved from the data at the location where CO_2 is being injected.

The area of most of the CO_2 bodies increases with time. Yet, the lateral termination of each body at any instant of time is characterized by a gradual amplitude reduction. This reduction could be an effect of the seismic imaging, or it could reflect a rising CO_2-water contact close to the termination of the layers. The amplitude reductions do not necessarily reflect the lateral termination of small structural traps within each layer (which, of course, would not change position with time). The possible sloping contacts could reflect the increased resistance for CO_2 to enter into new pores during migration as shown schematically in Fig. 4. Such resistance will partly result because the capillary entry pressure of the un-invaded pores must be overcome by the buoyancy, and partly that the relative permeability is low when few pores have been invaded by CO_2.

Migration into these individual CO_2 layers with a sloping CO_2-water contact close to the central feeder persists as long as the injection is ongoing [4]. When the injection stops some time in the future, the enlarged CO_2-water column close to the feeder will vanish, and the excess CO_2 will move towards the uppermost layers. Whether the equilibrium gas-water contact will (a) be determined by the structural closure of the traps or (b) be deeper than the structural spill points of each individual layer due to capillary trapping, remains to be seen. A residual CO_2-saturation of about 40 % (used as a general value by Juanes et al. [7]) will remain in the rocks that are presently filled with CO_2 but which will be drained when the injection ceases.

Currently, about 10 M tons CO_2 have been injected into the Utsira Formation. 2/3 of this CO_2 is presently trapped in layers 1-7. By assuming an irreducible water saturation of 10 %, we conclude that almost half of these quantities will remain at their present location as residually trapped CO_2. The rest, which is about 1/3 of the totally injected CO_2 volume, will either stay where it is or (partly) migrate to the top layers (thus creating a need for additional storage space), depending on the extent of capillary trapping. Migration from layer 8 to layer 9 would further enhance the need for storage capacity in this uppermost layer. This is however not perceived as a problem, as the Sleipner CO_2 injection site has a large enough structural closure to cap the CO_2 that will be injected from the Sleipner CO_2 gas separation.

The CO_2 injection at Sleipner has given important insight into the consequences of residual and capillary trapping for CO_2 storage. Such information is also important for accurate assessments of the storage potential in saline aquifers outside of or deeper than the structural closure elsewhere.

4. Conclusions

About 1/3 of the injected CO_2 in the Utsira Formation is presently stored within structural closure and above the structural spill point for the uppermost two layers. The remaining 2/3 are stored deeper than the structural spill point of these layers. This fraction will diminish as injection proceeds, and will also diminish after the injection has ceased. We suggest that about 1/3 of the presently injected volumes will remain below the structural spill points of layers 8 and 9 also after injection has ceased. The fate of the remaining 1/3 is unclear: parts of this CO_2 will remain where it is due to capillary trapping, and parts of it will move towards shallower positions.

Acknowledgements

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