CO_2 storage: setting a simple bound on potential leakage through thick offshore overburden successions

Andy Chadwick[1] Gareth Williams[1] David Noy[1]

[1]British Geological Survey

Abstract

Large-scale CO_2 storage opportunities are situated in very thick ‘post-rift’ sedimentary sequences developed on passive continental margins such as the NW European shelf, Gulf of Mexico, offshore Brazil etc. In these settings most storage site overburdens lie within ‘post-rift’ sedimentary successions where faults are rare and so-called ‘gas chimneys’ or ‘pipes’ are likely to provide the main risk for breaching geological seals. Seismic reflection data provide the main evidence for such features which are characteristically imaged as narrow sub-vertical zones of disrupted reflections (Fig. 1).

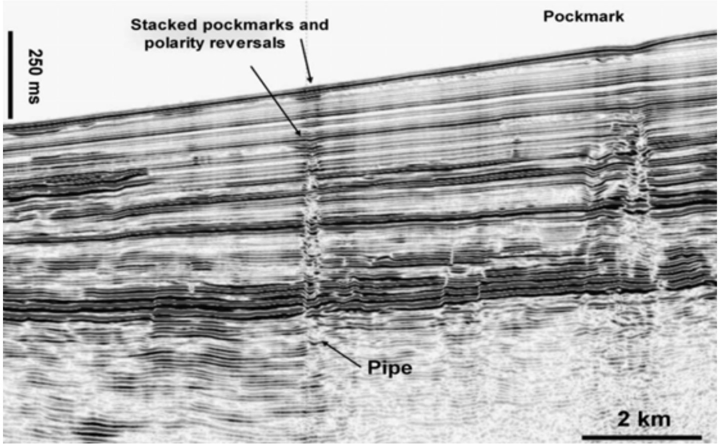

Figure 1 Small chimneys (pipes) imaged on a seismic profile

Chimneys formed conduits for gas or fluid migration at some point in their history, but their internal structure and fluid flow properties are very poorly-understood. This paper aims to set some bounds on CO_2 migration in chimneys in argillaceous lithologies by establishing simple boundary conditions. In our conceptual chimney model (Fig. 2), bulk permeability is controlled by two aspects: permeability of any fracture networks (controlled by the effective stress) and capillary flow effects (controlled by the resident fluid phases).

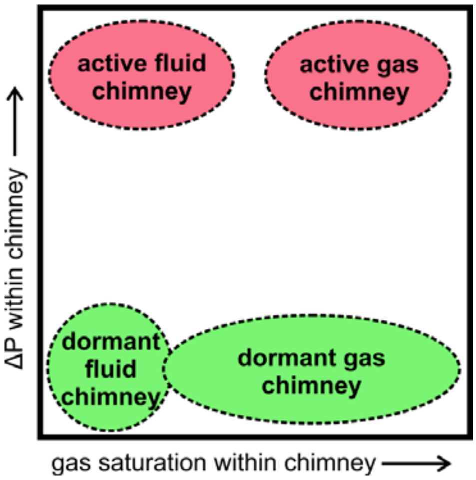

Figure 2 Conceptual model for chimneys in argillaceous strata

Active chimneys are assumed to have elevated pore-pressures, with fracture networks in a state of incipient shear or dilation and high effective permeabilities. Dormant chimneys have pore-pressures close to hydrostatic with fracture networks essentially closed and much lower effective permeabilities. Gas chimneys contain predominantly natural gas and fluid chimneys contain predominantly brine. Any residual gas will lower the capillary entry pressure to CO_2.

We use a scenario based on Sleipner where chimneys are believed to be dormant and relevant physical properties have been measured. 1-D TOUGH2 modelling of the dormant gas chimney scenario is used to explore the rates and mechanisms by which CO_2 migration might take place. We include relative permeability effects and set the capillary entry pressure to zero which for estimating unwanted CO_2 migration is conservative.

When CO_2 ponds beneath a sealing layer its buoyancy plus any reservoir overpressure provides the driving force for upward migration. We explore two 'end-member' pressure scenarios: one where pressure in the reservoir is assumed to be close to hydrostatic and one where it is just below the fracture limit. The former (Fig. 3) corresponds to the current Sleipner case where overpressure is very low, more-or-less limited to buoyancy forces at the plume top.

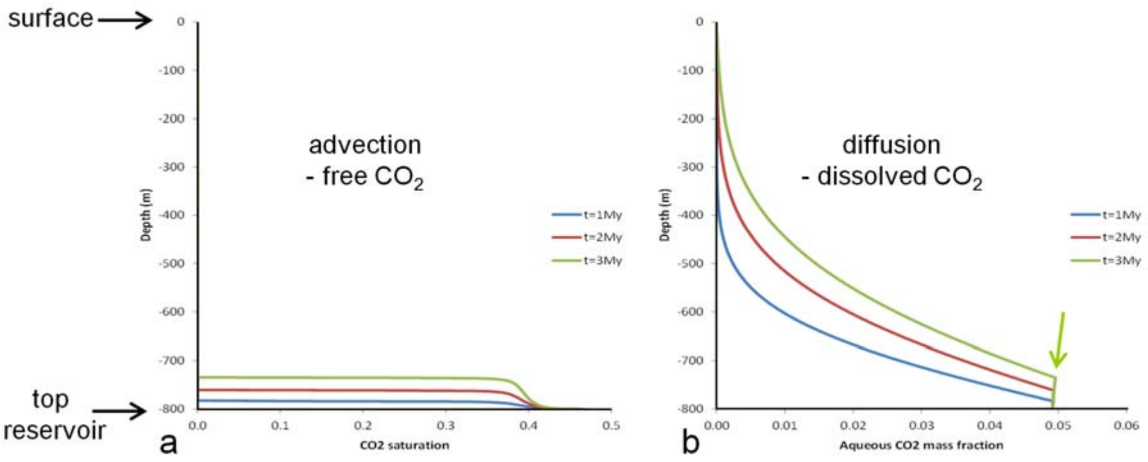

Figure 3 Near-hydrostatic pressure scenario. 1-D TOUGH2 flow simulation of a 'dormant gas chimney', situated on top of a CO_2 plume at 800 m depth showing upward migration of buoyant free CO_2 and CO_2 diffusing in the aqueous phase. Arrow indicates dissolved CO_2 in fully saturated pore-water behind the advancing free CO_2 front.

With the very low overpressure, advection into the low permeability seal is extremely slow. The free CO_2 front advances just 64 m into the overburden in 3 million years (My), with an average migration velocity of ~0.02 m per thousand years. Taking the spatial footprint of a typical small CO_2 chimney at Sleipner as 20000 m^2 this gives a total amount of advected free CO_2 in the overburden of ~107500 tonnes after 3 My, corresponding to an average flux of ~ 35 tonnes per 1000 years. Upward migration of CO_2 in the aqueous phase, driven by diffusion, is quicker than via advective migration, but because concentrations in the aqueous phase are quite small (reducing to zero at the leading edge) total dissolved CO_2 in the overburden is ~70500 tonnes after 3 My. This corresponds to a diffusive flux into the overburden of < 25 tonnes of dissolved CO_2 per 1000 years. In the high pressure scenario (Fig. 4), CO_2 beneath the topseal is pressurized to just below the fracture limit of the formation (75% of lithostatic). Fractures are assumed to remain passive and bulk permeability is unchanged from the low pressure end-member.

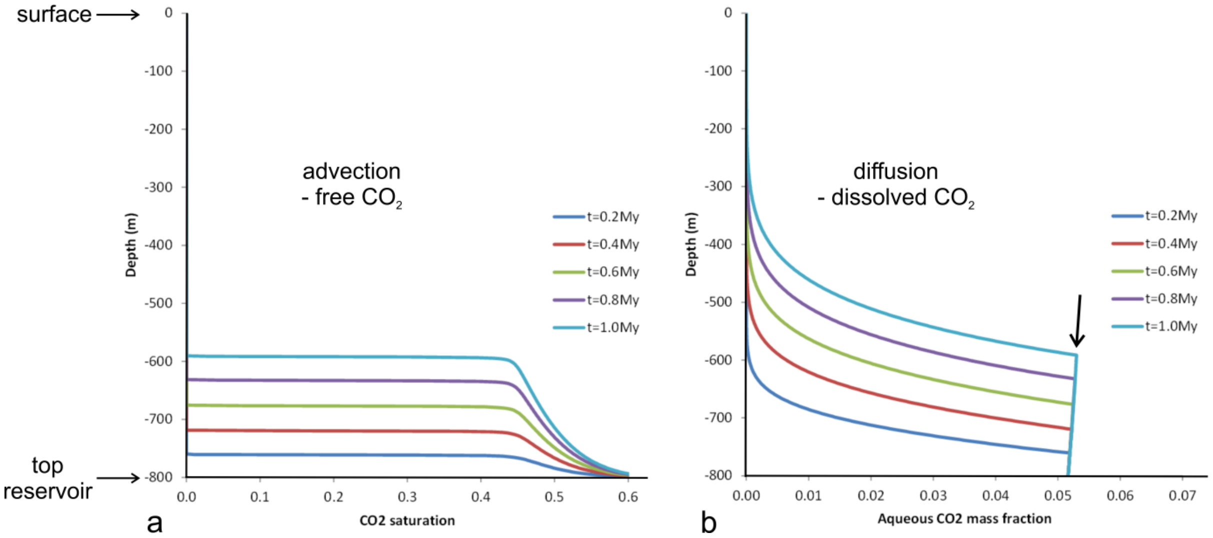

Figure 4 Overpressure scenario. 1-D TOUGH2 flow simulation of a 'dormant gas chimney', situated on top of a CO_2 plume at 800 m depth. The plots showing upward migration of buoyant free CO_2 and CO_2 diffusing in the aqueous phase.

With around 2.8 MPa of injection pressure drive, the leading-edge of the free CO_2 front advances about 210 m into the overburden in 1 million years, with an average migration velocity of ~0.2 m per thousand years. Advective advance into the overburden is therefore around ten times quicker than by buoyancy alone, but still very slow. Taking the spatial footprint of a typical small CO_2 chimney at Sleipner as 20000 m^2 gives a total amount of advected free CO_2 in the overburden of ~441000 tonnes after 1 My, corresponding to an average flux of ~ 440 tonnes per 1000 years. Upward migration of CO_2 in the aqueous phase results in a total dissolved CO_2 in the overburden of ~60500 tonnes after 1 My. This corresponds to a diffusive flux into the overburden of ~60 tonnes of dissolved CO_2 per 1000 years.

It is clear therefore that the dormant gas chimney scenario allows only very slow rates of CO_2 migration into the overburden, even with storage reservoir pressures significantly above hydrostatic. The CO_2 plume at Sleipner lies beneath a number of small chimney features and seismic bright-spots which are indicative of earlier natural gas migration and accumulation in the vicinity. The time-lapse seismic monitoring data show no evidence of detectable CO_2 ingress into these features. Changes in seismic reflectivity and time-shifts beneath the chimneys are within the general time-lapse repeatability error range. They are also comparable with time-lapse changes around a similar natural chimney situated well away from the plume, where no CO_2 could have migrated to.