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The mechanical behaviour of anhydrite and the effect of deformation on permeability development - implications for caprock integrity during geological storage of CO_2

Suzanne Hangx (1,2), Christopher Spiers (1), and Colin Peach (1)

(1) HPT-laboratory, Faculty of Geosciences, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, the Netherlands, (2) now at: Shell International Exploration and Production B.V., Kessler Park 1, 2288 GS Rijswijk, the Netherlands

Depleted oil and gas reservoirs offer one of the most easily and cheaply implemented options for geological storage of CO_2. Most of the stored CO_2 will mainly be present in the supercritical fluid phase and dissolved in the formation fluid, as CO_2 mineralisation reactions are slow and the mineralisation potential of most reservoirs is low. Therefore, long-term top-seal or caprock integrity is pre-requisite for guaranteeing the integrity of depleted reservoir storage systems.

In the long term, caprock integrity may be affected by fluid-rock interaction, i.e. chemical attack. However, as mentioned earlier, such reaction effects are slow and it is unlikely that they alone are significant for typical shale, mudstone or anhydrite caprock compositions and thicknesses. Probably more important is mechanical damage in the form of dilatation, fracturing, shear failure and associated permeability development, which can be caused by caprock deformation and the stress changes accompanying localised reservoir compaction during depletion, or localised heave during CO_2 injection.

One of the most widespread sealing formations topping hydrocarbon reservoirs around the world is anhydrite rock. Anhydrite also forms the caprock at several trial CO_2 injection sites currently under operation (e.g. Teapot Dome, USA; the Weyburn and Zama Fields, Canada; the K12-B field, the Netherlands). Furthermore, in the Netherlands and North Sea for example, many potential storage sites are overlain by the basal anhydrite of the Permian Zechstein evaporate sequence. For these reasons, there is accordingly much interest in quantifying damage development in anhydrite. Recent work by *Hangx et al.* has delineated the stress conditions under which anhydrite rock is mechanically stable, versus the conditions under which dilatant damage and failure occur. However, the magnitude of the permeability change accompanying dilatation and failure of anhydrite under reservoir conditions remains unknown.

We determined the effect of stress and deformation on the failure behaviour and permeability of Zechstein anhydrite under conditions ranging from mechanically stable (intact, non-dilatant), through dilatant conditions, (semi-brittle) failure and into the post-failure stage. To this end, we performed conventional triaxial (i.e. axi-symmetric) compression experiments performed at room temperature, confining pressures of 3.5-25 MPa and strain rates of $\sim 10^{-6}$-10^{-7} s^{-1}. At the same time, we measured the permeability of the material to argon gas, using transient pulse permeametry (P_p = 1-1.2 MPa). We used our results to complement our previous failure and dilatancy envelopes for dry anhydrite with permeability data, as well as providing data on the effect of stress state, notably mean stress, on gouge-filled fault permeability in anhydrite caprock.

Overall, we observed a transition from brittle to semi-brittle behaviour over the experimental range, and peak strength could be described by a Mogi-type failure envelope. Dynamic permeability measurements showed a change from "impermeable" ($< 10^{-21}$ m^2) to permeable as a result of mechanical damage. During deformation, permeability increased by $\geq$ 3-5 orders of magnitude, eventually reaching a constant, post-failure value, which decreased with confining pressure from $\sim 10^{-16}$ m^2 at 3.5-5 MPa to 10^{-19} m^2 at 25 MPa. The onset of measurable permeability was associated with an increase in the rate of dilatation at low pressures (3.5-5 MPa), and with the turning point from compaction to dilatation in the volumetric vs. axial strain curve at higher pressures (10-25 MPa). Sample permeability was largely controlled by the permeability of the shear faults developed. Static, post-

failure permeability decreased with increasing effective mean stress. Simple analytical calculations based on the elastic flexure of a seal formation, combined with our failure and dilatancy envelopes obtained in our studies, show that for realistic conditions caprock integrity will not be compromised by mechanical damage and permeability development.