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Fluid focusing and breaching of low permeability layers in reacting and visco-elasto-plastically deforming reservoir rocks

Nina S. C. Simon
Institute for Energy Technology - IFE, Dep. of Environmental Technology, Kjeller, Norway (nina.simon@ife.no)

The on-going injection of one million tons per year of CO_2 into the Utsira sand at Sleipner is used as an example for a highly successful CO_2 storage operation. Even at Sleipner, however, we observe features that are not straightforward to explain and quantify with exiting models. One such feature is the so- called chimneys that show up in the time laps seismic images. They are zones of disturbed layering that cut nearly vertically through the interbedded thin shale layers in the reservoir sands, not unlink the frequently observed pipe structures due to fluid venting. These chimneys have been ascribed to artefacts in the data or pre-existing fractures or pipes, and these explanations are difficult to rule out. If we take the seismic interpretations at face value, however, then the data suggest that the intensity and extent of the chimneys changes through time. The extent and thickness of the observed plume supports that the injected CO_2 is migrating through focused zones in the shales from the well at the bottom of the reservoir to the top layer immediately below the caprock much faster than predicted by Darcy flow through intact, low permeable shale layers.

We developed a fully coupled numerical model for fluid flow through a reacting and deforming porous rock. Reactions may be upscaled to add a viscous component to the rheology, or be modelled explicitly. In laboratory experiments, viscous compaction has been shown to take place in typical reservoir rocks due to the high reactivity of CO_2-rich brine. Other experimental studies show that unconsolidated sands, such as the Utsira sand, and clay-rich shales follow a visco-plastic flow law rather than behaving as purely poro-elastically. Hence, viisco-elasto-plastic deformation of the porous matrix is taken into account in our model and fluid focusing may occur due to non-linear couplings between porosity and permeability and viscosity. This phenomenon is known as a porosity wave. A non-linear viscous rheology (or viscous compaction in combination with plastic failure in decompaction) lead to the formation of high-porosity channels or jets. The formation of channels (or chimneys) in layered sediments depends on the rheological bulk behaviour of the rocks, the spacing and thickness of the low permeability layers, the permeability contrast between the shale and the sand and the effective pressure in the reservoir. We will present examples of models that predict the formation of high porosity channels at Sleipner using realistic input parameters. These channels also develop if the low-permeability layers are discontinuous.

Another implication of our modelling results is that low permeability caprock may fail as a barrier to flow if significant fluid overpressure is build up by the injection and/or due to viscous compaction. These results may be applicable to observations at In Salah. However, the temporal and spatial scales for the onset of focused flow in porosity waves strongly depend on a set of poorly constrained parameters. Thus, more experimental and numerical work and comparison to field data is needed to correctly assess these coupled reaction-deformation-flow processes.