Experimental and numerical investigation of wormholing during CO_2 storage and Water Alternating Gas injection

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Injection of acids into carbonate reservoir units can lead to reaction front instabilities and the formation of so-called wormholes, that can extend at least several meters into the formation. This phenomenon has the potential to dramatically enhance well injectivity or productivity, whilst with prolonged injection this may negatively impact rock strength and wellbore stability.

Wormholing has been studied extensively in the context of acid stimulation of oil production wells. In recent years the topic has received widespread interest in the context of CO_2 storage. However, most experimental and modelling studies conducted so far have been nearly exclusively limited to carbonated brine injection. This is different from ongoing and planned CO_2 injection operations, where nearly-pure (dry) supercritical CO_2 is injected, which only forms an acid after dissolution in the water phase. As pointed out before [1-3], with pure CO_2 injection, two-phase flow effects limit the acid mobility – and hence the reaction front instability and wormholing potential.

A numerical investigation of these effects was conducted in ref. [3], both at a fine scale and at a coarse scale. The fine-scale models have explicit representation of the wormhole dynamics ('full physics/chemistry'), while the coarse-scale models use an effective wormhole velocity model (extending a reduced physics description developed in the acid stimulation literature, the so-called Global Wormholing Model (GWM) [4,5]). The conclusion from ref. [3] is that with pure CO_2 injection the scope for wormholing is extremely small, while other operationally relevant injection scenarios (including Water Alternating Gas – WAG) could have the potential to grow macroscopic wormholes on operational timescales. However, the quantitative models developed in ref. [3] were based on mainly single-phase experiments and only two two-phase experiments, and therefore there were significant remaining uncertainties on the model input and validation.

The current work addresses these uncertainties. Nine new experiments were conducted, falling into three categories:

1. Single-phase experiments (carbonated water) at different flow rates with the objective to further test the application of the GWM to CO_2, and to pin down the transition from compact dissolution to wormholing.
2. Two-phase experiments (water plus CO_2 co-injection) at different flow rates with the objective to test the wormholing suppression caused by the free CO_2 phase, as a function of flow rate.
3. A two-phase Water Alternating Gas injection experiment (alternating pure CO_2 and pure water injection).

These experiments were conducted at 50 °C and 100 bar on 7.5 cm diameter Estaillades outcrop core of 7.5-15 cm length, using a medical scanner to dynamically monitor the 3D dissolution pattern, and with pressure transducers to dynamically monitor the pressure drop.

The fine-scale and coarse-scale models developed in ref. [3] reproduced the single-phase experiments without any further tuning except a minor tuning of the effective diffusion coefficient which was identified in ref. [3] as the remaining parameter not yet fully tied down by prior experiments.

The two-phase co-injection experiments showed complete wormhole suppression at lower flow rates, and only partial wormhole suppression at higher flow rates. This lead to a better understanding of the different behavior observed in the two previous two-phase injection experiments [1,2] which were difficult to interpret because they were conducted on different core materials and with a different geometrical setup. After a small correction in the treatment of the back-coupling between mineral dissolution and multiphase flow parameters, the fine-scale models developed in ref. [3] quantitatively reproduce the behavior, as a function of flow rate (whilst previously they predicted minor suppression at all flow rates).

The WAG experiment created wormholing over the entire core length (15 cm), after 50 gas-water injection cycles (*Fig.* 1). The updated models reproduced the WAG experiment semi-quantitatively without any further model tuning (while minor parameter tuning produced a fully quantitative match). The modelling indicates that the wormhole growth mainly occurs shortly after the start of each water injection period, however with some additional growth shortly after the start of each CO_2 injection period. Further work will be required to understand the relevance of this result for ongoing and planned CO_2- storage and CO_2 WAG operations in carbonates, keeping in mind that the number of unplanned injection shutins and startups can be large in real operations.

This presentation will give an overview of the new experiments and models.

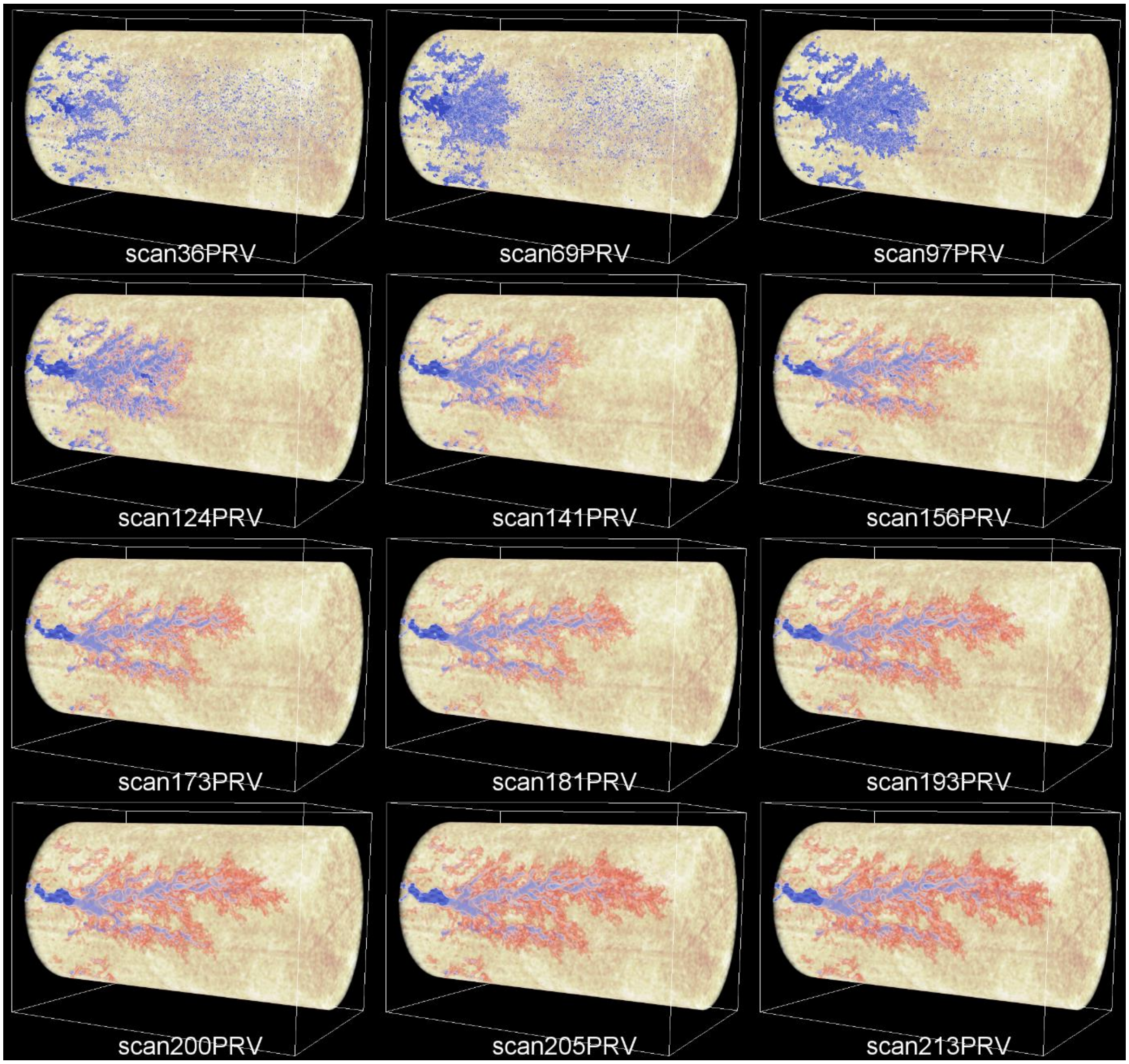

Figure 1: Wormhole development during the Water Alternating Gas (WAG) experiment

References

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