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Temporal and spatial scale for mineral reactions in the near-well zone of CO₂ injectors – Implications for flow paths, storage filling pattern, pressure dissipation and leakage risk

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Abstract

Two phase (water and supercritical CO₂) residence times close to and further away from injectors depend on heterogeneous flow fields and mineral reactions. Residence times are here shown to be sufficiently long for fast reactions like carbonate dissolution or salt precipitation to occur fairly close to the injection well, while slower reactions like silicate dissolution may be sufficiently fast only in far-field locations. Significant poroperm changes in the near-well area are thus only likely to be observed in sediments with a considerable carbonate content, and in sediments with very saline formation waters. Sufficient proton consumption for pressure dissipation will only occur at a considerable distance from the injection point, but since pressure transfer is fast, mineral induced pressure dissipation is likely to affect injection rate in storages with a significant content of immature mineral components. CO₂ storage filling patterns will thus rely on both fast and slow reactions. The impact of fast reactions is to modify porosity and permeability in the near-well zone, while slow reactions in the far-field zone have an influence on injectivity and flow directions through their feedback on CO₂ partial pressure, and they may be important pressure reducers.

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Keywords: two-phase; residence time; porosity; permeability; pressure dissipation; injectivity; storage filling

1. Introduction

CO₂ storage management can draw upon a lot of experience from oil production technology, but there are some obvious differences concerning the long term learning effect from storage operations. Whereas production data can be effectively used to history match reservoir behaviour, and tracers can be used to verify flow paths, CO₂ storage has to rely on other sources of information about storage behaviour. This

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calls for a strong focus on the injection process, and particularly on the behaviour of the near-well environment. The risk of leakage to the surface must to a large extent be related to rigid injection prediction, control and near-well monitoring. Precise tools for this purpose are still not developed. Very few reservoirs are devoid of important barriers or baffles that restrict, impede or redirect fluid flow. Compartment structure may be extremely difficult to define from pre-injection seismic data, from log data or from sedimentology. Only reservoir geochemistry of reservoir core material (eg Sr isotopes; [1]) may have sufficient resolution. Mineral- and fluid reactions may strongly affect near-well fluid flow during CO₂ injection, if the residence time of reactive components is sufficiently long. Another important effect is that reactions may also reduce fluid pressure, because volatile CO₂ is transferred to less volatile dissolved or solid states. If dissolution is occurring faster in some beds or pathways than in others, these conduits may capture an increasingly larger proportion of the flow, compared with other pathways, and thereby direct much of the flow to certain storage compartments. This may on one hand be advantageous by improving the filling of distal subvolumes, but on the other hand this fluid focussing may also represent an enhanced risk by transmitting pressure to smaller areas. After a considerable time interval of injection, we anticipate that the injected CO₂ will flow into the storage without contact with water or hydrated and OH-bearing minerals. At this stage there is no longer a chemical potential for reactions. Before this stage, a complicated two-phase fluid system will prevail, and many solid phases may contain reactive components. The two-phase stage will be characterized by dispersive displacement of original formation water by injected CO₂. The dispersion will operate on many different scales (pore, bed, compartment and storage scale). Strong permeability contrasts between different paths, and the contrasting mobility rates between water and CO₂ phases (fingering), will tend to enhance such dispersive effects. In the two-phase time interval of a given subvolume at a given radial distance from the injection point, carbonic acid will be an abundant component, and could potentially trigger extensive alterations of the plumbing system for fluid flow. Reactions like the desiccation of minerals, vaporization of water, dry and wet carbonation reactions, and mineral dissolution and precipitation show very contrasting kinetic rates. Some reactions, like dissolution of H₂O into the CO₂ phase may be very fast. Carbonate dissolution, and carbonation of solids with abundant bound water, hydroxyl and divalent metals, are also examples of relatively fast reactions. Kinetic data for reactions like clay desiccation and aluminosilicate dissolution are much more uncertain. More experimental work is needed for the simulation of CO₂ injection environments. Since the volume change associated with near-well reactions may be positive or negative, the prediction of their impact on fluid flow needs input from reactive fluid flow experiments. Given a constant CO₂ injection rate, an idealized spherical plume will expand rapidly in the beginning, and much slower as the radius of the plume increases. The distance of water displacement will thus not be very large (figure 1), and the water flow rate moderate (figure 2).

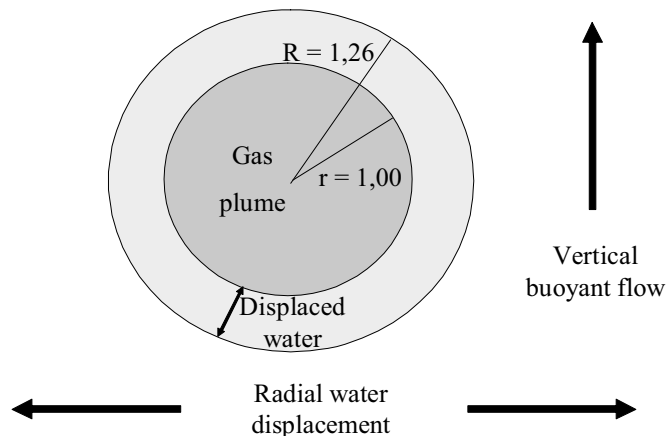


Figure 1 The horizontal radial distance of water displacement (idealized plume geometry) will be 26% of the radial plume size.

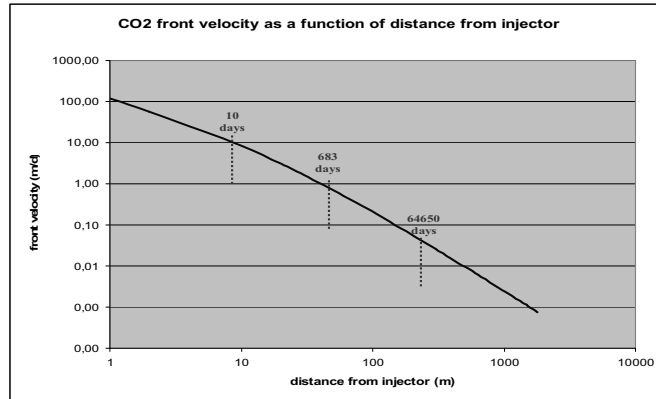


Figure 2 The water displacement velocity (idealized plume geometry) will decrease strongly after a short duration of injection.

Very close to the injector the water will be rapidly displaced and dissolved in the CO₂ phase. Further out a zone of 2-phase mixing and displacement will persist for some time. The two-phase residence time (TPRT) will increase away from the injector. Zone II and III in figure 3 illustrate the spatial evolution of the TPRT.

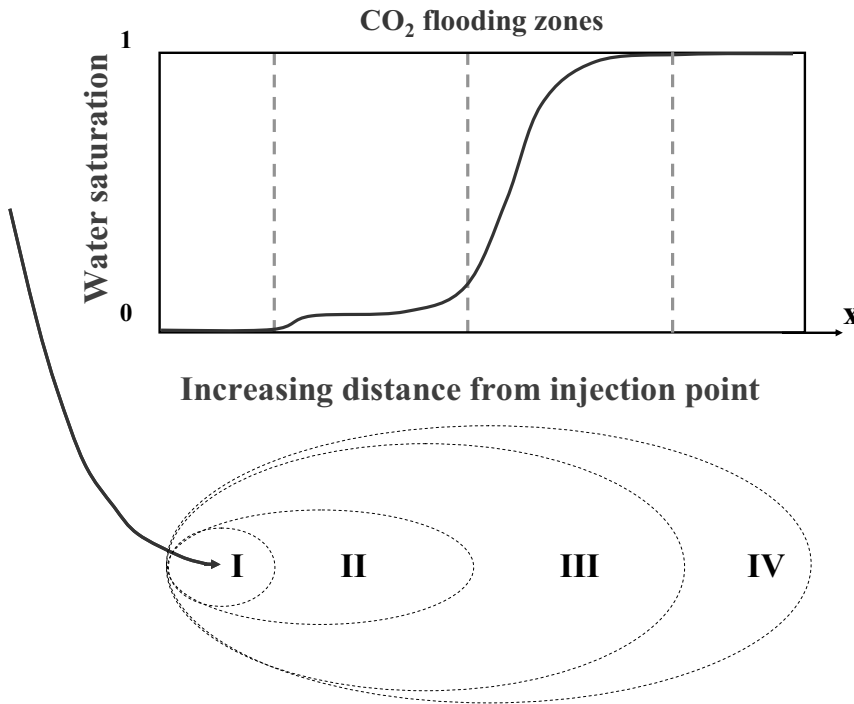


Figure 3 Characteristic zones of decreasing CO₂ saturation as a function of distance from injection point

The displacement and mixing process is complicated by dispersive processes due to sedimentary and diagenetic heterogeneities. These operate at all possible length scales, from typical pore space scale (figure 4a), via typical bed scales (figure 4b), to large compartment and reservoir scale (figure 4c).

Micro (pore) scale

Microscale multiphase dispersion

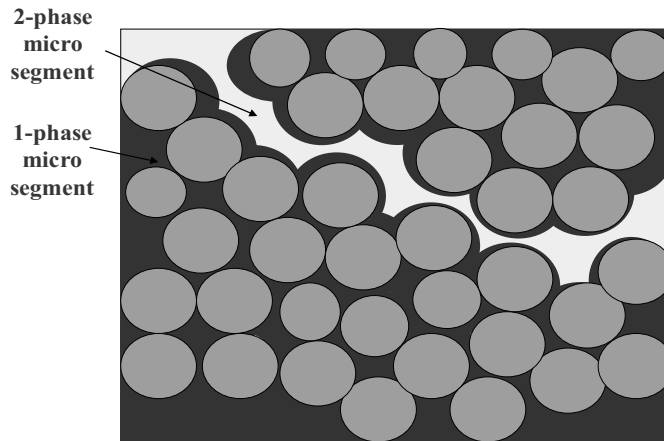


Figure 4a Grain-pore scale dispersion, mixing and fingering of water and scCO₂.

Meso (bed) scale

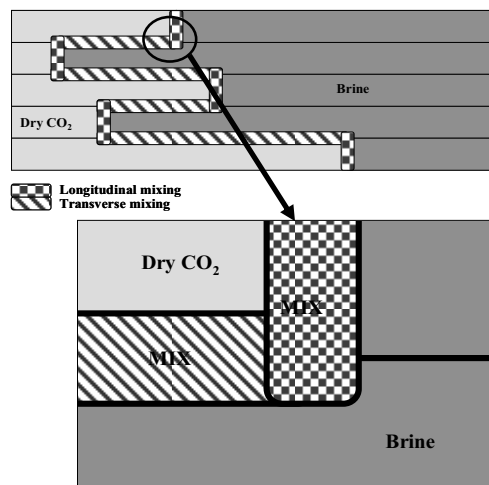


Figure 4b Bed scale dispersion, mixing and fingering of water and scCO₂.

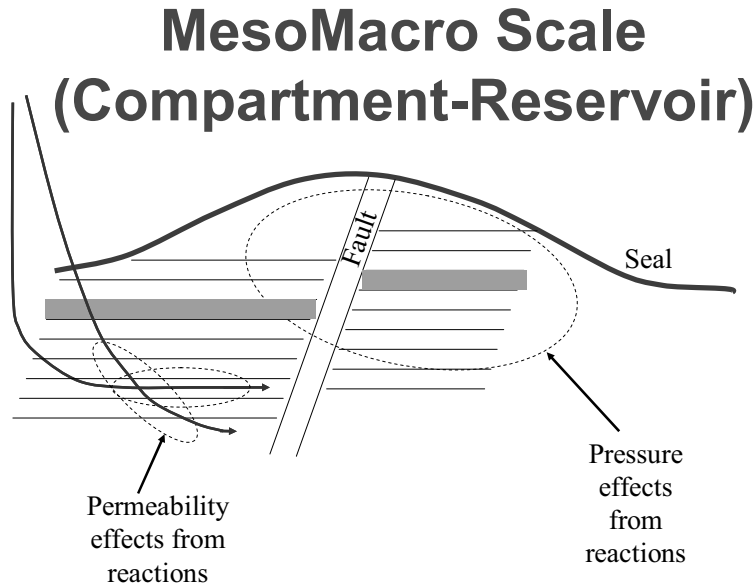


Figure 4c Compartment-reservoir scale dispersion, mixing and fingering of water and scCO₂.

2. Method

In the lack of precise experimental data, existing kinetic literature data has been used to produce a rough prediction of characteristic time and length scales for the near-well environment. Previous work on the impact of heterogeneity and reactivity, and the feedback on injection pressure, includes [2], [3], [4] and [5]. On the basis of a given single well CO₂ injection rate, a given length of the perforation, and assuming some kind of radial expansion of the CO₂ plume (eg cylinder shape), modified by bedscales permeability variations, simplified calculations of characteristic time scales for dispersive two-phase conditions, has been performed. The assumptions and input to these calculations (spreadsheet) has been: Spherical bubble growth geometry, radial water displacement velocity, porosity, injection rate and CO₂ density.

An analytical solution to the 1D-1C (one component) advection-diffusion/dispersion-reaction equation [6] was used to determine characteristic length scales of equilibration for dissolution of various types of fast (carbonates) and slow (silicates) mineral reactions. Dimensionless analysis of this situation, with given constraints on diffusion and reaction rate constants (Darcy flow, Peclet and Damköhler numbers), has been used to set up spreadsheet models for mineral reaction residence time and reaction progress in various distances from the injection well. On the basis of input injection rates, simple cylindrical expansion of the CO₂ plume and bed scale permeability contrasts, a given length of the perforation, two-phase residence times (TPRT) at various distances from the injector has been estimated, and compared with assumed rates for certain characteristic reactions. The relatively high flow rate of injection results in reaction regime that is strongly rate limited by mineral surface transport, and thus very sensitive to pore size variations.

3. Results and discussion

Characteristic two-phase residence times of coexisting water and supercritical CO₂ phases, subjected to dispersive mixing and reactions, has been calculated as a function of distance from the injector. Figure 5 illustrates how the TPRT will be at various spatial locations, assuming two beds with a 5X permeability contrast. Very close to the injector, TPRT is very short, but it increases rapidly outwards.

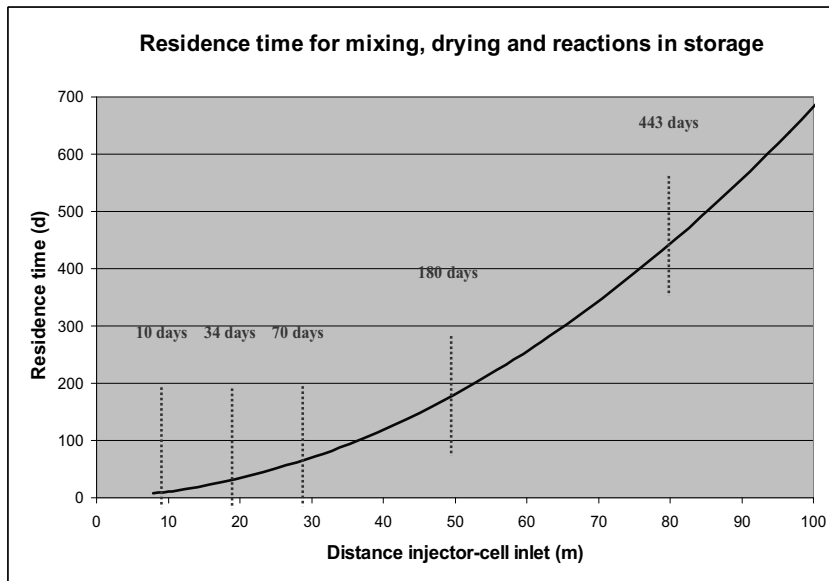


Figure 5 The two phase residence time will increase strongly as the distance from the injector increases

At high injection rates (a single well injecting 1 Mt CO₂ per year) reaction rates will be completely surface controlled (Peclet/Dahmköhler ratios $\gg 100$). Such calculations suggest that characteristic TPRTs for a 5 m long cell in a distance of less than 10 m from the injector is about 1-2 weeks. TPRTs 30 and 80 m from the injector should be in the range of 3-5 months and 1-2 years, respectively. Even the closest zone may have TPRTs long enough for a significant progress of some reactions (dissolution of H₂O into the CO₂ phase; salt precipitation; carbonate dissolution; carbonate replacement of steel), while existing kinetic data makes it uncertain what TPRT is required for presumably slower reactions (dry or wet carbonation of water-and-metal bearing solids; clay desiccation; aluminosilicate dissolution; wormholing; pressure solution; chemical compaction). Figure 6 illustrates the significantly different distances needed to reach equilibrium during dissolution, depending on the reactivity of rapidly (carbonates) or slowly reacting minerals (silicates). Two-phase dispersive intermingling at the pore scale may be very important for

reaction rates, because pore scale diffusional exchange of components between the two phases may be fast enough to maintain high reaction rates.

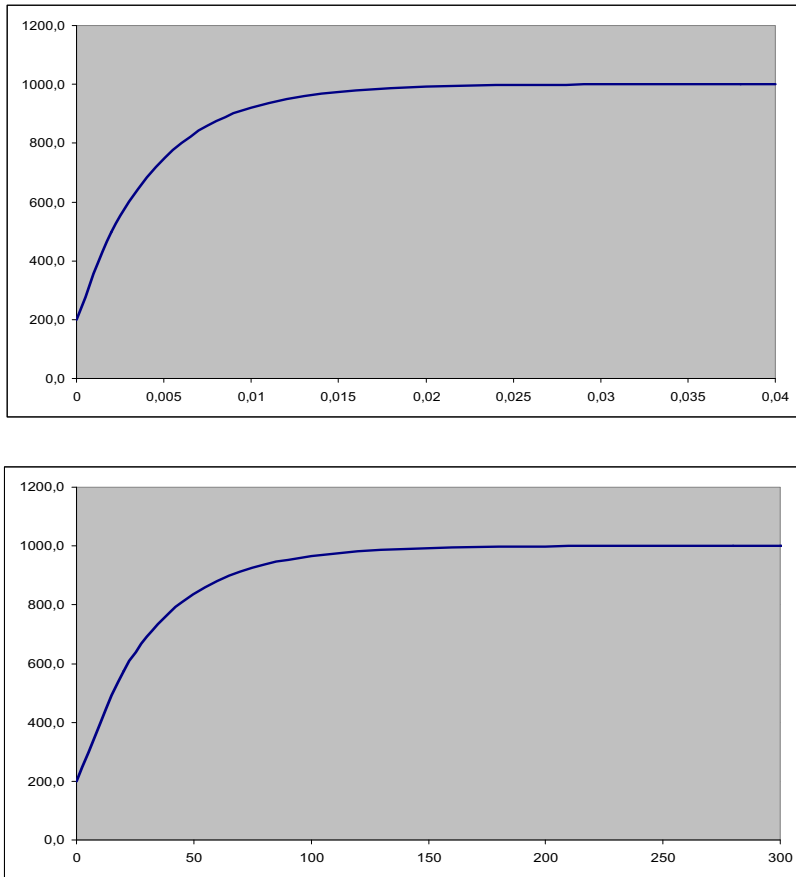
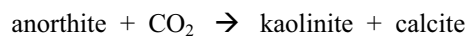


Figure 6 Slow (silicates; lower graph) and fast (carbonates; upper graph) mineral reactions display very different lengths of equilibration.

A sandstone with 10% plagioclase with an AN content of 20%, and a porosity of 20% is sufficient to decrease the partial pressure of CO₂ by about 20 bar, when all plagioclase anorthite has been carbonated, according to the equation:



Average porosity is increased from 20 to 24 % when 5vol% calcite is dissolved, and this can be achieved in 3-30 days, according to kinetic calculations. Dissolution of calcite by CO₂ leads to a temporary

pressure decrease of the same order as plagioclase dissolution, but this pressure reduction is reversed if calcite reprecipitates in a more distal location in the reservoir.

4. Implications and conclusions

The implications of these computational exercises are that certain rapidly reacting minerals may contribute to modifications in porosity and permeability relatively close to injectors (eg carbonate dissolution and salt precipitation), while other slow mineral reactions (eg feldspar dissolution) may occur further out from the injectors, and thus not contribute significantly to modifications of the nearwell flow regime, but they may still have a significant influence on the injection through the reduced partial pressure of CO₂, which will be a result of proton consumption. The far-field pressure response to silicate dissolution is rapidly transferred (acoustic velocity of fluids) to the near-well environment, and is thus also influencing injectivity and direction of bubble movement. Since fluid pressure is transmitted much more rapidly than fluid movement, the pressure front will advance much faster than fluid flow fronts. Pressure may therefore show only a minor sensitivity to near well mineral reactions, while distal storage mineral reactions may be of more importance for pressure dissipation. CO₂ storage filling patterns will thus rely more on permeability in the near-well zone, while mineral reactions in more distant zones may be important pressure reducers.

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