Effect of Permeability Heterogeneity on Area of Review

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Abstract

The Area of Review is one of the most important aspects of a geologic CO₂ storage site permit application and regulatory requirement. The US Environmental Protection Agency (EPA) has implemented an Area of Review (AoR) requirement for Class VI CO₂ injection wells for geologic sequestration (EPA, 2010). AoR is defined as “the region surrounding the geologic sequestration project where underground sources of drinking water (USDWs) may be endangered by the injection activity”. Potential endangerment includes migration of not only CO₂ but also in-situ brine into a USDW. This requires defining the AoR using the areal extent of the CO₂ plume as well as the area where reservoir pressure is sufficiently increased to drive native brines to shallow depth. Once the AoR is identified, potential conduits for fluid movement within the AoR, e.g., improperly abandoned wells, natural fault or fracture zones, need to be identified and remediated where necessary.

Reservoir permeability is one of the most important parameters controlling AoR evolution but is generally highly heterogeneous and difficult to constrain. We have used the Rock Springs Uplift (RSU) in Wyoming as an example site to characterize how the heterogeneity in reservoir permeability affects AoR. We have performed multiple reservoir simulations using multiple, equally-likely realizations of heterogeneous permeability. Site-specific geologic data, including wellbore density and neutron porosity logs, are used to develop a geologic model for the site. Each of the four main geological units at RSU is further subdivided into high, medium and low permeability sub-regions, with the permeability values for each derived from core analysis. An indicator geostatistics approach with transition probabilities is then applied to generate 29 statistically-identical realizations of the spatial distribution of these discrete sub-units (Deng et al, 2012). This geologic model was subsequently used to perform numerical simulations of CO₂ injection and subsequent evolution of pressure and CO₂ plumes. We considered multiple CO₂ injection scenarios with varying injection rates (0.1 to 15 Mt/yr), varying injection times (one to fifteen years) and with post-site monitoring up to 90 years post-injection. The injection scenarios were repeated for all 29 permeability realizations to define the effect of permeability heterogeneity.

We consider both tiers of AoR – CO₂ and overpressure – here onwards referred to as AoRC and AoRP, respectively. AoRC and AoRP are defined as the areas enclosed by threshold values of CO₂ saturation and reservoir overpressure, $S_{crit}$ and $ΔP_{crit}$, respectively. For CO₂ plume we used $S_{crit}=0$ while we used multiple thresholds $ΔP_{crit}$ to define AoRP.

Figure 1 shows the trends in AoRP and AoRC for three simulation sets (each set comprising 29 permeability realizations) of CO₂ injection for a three year period at rates of 0.1, 1 and 5 Mt yr⁻¹. For
the two higher injection rates, the pressure AoRP grows linearly with time during the injection phase and continues to grow after injection has ceased (Figure 1(A)). A maximum is reached 1 to 5 years after the end of injection after which time the size of the AoRP declines. As can be seen from Figure 1A even though the overall broad time behavior is consistent for all AoR profiles, the permeability heterogeneity leads to scatter in calculated AoR.

![Figure 1: Summary of AoR calculations for 3 year injection simulations at three different injection rates: 0.1 (black), 1 (green) and 5 Mt yr⁻¹ (blue). Individual realizations are lightly colored while the ensemble average is bolded. (A) AoR for ΔP_{crit}=1 MPa as a function of time. The end of injection is indicated by a red dotted line. (B) AoRP at the end of injection for different ΔP_{crit}. (C) AoRC for S_{crit}=0 as a function of time. (D) AoRC at the end of injection for different S_{crit}.](image)

The size of AoRP clearly depends on the value of ΔP_{crit} used to define it (Figure 1(B)), with lower thresholds enclosing much larger areas. At a given time, AoRP is larger for higher injection rates. Figure 1(C) shows the evolution of AoRC with time. At all injection rates, AoRC is smaller than AoRP for the corresponding time, although the decline in AoRP with ongoing dissipation of the pressure plume (Figure 1(A)) suggests this may not always be the case. Unlike for pressure, the CO₂ plume does not diminish in size at the end of the injection. Figure 1(C) shows that the AoRC is mostly stable or slowly increasing in the post-injection period. Similar to the pressure AoR, permeability heterogeneity contributes uncertainty in the stable size of the CO₂ plume by as much as ±33%. AoRP and AoRC calculations for longer CO₂ injection scenarios (10 year) are broadly consistent with those presented in Figure 1, except that the AoRs are generally larger, consistent with the higher volume injection. Similar to the smaller volume injections (3 year injection), the variability around the ensemble mean is also consistent with the 3 year injection case, with the largest uncertainty associated with the size of the CO₂ plume (Figure 2(C)).
Results of our study demonstrate that uncertainty in permeability heterogeneity can significantly influence AoR for both CO2 and pressure. In our example, the CO2 AoR varied by as much as 2–3 times while the pressure AoR varied over 1.5–2 times. Such type of variability can have significant implications in defining AoR for site permit applications.

References
