Feasibility study of CO_2 monitoring using Controlled Source Electro-Magnetics, CSEM

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Abstract
A secure and reliable monitoring scheme is required to store captured CO_2 safely. To reduce risk, it is essential to detect and monitor the extension of the CO_2 plume. Injected CO_2 tends to rise to the closest sealing impermeable rock due to natural buoyancy. From here the gas spreads outward underneath the seal and accumulates in thin plumes. Monitoring of injected and sequestered CO_2 using seismic methods has limitations. Electrical resistivity of injected CO_2 is on the other hand strongly dependent on the saturation, and CSEM data is sensitive to sharp resistivity contrasts. This work is a feasibility study which investigates both the sensitivities of 1D and 3D CSEM data for CO2 storage. The difference between CO_2 in layered models and a 3-Dimensional CO_2 reservoir will be modeled and examined to determine whether CSEM is suitable for monitoring. Most interesting is the sensitivity of the method to the lateral extension of the thin CO_2 plumes with different saturations.

Introduction
Marine controlled-source electromagnetic (CSEM) survey techniques are used extensively in oil and gas exploration, and have been identified as a powerful tool for imaging high resistive layers in the subsurface. The hydrocarbon saturated rocks have higher electric resistivity compared with water saturated rocks. In contrast, the elastic sensitivity given by seismic data, e.g., P-wave velocity, to such a saturation change is limited. The CSEM technology has been recently adopted into CO_2 monitoring [1]. One very important feature of using CSEM is its ability to quantitatively monitor the CO2 plume development both during and after the injection. However, the sensitivity of CSEM is not yet fully understood, and needs to be further tested. We attempt to use a realistic synthetic dataset, and analyze the use of CSEM data for making estimates of the post-injection accumulations of CO_2 layers in the subsurface. We will analyze three different cases of injected CO_2, with 1D and 3D modeling, and illustrate the general effects these cases have on the data.

Methodology
We use here a realistic synthetic model to simulate the real CO_2 storage site. We assume the injected gas is accumulated in radial expanding thin plumes underneath a series of sealing impermeable cap rocks, and the expansion is driven both by the natural buoyancy and the injection itself. The plume is no more than a couple of meters thick in its initial development phase, except above the injection point, and the plume is thinnest at the edges of the extending plume.

Modeling plane layers, 1D geometry
We start the modeling the 1D case, as shown in Figure 1. The synthetic data were obtained using the reflectivity method developed by [2]. The model consists of a 2 Ωm half-space (1a), to which we added; A 2 meter CO_2 layer at 1km below the seabed (1b), later referred to as stage I, stage IIa: one 4m thick layer at 1km depth (1c), and stage IIb; The same volume of CO_2 in two separate 2m layers 100m apart (1d).

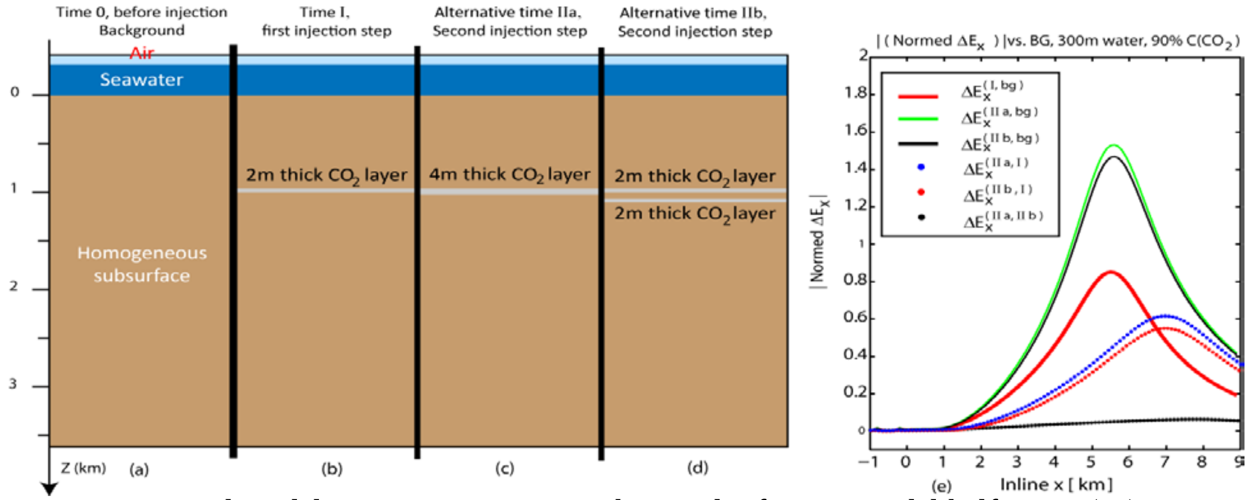

Figure 1, Layered models in 1D-geometry. Background reference model half space (1a), stage I: a 2m thick CO_2 layer at 1km (1b), stage IIa: a 4m thick CO_2 layer at 1km (1c), stage IIa: two 2m thick CO_2 layers at 1 and 1.1 km. Normalized amplitude differences of the 1D models. Comparing with the reference data (1e); Stage I (red), stage IIa (green), stage IIb (black). Comparing later injection stages with each other stages with each other (dotted red, blue and black).

Figure 1e shows that the CO_2 volume is strongly linked to the normalized amplitude difference. At stage I, an EM amplitude change about 70% is observed, given a CO_2 theoretical maximum saturation of 90%. For all cases in 1D, the EM amplitude change is >20%, thus much higher than an assumed 10-15% noise level. This demonstrates that use of CSEM for CO_2 monitoring is realistic. Once the second stage with double the amount of injected CO_2 is reached the difference in the EM amplitude are significantly larger than those after the first stage. However, Figure 1e show that it is not possible to differentiate between the two second stage models in the layered models. CSEM surveys thus have limits, depending on the depth of the target, sensitivity for discriminating layers, but indicate significant differences when increasing the injected volume.

4. Modeling CO_2 plumes as 3D structures

For the 3D, we have the same setup as in Figure 1(a-d), but here the CO_2 accumulations are in lateral 2x2 km plumes with their centers at the source-receiver-offset where we expect the largest EM amplitude difference. The modeled 3D data were produced using the code developed in [3]. The 3D-case produces less amplitude anomaly compared to the layered cases, but nevertheless significant normalized amplitude differences are clearly observed. The amplitude anomaly for stage II is much stronger than stage I, and we were not able to distinguish the stage II cases from the observed amount of EM amplitude anomaly with such a deep storage site.

Summary

We have shown that CSEM may be used to add the safety in CO_2 storage by increasing the monitoring accuracy. There is significant difference in normalized amplitude for data modeled for 3D-structures in when comparing with a reference data set. CSEM is shown to be very sensitive to injected volume of CO_2. But at the same time, has a limited ability to detect whether the injected volume is located in one or multiple layers, especially for deeper storage sites. Lateral termination of accumulated CO2 plumes are clearly detectable using CSEM 3D modeling, which leads to the conclusion that CSEM may be a promising tool for monitoring CO_2 storage. Thus, tests on more complex synthetic models and further on real data will determine the real significance of the method.

References

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