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Electromagnetic characterization and monitoring of CO2 sequestration sites: feasibility studies and first field results from Ketzin, Germany

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Bulk electrical resistivity of sedimentary units depends strongly on the pore fluid content and pore connectivity. Since carbon dioxide exhibits significantly higher electrical resistivity than saline pore fluids, electrical and electromagnetic methods are key geophysical techniques for investigating CO_2 sequestration sites. Electrical resistivity tomography has been successfully applied for monitoring the immediate vicinity of CO_2 injection wells; however, techniques having a wider spatial footprint are required for imaging larger regions beyond the wells, particularly for prospective industrial-scale injection.

Low-frequency electromagnetic methods are sensitive to thin resistive layers and may thus provide a suitable tool for larger-scale injection monitoring. The resolution power can be expected to depend strongly on local geology and the layout of the sensor network. Here, we present results of synthetic controlled-source electromagnetic (CSEM) resolution studies, and initial results of a large-scale field experiment carried out at the Ketzin CO_2 sequestration site.

For synthetic studies, we have developed 1D quasi-analytic and 3D finite-difference modelling tools. To enable accurate CSEM simulations in the frequency range and for the geometries of interest, our modelling tools include exact representations of long grounded wire sources, and numerical stabilization at low frequencies by explicitly prohibiting non-physical current sources. Because inherent limitations of the numerical approaches employed or improper use of modelling tools may lead to inaccurate results and possibly false conclusions, we first assess the modelling accuracy. Comparison of 1D to analytical results for homogeneous models indicates errors mostly less than 0.01%, and comparison of 1D and 3D results for layered models indicate 3D modelling errors generally no more than 1-3%, with exceptions in regions of very low EM field amplitudes.

We then study the sensitivity of surface-to-surface and borehole-to-surface source-receiver configurations for layered and 3D resistivity models roughly mimicking the geology of the Ketzin site. We find that a resistive layer having the resistivity and thickness of the CO_2-bearing sandstone should be detectable, but the present CO_2 reservoir is probably too small to be resolvable by surface measurements alone. Configurations involving borehole instruments positioned more closely to the CO_2 reservoir exhibit much higher sensitivity and may thus be particularly useful for monitoring applications. We also observe a trade-off between absolute field amplitudes and sensitivity in terms of relative EM field changes due to the anomalous layer. Hence, low-noise instrumentation capable of accurately measuring low-amplitude fields is essential for successful CSEM measurements. Most information on subsurface structure is contained in the electric field components, whereas the magnetic field is largely insensitive to the small resistors.

For a first large-scale CSEM field experiment at Ketzin, we deployed a newly developed CSEM transmitter equipped with three grounded source electrodes at eight different locations to inject currents in the frequency range of 1/64 to 64 Hz. The horizontal electric and three-component magnetic fields were recorded by 39 surface receivers; additionally, natural-source EM fields and ambient noise were recorded during transmitter-off periods. Initial data analysis indicates that the lower-frequency source signals can be traced over distances of $\sim$10 km. We present data examples and first transfer functions indicative of subsurface resistivity distribution.