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Time-lapse CSEM monitoring of the Ketzin (Germany) CO_2 injection using 2xMAM configuration

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Abstract

This paper deals with the electrical resistivity monitoring of the Ketzin CO_2 injection pilot (CO2ReMoVe EC project) through time-lapse CSEM measurements. There, 3 boreholes about 800 m deep have been especially designed for current injection at reservoir (sandstone) depth. CO_2 is directly injected in a saline (~240 g/l) aquifer. Prior modelling results indicated that the increase of electrical resistivity generated by the CO_2 plume (gaseous and liquid CO_2 phases) supposed to be highly resisitive, would generate measurable changes in the EM fields on the surface, when injecting current directly inside the reservoir. In order to highlight and follow these expected resistivity changes, 3 CSEM surveys were performed in August 2008 (baseline prior to injection), June 2009 and August 2010. Each time, 13 EM stations have been recorded during current injection of a square wave at 3 frequencies (0.125 Hz, 0.5 Hz and 4 Hz) in two configurations (“double mise à la masse” (2xMAM) and “mise à la masse – surface” (MAM-Surface)). This paper only presents results of the 2xMAM configuration at 0.5 Hz.
In spite of a very noisy area (gas pipes, high voltage power lines), we measured signal amplitude 10 times higher than noise amplitude. We show that EM fields vectors (both inphase and quadrature components) measured on the surface are very similar to the forward modelling EM responses computed with COMSOL Multiphysics®. Models also show that electric field spatial distribution is strongly affected by a thin and resistive layer (35 m - 200 Ωm) of anhydrite above the reservoir, making E field diverging from the boreholes whereas a dipolar pattern was expected for the dipole current injection used here. Moreover, while June 2009 survey highlighted the expected strong increase of electric field (increase of resistivity), August 2010 survey showed electric field amplitudes similar to the 2008 baseline survey, revealing therefore major changes of the reservoir properties. Finally, the directional sensitivity of the 2xMAM array is tested through modelling residuals computed for five CO_2 plume spatial distributions. Results show that a north-eastward migration of the CO_2 plume is expected to fit field data.

Keywords: CSEM; CO_2; Time-lapse monitoring; Mise à la masse; EM modelling; Ketzin

1. Introduction

Several teams [1; 2; 4; 6] have proposed to monitor CO_2 injection through the time-lapse variation of electrical resistivity at depth. This approach is especially appropriate in the case of a CO_2 injection in a saline reservoir where the CO_2 plume is expected to strongly modify the current paths due to an increase of electrical resistivity (for

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instance of about 200 % in the Ketzin (Germany, west of Berlin) context, [4]). However, because the reservoir must be deep enough to keep CO_2 in a supercritical state (at a depth greater than 800 m, depending on temperature and pressure gradients, [5]), highlighting any temporal change of its electrical properties is difficult using classical surface electrical methods [2]. Logging and cross-hole electrical or electromagnetic (EM) imaging techniques overcome this limitation but need boreholes intersecting the reservoir and technically designed for such measurements. In addition, the lateral investigation is limited to the inter-well area or to the close vicinity of the unique well in the case of logging or single-well methods.

In the framework of the CO2ReMoVe EC project, we performed three CSEM surveys at the CO_2 storage pilot site near Ketzin (Germany) (Figure 1). The first one has been performed in August 2008 before the injection of significant amount of CO_2 and corresponds to the baseline. The second survey has been carried out in June 2009 after one year of CO_2 injection (i.e. 17200 tons of CO_2 injected) and the last one in August 2010 (around 34000 tons of CO_2 injected). In the present paper we highlight the deep CO_2 plume through electric and magnetic fields measurements at the surface (Figure 1, right) induced by a grounded injection of electrical current through the available metal-cased electrodes along boreholes K201 and K202. We designate this array "Double Mise à la Masse" (2xMAM). Measurements are performed in a time lapse implementation: for each survey repetition, the time-lapse CO_2 response is calculated as the electric (or magnetic) field difference between the last dataset and the previous one or between the last dataset and the initial "baseline" measured before CO_2 injection. In this manner, only volumes of varying resistivity are revealed, essentially the regions where the CO_2 has replaced the initial brine. Considering industrial-scale CO_2 injection rates (≈1 Mt/y), numerical simulations performed within the projects GeoCarbone-Monitoring and EMSAP-CO_2, funded by the French Research Agency (ANR) [2; 3], have shown that, when the volume of the plume increases, the resulting electric field modifications at the surface should be measurable using the LEMAM array. Furthermore, this array shows a good sensitivity to the plume shape. A close cooperation with the teams involved in the CO2SINK project will allow to compare and combine the different monitoring approaches based on the electrical resistivity: either cross-borehole electrical resistivity tomography (VERA experiment, Helmholtz Centre Potsdam/ GFZ) or surface injection coupled with surface and downhole measurements (in cooperation with University of Leipzig).

2. Location and survey configuration

Technically, the boreholes at the Ketzin site are equipped with electrodes behind an insulated casing to perform the already mentioned CO2SINK electrical experiments (GFZ). The vertical separation between electrodes is 10 m. To perform the 2xMAM injection, we grouped 8 adjacent (10m spaced between 655 and 725 m deep) electrodes just below the reservoir in the CO_2 injection borehole K201 (pole -) and 8 adjacent electrodes (10 m spaced between 590 and 660 m deep) encompassing the reservoir and the bottom of the cap-rock in the observation borehole K202 (pole +), distant from 112 m. We applied a very stable square alternating current of 7 A amplitude at frequencies 0.125 Hz, 0.5 Hz and 4 Hz. Current was monitored using both a Hall effect sensor and a digital clamp meter connected to a ADU06 (Metronix).

For each injection frequency, we recorded both horizontal electric (Ex and Ey) and magnetic (Hx and Hy) field components at 14 stations spread out on two circles of approximately 0.8 km and 1.5 km radius centred on the CO_2 injection borehole K201 (Figure 1, left). Both transmitter (Tx) and receiver (Rx) were synchronized using GPS time synchronization in order to compute complex components (i.e. modulus and phase) of the electric/magnetic field vectors (related to expected inductive effects). The spread of the receiver stations is similar to that used for the ERT surface-to-borehole measurements (in which, however, a single component of the electric field has been measured radially to the CO_2 injector borehole, [4]). The length of electric dipole was 200 m, except for station 17 (100 m). Electric and magnetic vectors were then rebuilt from their x and y components.

A specific data processing software was developed to get the whole information (in Cartesian and polar coordinates) from the Tx and Rx synchronized time series. Briefly, amplitude spectra of Ex-Ey-Hx-Hy are normalized by the injected current over about 150 periods to get comparable results. Noise is also computed from these spectra. The software also allows (according to data quality) the reliable use of the odd harmonics of the transmitted frequencies (f0, 3f0, 5f0, etc…).

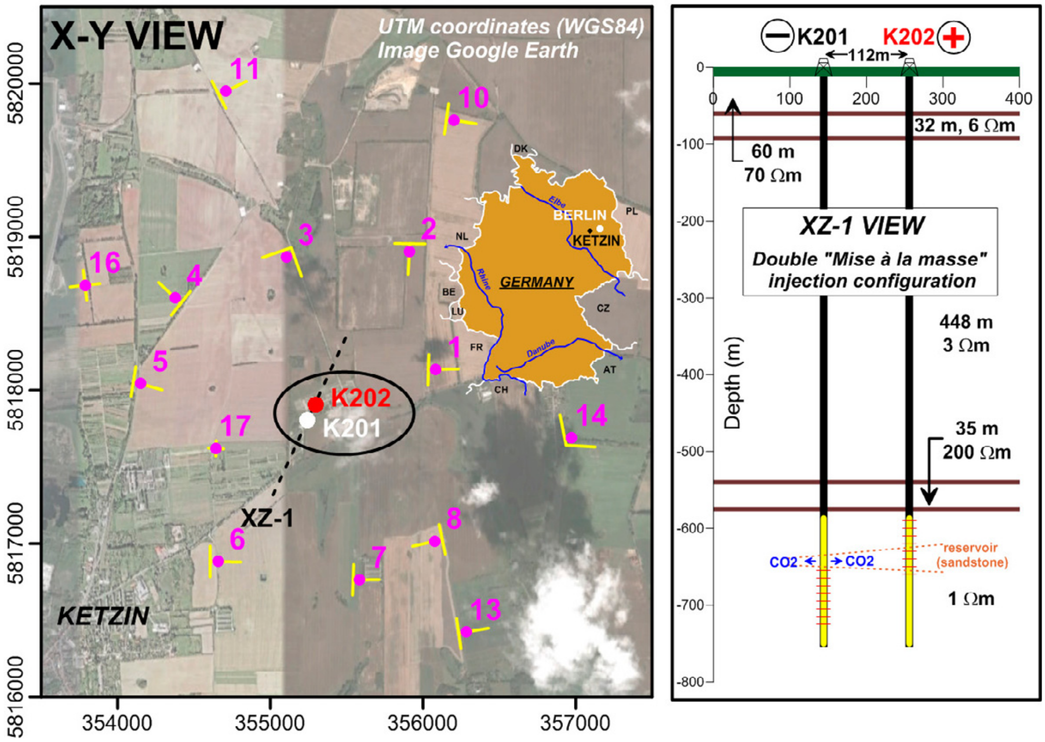

Figure 1 : Left map XY-VIEW : Contour of Germany with Ketzin location, west of Berlin. Location of the Ketzin CO2 injection pilot (black circle) with boreholes K201 (injection) and K202 (observation) - borehole K200 not represented here. Yellow crosses or T-shape yellow lines are the telluric lines Ex and Ey at the 14 EM stations (purple dots) measured in 2008, 2009 and 2010 (excepted station 17, only recorded in 2010 with 100 m telluric lines). XZ-1 black dashed line is the trace of the schematic cross-section represented on the right (2xMAM configuration). Right drawing: Schematic configuration of the 2xMAM configuration (XZ-1 VIEW). Resistivity model used to compute forward modelling responses is indicated. Resistivities of the first 2 layers (60 m/70 Ωm and 32 m/6 Ωm) have been deduced form Schlumberger and TEM soundings carried out in 2010 close to stations 13, 2 and 17. Below, resistivity model comes from geophysical logging (448 m/3 Ωm is the cap rock, 35 m/200 Ωm corresponds to the anhydrite layer and the deepest layer 1 Ωm is the Stuttgart Formation (Middle Keuper) with the reservoir).

3. Location and survey configuration

The following figures display both field data and model responses computed in frequency domain with the ACDC package of the generic finite-element partial differential equation solver COMSOL Multiphysics®. The three dimensional numerical model (composed of about 25000 mesh elements) has been built to approach as much as possible the reality, especially a great effort has been made to include cables, electrodes and casings expected to be responsible for the inductive effects (i.e. complex part of the electric and magnetic fields). The resistivity layering presented on Figure 1 has been used and thickness of the anhydrite layer has been increased from 20 m to 35 m for mesh design. Figures 2, 3 and 4 present the last August 2010 survey (in red) and model responses (which includes a 150x150x20 m-3 Ωm CO_2 plume, centred on borehole K201). Electric field vectors revealed the importance of a thin and resistive layer of anhydrite (200 Ωm) which controls E field spatial distribution. While without anhydrite electric field distribution provided by models shows a dipole shape, this layer changes dramatically electric field distribution to a source point (Figure 2) when including it.

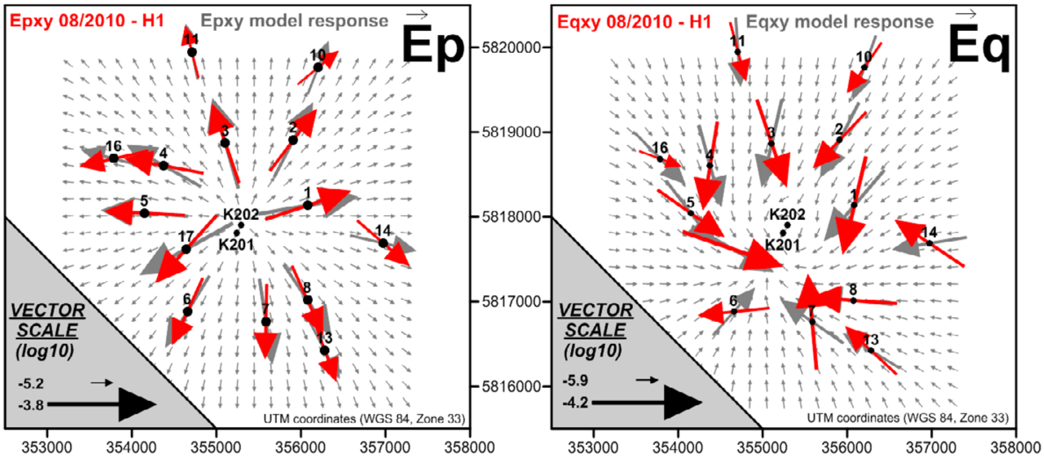

Figure 2 : Normalized to 1 A current electric field (inphase Ep (left) and quadrature Eq (right) in mV/m) responses of the 2xMAM injection configuration at frequency 0.5 Hz. Large red arrows are the 2010 field data. Large grey arrows are the modelling responses at the stations of a centred CO_2 plume of 100x100x20 m at 3 Ωm. Small grey arrows show the electric field model response all over the area (without scaling).

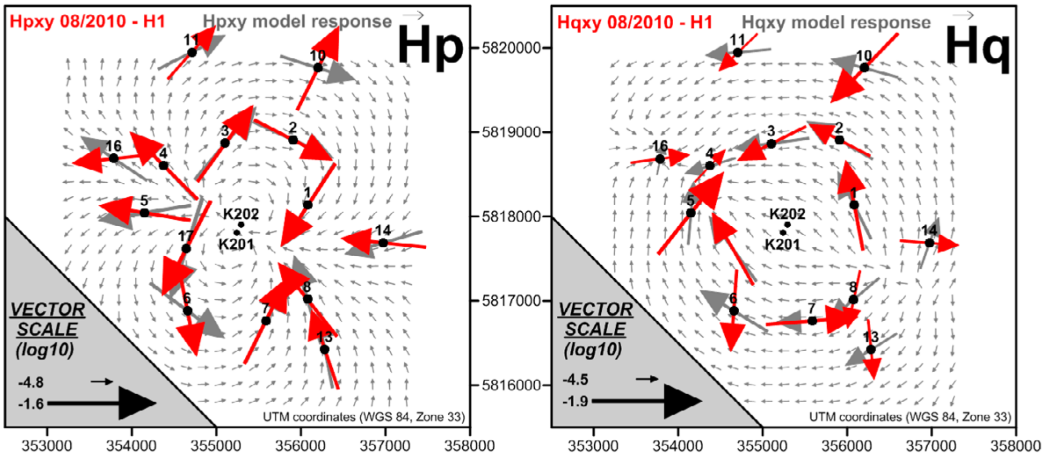

Figure 3 : Normalized to 1 A current magnetic field (inphase Hp (left) and quadrature Hq (right), in mA/m) responses of the 2xMAM injection configuration at frequency 0.5 Hz. Large red arrows are the 2010 field data. Large grey arrows are the modelling responses at the stations. Small grey arrows show the electric field model response all over the area (without scaling).

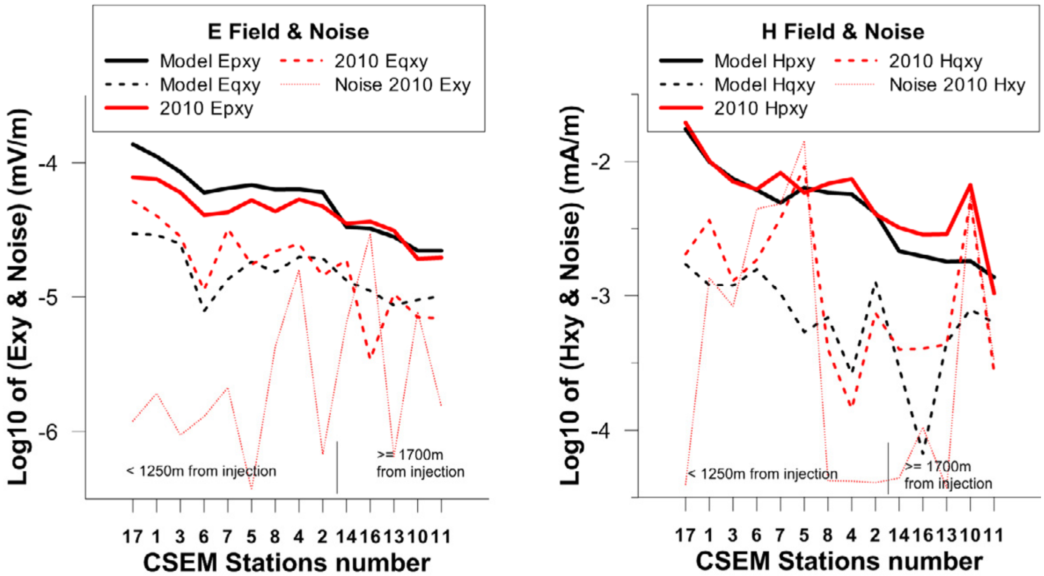

Figure 4 : Normalized to 1 A current electric (inphase and quadrature, left) and magnetic (inphase and quadrature, right) field amplitudes of 2010 field data (red lines) and model responses (black lines).

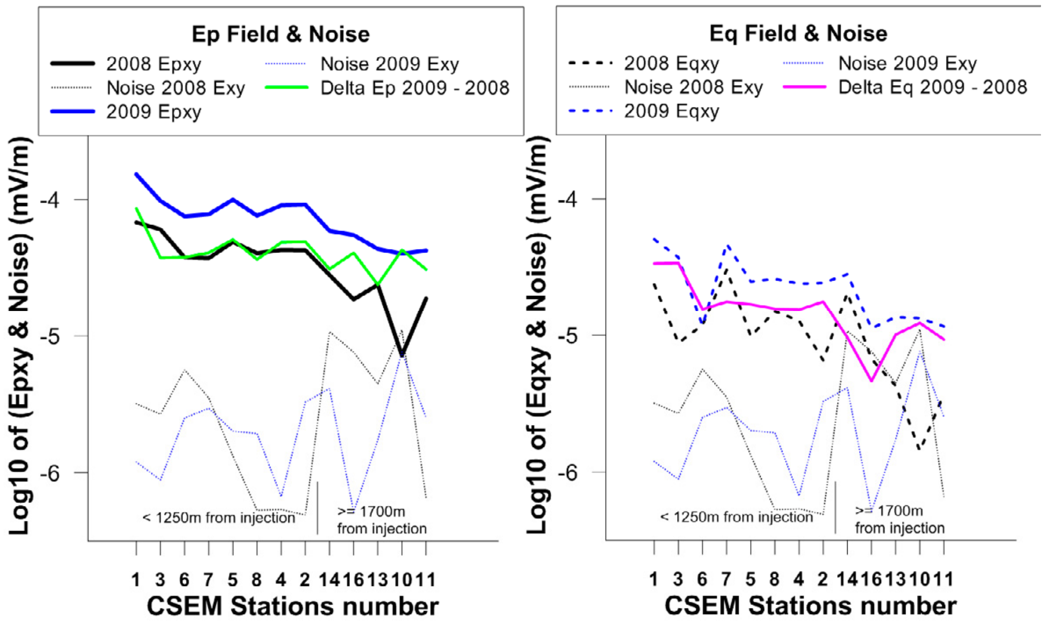

Figure 5 : Normalised to 1 A, 2008 (black lines) and 2009 (blue lines) electric fields (inphase - left, quadrature - right and noise) measured at 13 sites. Green and purple lines are the residual components between 2009 and 2008.

Despite a high electromagnetic noise environment due to nearby power lines, gas pipes and an electric railway track which particularly affects the lowest quadrature component of the E field and the magnetic measurements (Figure 2 and 3), vector amplitudes and intensities are very similar for both model and field data (Figure 4). The small differences (E field) existing between 2010 data and model for the 9 closest EM stations can be reduced if CO_2 plume size decreases. It is also important to note that the total injected current intensity (5 to 7A) was strongly limited by both the number of available electrodes and the maximum injectable current intensity on each cable (~1A) which may vary according to resistivity lithology variations. This current limitation explains the decreasing signal/noise ratio we observed on distant stations and therefore the capability of the method to resolve small resistivity changes at larger distances. As demonstrated by [3] in the case of not especially designed casing (simple metallic casings without electrode and insulated part), the LEMAM ("Long Electrode Mise à la Masse") array may overcome this limitation even if intermediate conductive layer is present between the surface and reservoir.

The time-lapse differences between 2009-2008 (Figure 5) and 2010-2008 (Figure 6) surveys allow detecting resistivity variations that are being analyzed by comparison with numerical modelling of various scenarios (see Figure 7 and 8). The most important result is the clear difference between the 2008 baseline and the 2009 survey, where resistivity around electrodes in the borehole K201 dramatically increased due to CO_2 gaseous phase (Figure 5). 2010 survey revealed that EM field recovered its initial state for the stations located in the first radius around boreholes (Figure 6). The increasing 2010-2008 E-field time-lapse response with distance to transmitter (borehole K201 and K202) suggests that the CO_2 plume expanded and that the gaseous phase strongly decreased around the boreholes.

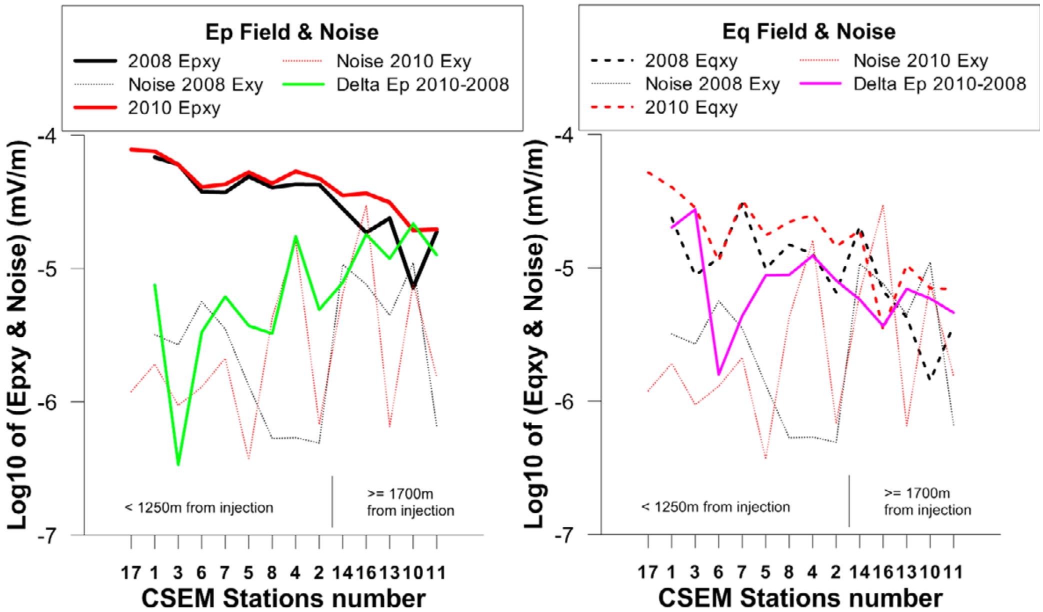

Figure 6 : Normalised to 1 A, 2008 (black lines) and 2010 (blue lines) electric fields (inphase - left, quadrature - right and noise) measured at 14 sites. Green and purple lines are the residual components between 2010 and 2008.

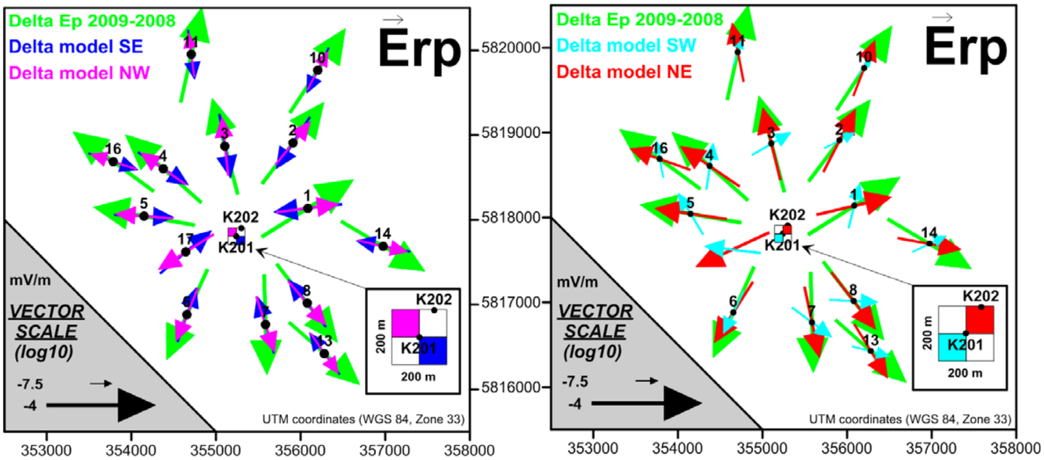

Figure 7: Normalised to 1 A current electric field (inphase response) residuals. Green arrows show Ep field data residual between 2009 and 2008 surveys. Purple, red and blue arrows show residuals between models with CO_2 plume (3 Ωm) respectively located NW and SE (left), and SW and NE (right) of borehole K201 and a model without CO_2 (1 Ωm). Insets show zoom on plume size and location.

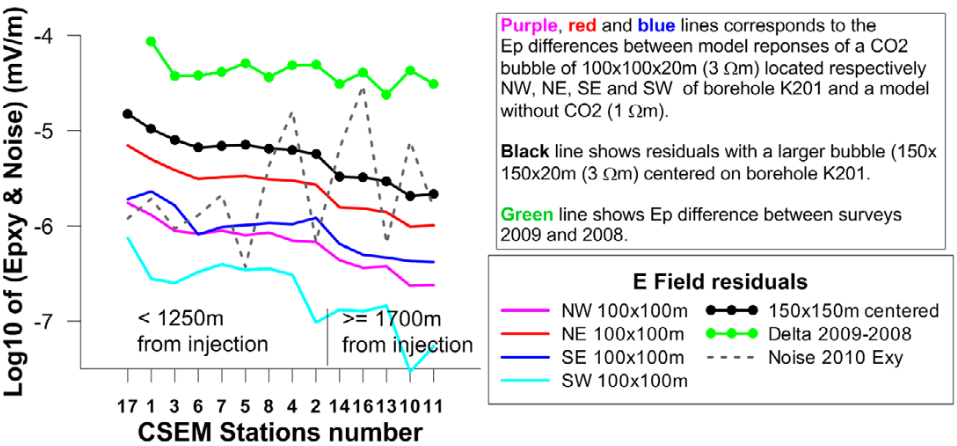

Figure 8 : Normalized to 1 A electric current Ep residuals. See inset for details. Exy 2010 noise shows that at greater distances from the boreholes, resolution of the residuals decreases but still remains significant.

In order to investigate the CO_2 plume location from field results and evaluate the directional sensitivity of the 2xMAM array, residuals between a 100x100x20 m – 3 Ωm CO_2 plume and the initial state were computed for four different scenarios (CO_2 plume successively located NW, SE, SW and NE of borehole K201). A fifth scenario with a 150x150x20 m – 3 Ωm CO_2 plume centred on borehole K201 was also evaluated (Figure 7). Theses results are compared with the time-lapse 2009-2008 response of the CO_2 plume measured on the field. While the SW plume shows the lowest response (opposite direction from K201-K202), the NE plume has the strongest response. The NW and SE plume have an intermediary response being perpendicularly located from K201 K202 axis. Time-lapse variation on field data is stronger than the model response presented here (Figure 8) and can be explained with a larger or more resistive plume (as suggested by the 150 m plume). Note that fit should not match only amplitudes but also the vector direction (Figure 7). Thus, the responses of SE and SW plume configuration do not fit at all the data. These preliminary results strongly suggest that CO_2 plume would move north-eastward. This assumption will be compared with other monitoring techniques within the CO2ReMoVe EC project.

4. Conclusions and further works

The three year CSEM monitoring experiment performed at Keztin CO_2 injection pilot allowed us highlighting clearly the strong modifications of the electric field amplitude (and therefore resistivity) induced by a deep CO_2 plume, on the surface. While 2009 survey highlighted clearly the expected resistivity change at depth, 2010 survey revealed a considerable and unexpected modification of the reservoir properties since approximate initial EM conditions (2008 baseline) recovered. We speculate that this change could be attributed to the decrease injection rate of CO_2 (2009-2010), certainly related to a decrease of the CO_2 gaseous phase (and its dissolution in the aqueous phase) in the vicinity of the borehole and/or to a migration of the CO_2 plume in some parts of the reservoir. We hope that a fourth CSEM survey planned for 2011 and fruitful collaborations with the other teams involved in the CO2ReMoVe EC project will help to answer this question.

Modelling residuals computed for five CO_2 plume spatial distributions show that a north-eastward migration of the Ketzin CO_2 plume is expected to fit field data. The latter will have a larger size and/or being more resistive than the one tested in the present models. Data and models also show that electric field spatial distribution is strongly controlled by a thin and resistive layer (200 Ωm) of anhydrite making E field diverging from the boreholes. In spite of extremely noisy EM conditions, our results, supported by multiple numerical modelling scenarios, prove the ability of CSEM to resolve deep resistivity changes in similar current injection and low resistivity context. Additional EM stations and shorter time-lapse experiments would clearly help to better resolve and follow the resistivity perturbation generated by the moving CO_2 plume. Ideally, a permanent acquisition system should be implemented.

Acknowledgments

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References

[1] Börner JH, Herdegen V, Börner R-I, Spitzer K. Electromagnetic Monitoring of CO2 Storage in Deep Saline Aquifers - Numarical Simulations and Laboratory Experiments. 2nd EAGE CO2 Geological Storage Workshop - March 2010, Berlin, Germany.

[2] Bourgeois B, Girard J-F. First modelling results of the EM response of a CO2 storage in the Paris basin. Oil & Gas Science and Technology - Rev. IFP 2010; 65(4): 597-614.

[3] Girard J-F, Bourgeois B, Rohmer J, Schmidt-Hattenberger C. The LEMAM array for CO2 injection monitoring : modelling results and baseline at Ketzin in August 2008. EGU General Assembly - 19-24 April 2009, Vienna, Austria.

[4] Kiessling D, Schmidt-Hattenberger C, Schuetta H, Schilling F, Krueger K, Schoebel B. et al. Geoelectrical methods for monitoring geological CO2 storage: First results from cross-hole and surface-downhole measurements from the CO2SINK test site at Ketzin (Germany). International Journal of Greenhouse Gas Control 2010; 4: 816-826.

[5] Law DHS, Bachu S. Hydrogeological and numerical analysis of CO2 disposal in deep aquifers in the Alberta sedimentary basin. Energy Conversion Management 1996; 37: 1167-1174.

[6] Nakatsuka Y, Xue Z, Garcia H, Matsuoka T. Experimental study on CO2 monitoring and quantification of stored CO2 in saline formations using resistivity measurements. International Journal of Greenhouse Gas Control 2010; 4: 209-216.