AAPG/SEG/SPE HEDBERG CONFERENCE
"GEOLOGICAL CARBON SEQUESTRATION: PREDICTION AND VERIFICATION"
AUGUST 16-19, 2009 – VANCOUVER, BC, CANADA

Numerical Modelling of the Time-Lapse EM Response of a CO_2 Injection in a Deep Saline Aquifer Using Metallic Casings for the Current Injection

Bernard Bourgeois, Jeremy Rohmer and Jean-François Girard

BRGM, "Natural Hazards and Safety of CO_2 Storage" Division, Orléans, FRANCE

Numerical models have been calculated to study the feasibility of monitoring a supercritical CO_2 injection in a deep saline aquifer by means of electromagnetic (EM) methods operated from the ground surface (EM being taken here in a broad sense, including DC electrical methods). Given the similarity of the problem with oil exploration, it can be anticipated that the transmitter/receiver array appropriate for CO_2 monitoring should be similar to that used in CSEM, *i.e.* a grounded current injection and a grid of sensors at the surface.

When looking for a resistive target in a conductive host, the closed eddy currents emblematic of EM induction ("vortex response") cannot develop in the target itself (Bourgeois *et al*., 2000): the EM effect of a resistive CO_2 body in a conductive aquifer can only consist in the diversion about the body of the primary electrical currents generated by the EM source in the aquifer. This by-pass mechanism is known as the "galvanic response" of the resistive target (for a conductor, the galvanic response would consist in the channelling of the primary electrical currents through the target). Since the triggering field at the origin of the galvanic response is electric in nature, such a response is best energized by a galvanic source, which consists of two electrodes A and B injecting current into the ground (grounded bipole): this kind of source mainly produces electric field, as opposed to an ungrounded closed loop (magnetic source) that mainly produces magnetic field.

Given the interest of the supercritical state for storage efficiency and safety, and given that CO_2 is supercritical at a depth greater than 700-800 m (depending on temperature and pressure gradients), most existing or envisaged CO_2 injections occur below 1000 m. On the other hand, adequate reservoirs with sufficient porosity and permeability are relatively thin (< 100 m) compared to this depth. In these conditions, if the current is injected from standard electrodes at the surface, it is anticipated that the fraction of current flowing through the reservoir will be small and that the CO_2 response will be close to the background noise (Figure 1a).

Consequently, we advocate the use of deep metallic casings, acting as long electrodes, to distribute the current deeper into the ground. This distributed current source, designated as LEMAM (for Long Electrode Mise A la Masse), is slightly different from the conventional MAM (Mise A la Masse), in which the injection is performed by a point electrode at the reservoir depth (requiring the absence of casing). A first field trial performed on an active oil-field (located near Montargis, Loiret, France), using a pair of 700 m water-injection wells for injecting the current, has shown the quality of the grounding obtained with such long electrodes: the global contact resistance was less than 1 ohm for the two wells. As a result, it was possible to inject a high-intensity current (>10 A) with a transmitter of moderate power (3 kW) and to observe a good signal-to-noise ratio up to several kilometres from the source.

Whatever the injection scheme, the CO_2 response will be measured periodically, in a time-lapse implementation, using standard electric/magnetic sensors scattered at the ground surface. For each survey repetition, the time-lapse CO_2 response will be calculated as the electric (and possibly magnetic) field difference between the last dataset and the previous one ("sequential" differencing) or between the last dataset and the initial "baseline" measured before CO_2 injection ("global" differencing).

Numerical simulations are presented for a generic model representative of an area in the SE of the Paris Basin, where the aquifer envisaged for CO_2 sequestration is a 75-m-thick carbonate formation of Bathonian age (Dogger oolite), located at a depth of about 1700 m below ground surface. The CO_2 plume is simplified to a square or rectangular horizontal slab, with sides of 1 to 3 km, 70 m thick, floating at the top of the reservoir. A uniform CO_2 saturation of 70% (by default) is assumed throughout the plume, corresponding to a resistivity contrast of 11 with the initial aquifer (applying Archie law with n=2). Most models are calculated with a 0.5 Hz time-harmonic source current.

Several aspects of the simulated responses are examined:
- LEMAM current injection vs. standard short-electrode injection at the surface,
- electric vs. magnetic responses,
- influence of the conductivity and thickness of the saline aquifer, compared to that of the other layers intersected by the long electrodes,
- shape and location of the CO_2 plume
- CO_2 saturation in the plume (50 to 80%).

For example, Figure 1 shows that the LEMAM current injection array permits to multiply by a factor of 3 the time-lapse electric response of the CO_2 plume at the surface, as compared to a standard point-electrode injection. Figure 2 illustrates the good horizontal resolution achieved with the LEMAM array, the time-lapse electric field directly giving a clear image of the horizontal shape of the plume, without any inversion nor any transformation in apparent resistivity or other normalization process.

Acknowledgements
This work is supported by the French National Research Agency (ANR) under programme "*Captage et Stockage du CO_2*", as part of the project "EMSAP-CO_2" (ANR 07-PCO2-001-02, 2008 to 2010). It benefited from a previous study carried out in the project "Géocarbone-Monitoring", also supported by the CO_2 programme of the French ANR (ANR 05-CO2-008, 2006 to 2008). Toreador Energy France is acknowledged for authorizing the field test of the LEMAM injection in the Montargis area (Loiret).

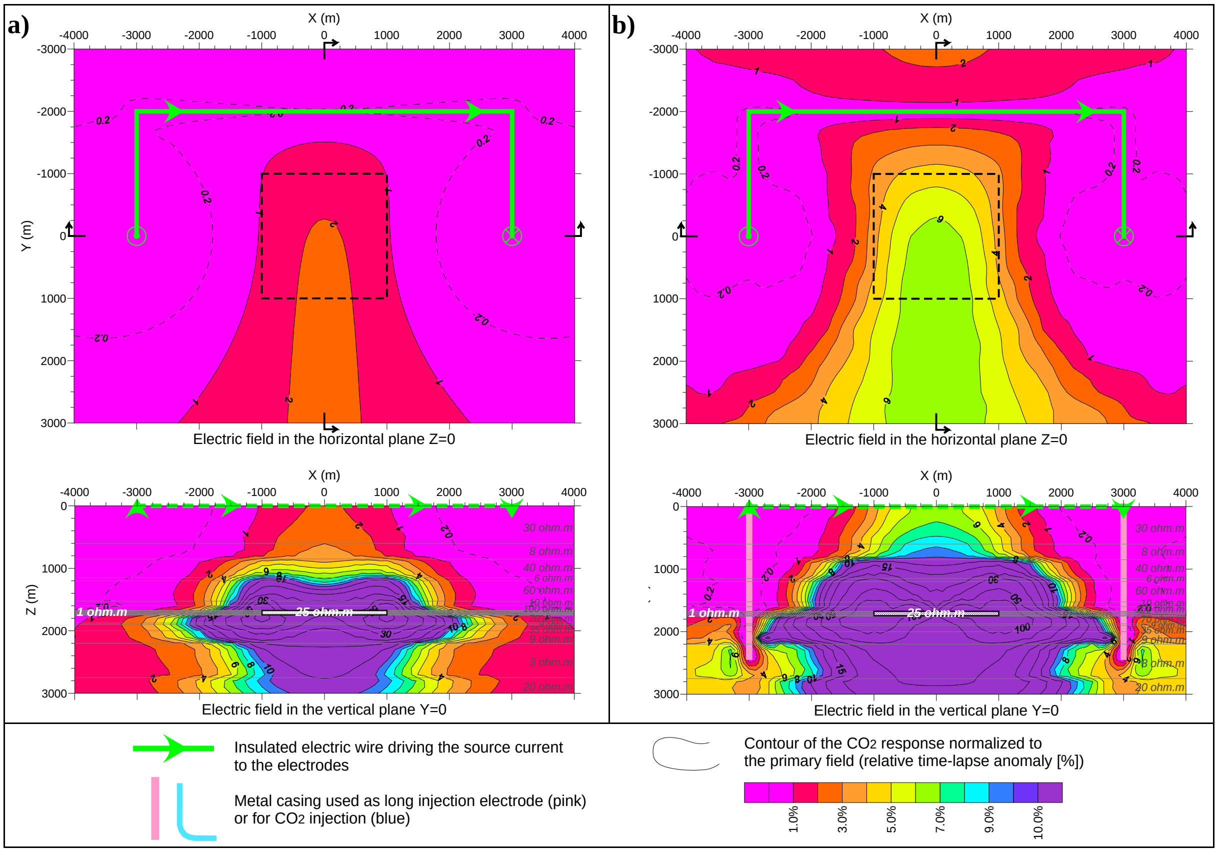

Figure 1: Time-lapse electric response (major axis of the polarization ellipse) obtained at 0.5 Hz from a 2 km´ 2 km´ 70 m CO_2 bubble, of 25 ohm.m resistivity (S_{CO2}=80%), embedded in a 1 ohm.m reservoir a) for a short-electrode injection at the surface; b) for a LEMAM injection via a pair of vertical casings (2400 m long). In both cases, the electrodes are separated by 6 km. The response is expressed as a percentage of the magnitude of the electric field calculated without CO_2 bubble (*i.e.* initial field before injection). Since the repetition noise is presently estimated to about 1% of the initial field, responses below 1% are deemed to be non measurable.

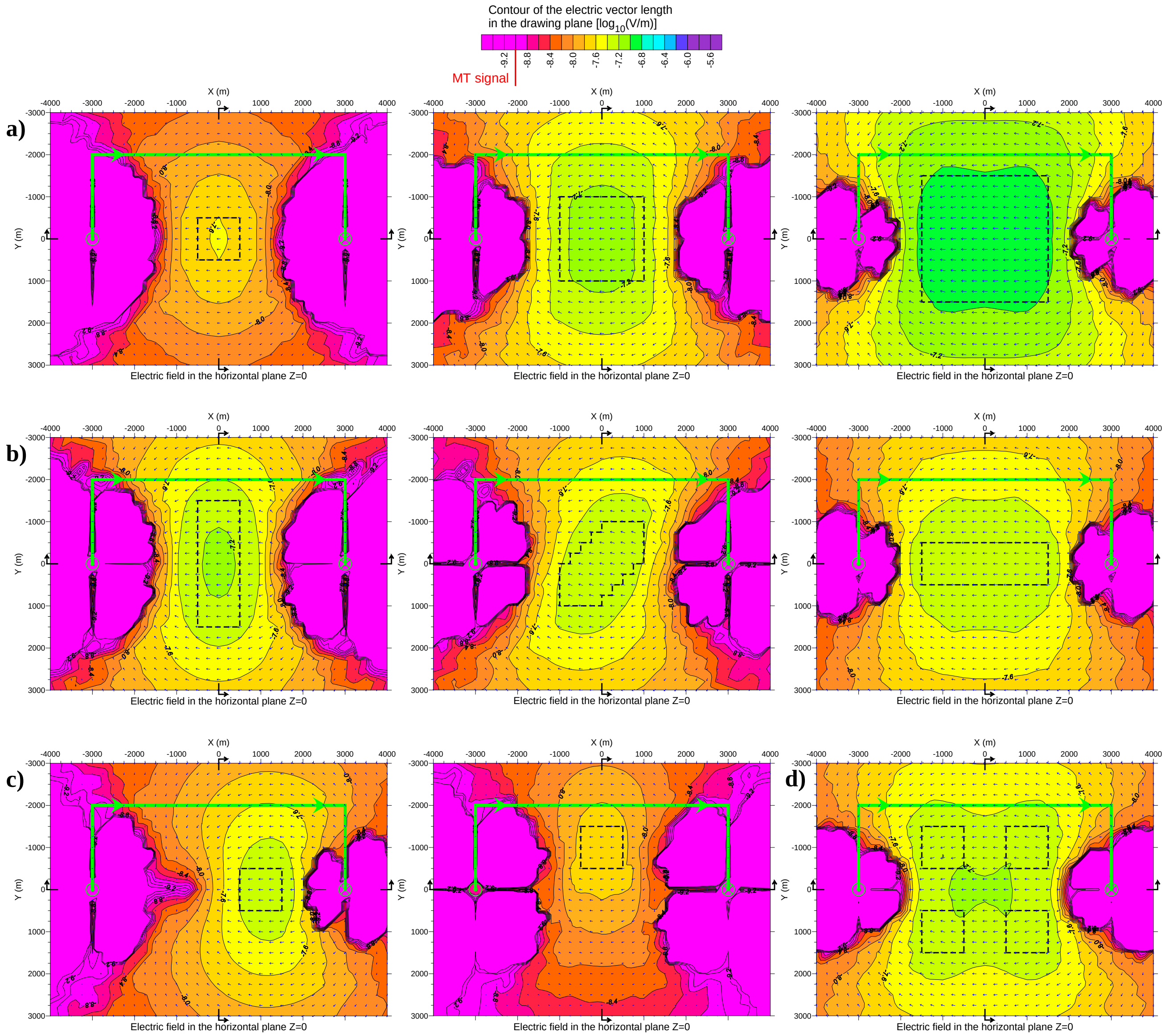

Figure 2: In-phase secondary electric field at 0.5 Hz from a 70 m thick CO_2 bubble of 10 W.m resistivity (S_{CO2}=70%), embedded in a 1 W.m reservoir at 1700 m depth, for a LEMAM injection via a pair of 1900 m long vertical casings. The different plots correspond to different geometries of the CO_2 bubble in the horizontal plane a) variations in size, b) variations in strike, c) variations in location and d) broken bubble. The coloured contours represent the magnitude (norm) of the in-phase time-lapse electric field in $\log_{10}$(V/m) for a 1A source current. The elementary bubble (1 km´ 1 km) shown in the top-left corner of the figure represents about 5 Mt of CO_2 in the physical conditions of the Dogger aquifer.

References

Bourgeois B., Suignard K., and Perruson G., 2000. Electric and magnetic dipoles for geometric interpretation of three-component electromagnetic data in geophysics, Inverse Problems, **16**, 1225-1261.

Bourgeois B., Girard J-F., submitted. First modelling results of the EM response of a CO2 storage in the Paris Basin, submitted to Oil & Gas Science & Technology (OGST) journal.

Daily W., Ramirez A., Newark R. and Masica K., 2004. Low-cost reservoir tomographs of electrical resistivity. The Leading Edge, **23**, 472-480.

Hatanaka H, Tetsuo A, Mizunaga H and Ushijima K, 2005. Three-dimensional modelling and inversion of the Mise-a-la-Masse data using a steel-casing borehole. Proceedings of the World Geothermal Congress, Antalya, 24-29 April 2005.