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New developments in CSEM (Controlled Source EM) for reservoir characterization and monitoring.

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The use of CSEM onshore monitoring for CO₂ plume migration characterization completes the information brought by seismic methods (localisation of saturation fronts): it is sensitive to the positive resistivity variations in the aquifer induced by supercritical CO₂ injection. Once a baseline 3D seismic survey is done and the structural seismic horizons are known, CSEM monitoring could compete with seismic monitoring because of its really low cost and its ease of implementation. CSEM monitoring also brings complementary information to the electrical methods of monitoring: the depth of investigation is significantly higher than electrical methods, and CSEM permit to inject multi-frequency currents in the ground (which allows a multi-scale scanning of the subsurface). Electrical methods have a very narrow resolution in the superficial subsurface while CSEM map greater depths and larger volumes. Moreover, CSEM surveys are also easy repeatable due to developments in current injections devices and the use of differential GPS monitoring of surface electrodes positions.

Accuracy of CSEM double LEMAM ("Longue-Electrode-Mise-à-la Masse", using boreholes metallic casings as long electrodes) and double MAM method ("Mise-à la Masse", using downhole electrodes) for CO₂ injection monitoring has been tested several times. While the repeatability noise is of a 1% order (shown by *Bourgeois et al., 2012a*), the electromagnetic response of a CO₂ plume in a 1-km deep saline aquifer can reach several percents respect to the original baseline fields (*ie* pre-injection measurements), depending on the source and reservoir setup. Both double LEMAM and surface-to-LEMAM (or single-LEMAM) setups are particularly suited for deep CO₂ injection monitoring because they are based on current injection directly in the deep aquifer layers using the borehole metallic casings as electrodes. The BRGM knowledge in this domain has been constructed on several consecutive and coherent projects (EMSAPCO₂, CO₂ReMoVe, CO₂CARE and EM HONTOMIN) integrating field operations, data processing, uncertainties analysis and modeling (Bourgeois et al., 2012b).

Double MAM CSEM monitoring proved its ability to map the CO₂ plume and to characterize its migration during the Ketzin experiment (Girard et al., 2011). CSEM fields (electric and magnetic fields) measurements showed variations above the repeatability noise and spatially associated with the CO₂ plume migration at short/medium term migration process (the CSEM method was at least able to detect a 17200 t CO₂ bubble propagating at 700 m depth).

At Hontomín, a CSEM baseline dataset has been acquired in December 2013 using a new type of CSEM source, involving surface electrodes and one borehole casing, the so-called surface LEMAM setup, which is supposed to be more sensitive to a CO₂ plume than the classical double LEMAM setup (results to be published). The Hontomín experiment is challenging for the CSEM approach because a lower volume of CO₂ than Ketzin will be injected at a depth twice the injection depth at Ketzin. Our strategy to overcome these conditions was to use a dense network of CSEM receiver station, with multi frequency acquisition, two different geometries of source polarization and current injection directly in the reservoir by the surface-LEMAM method. First results will be presented.

In addition, in order to assess the feasibility of CSEM imaging for reservoir characterization, we will also present one application in the frame of geothermal exploration: a CSEM survey was

performed at the Le Lamentin area (Martinique, French Indies) using 400m long energized metallic casings of two deep exploration boreholes as long electrodes for current injection (the so-called double Longue Electrode Mise-à-la-Masse setup, hereafter 2xLEMAM). Imaging results (frequency dependent apparent resistivity maps and profiles) reveal a very conductive area north of the Fort de France Bay connected to a known poly-phased geothermal system and shallow salt water intrusion. The most conductive body is proposed to be the geo-electrical signature of an active hydrothermal system, superimposed on the signature of a conductive fossilized geothermal system. It is spatially well correlated with high temperature borehole logs. Meanwhile, low temperature areas associated with the fossil hydro-thermal system plugged by clay minerals display less conductive values.

Bourgeois, B., Coppo, N., Girard, J.F. (2012). Tests de reproductibilité de la méthode LEMAM sur un site pétrolier près de Chuelles (Loiret) - Influence du bruit ambiant et des variations d'humidité saisonnières. *BRGM report*. BRGM/RP-60982-FR

Bourgeois B., Rohmer J. et Girard J.F., 2012, Étude par modélisation numérique des performances de l'électromagnétisme appliqué au monitoring des stockages de CO₂ - Influence du contexte géologique et effet des variations extérieures au réservoir. Rapport BRGM/RP-60981-FR.

Girard, J. F., Coppo, N., Rohmer, J., Bourgeois, B., Naudet, V., & Schmidt-Hattenberger, C. (2011). Time-lapse CSEM monitoring of the Ketzin (Germany) CO₂ injection using 2× MAM configuration. *Energy Procedia*, 4, 3322-3329.
