3D modelling for time-lapse cross-well CSEM monitoring of CO2 injection into brine filled reservoirs.

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SUMMARY

Carbon Dioxide (CO2) sequestration is one proposed solution to the possible detrimental effects of increased CO2 emissions into the Earth's atmosphere. A proposed method for CO2 sequestration is capture and storage below the earth's surface in deep saline reservoirs. Australia's CO2CRC research group is currently trialling this method of CO2 sequestration by injection into the Paaratte formation in the Otway Basin Australia. As CO2 is injected into brackish or saline water saturated sediments it is expected to create a zone of increased electrical resistivity around the injector well. The cross-well controlled-source electromagnetic method may be capable of mapping the movement of injected CO2 as it expands out from the injection interval.

We simulate time-lapse in-hole controlled source electromagnetic surveys using expected change in electrical resistivity that might be associated with CO2 injection. We demonstrate that controlled source electromagnetic methods will successfully monitor CO2 injection given; (i) suitable transmitter type and frequency range; (ii) a monitoring well design that can facilitate the electrical methods and (iii) correct monitoring well location relative to the injection well. In particular we find that, because of the large volume of CO2 that would likely be injected during a large sequestration project even relatively small changes of less than 10% in electrical resistivity associated should be readily detectable. We provide images of the time lapse cross well electromagnetic response for an expanding disk representing 0.1 to 10 kilo tonne of CO2.

Key words: Time-lapse, Cross-well, Controlled-source, Electromagnetic, Sequestration.

INTRODUCTION

Through to the foreseeable future, fossil fuels will continue as the primary energy supply locally within Australia and globally. The International Energy Agency predicts a 40% increase in global energy demand by 2030 (CO2CRC, 2010). The combustion of these fossil fuels to meet global energy demands follows the reaction, Hydrocarbon + Oxygen = Carbon Dioxide + Water + Energy (Chemical Formula, 2011). Substantial increases in carbon dioxide (CO2) resulting from increased energy demand are said to be in part responsible for climate change that may have future detrimental effects (Time for change, 2011).

CO2 sequestration is proposed as a possible solution to mitigate consequences of rising CO2 emissions. For CO2 sequestration CO2 is captured before it is emitted into the environment and injected into the Earth's subsurface. Large deep saline sandstone formations have been identified as reservoirs that may be suitable for subsurface storage of CO2. A trial CO2 sequestration project is being completed by Australia's CO2CRC research group. This group will trial the injection of CO2 into the Paaratte formation in the Otway Basin, Victoria, Australia. The injection of CO2 into such saline sandstone reservoirs would likely result in an expanding zone of increased electrical resistivity around the injector well. The time lapse cross-well controlled source electromagnetic (CSEM) method may potentially be capable of mapping the migration of CO2 into the formation.

One possible cross-well CSEM survey configuration may consist of a vertical electrical bipole transmitter at frequencies in the approximate range 1 – 10000 Hz. The transmitting antenna could be either electrical or magnetic. At present the only cross-well CSEM systems commercially and readily available are based on vertical magnetic dipole (VMD) transmitting and receiving antennas (SLB, 2008). While the VMD antennas are the only transmitters in use a good case could be made for development of a vertical electrical bipole cross well CSEM source (Harris and Pethick 2011).

For operation of the cross-well CSEM method the transmitter could be located towards the bottom of the specifically designed monitoring well and towed up hole several times using a different monochromatic frequency for each run. The resultant EM field could be recorded in one or more wells by an array of receiving antenna (e.g. SLB, 2006). Alternatively a time domain CSEM would potentially require only one run with the transmitting antenna. Here a challenge would be to create sufficient transmitter moment.

A cross-well CSEM survey is appropriate for monitoring CO2 injection due to the change in electrical resistivity associated with CO2 injection (Borner, 2009). We note that in reality the injection of supercritical CO2 may generate a complex change chemistry depending of formation and water chemistry and hence in detail resistivity changes are not simple (Fleury, 2008). However the key point is that CO2 injection will create a change in electrical resistivity with time and that should be readily detectable by the cross well CSEM methods.

Cross-well CSEM numerical modelling was completed with two principle objectives:

> To establish a basic understanding of the amount of CO2 that could potentially be detected with the cross-well CSEM method.

To simulate the expected outcome from a time lapse CSEM survey in section and plan view for injection into a single thin brackish water saturated sandstone interval such as might be expected in the Paaratte formation of the Otway basin.

METHOD

The CSEM modelling interface 'CSEMoMatic' (Pethick, 2011) was used to complete all numerical simulations and visualisations presented in this paper. CSEMoMatic is an open source single graphic user interface, incorporating a broad range of CSEM code (see: http://www.MCSEM.com and AMIRA, 2011). Shapes for the modelled 3D bodies were an approximation of a cylindrical disk, expanding laterally over time.

Baseline modelling was completed with a cross-well CSEM configuration located in a layer Earth. The open source CSIRO developed code MARCO was used for modelling (AMIRA, 2011). The model was made of a 20 Ohm.m thin resistive layer located at 1485m depth. It thickness was 10m and host resistivity was 10 Ohm.m. The geo-electrical model broadly simulated a high permeability sandstone layer within a more shale dominated formation as might be expected within the lower part of Paaratte formation in the Otway basin.

After 1D modelling was completed a time-lapse CSEM survey for CO2 injection was simulated. The simple model was intended simulate CO2 injection into a single thin sandstone layer saturated with brackish water. This transmitting antenna used was a vertical electrical dipole with monochromatic frequency set to 100Hz. The transmitter well was offset by 300m from the site of CO2 injection (Figure 1).

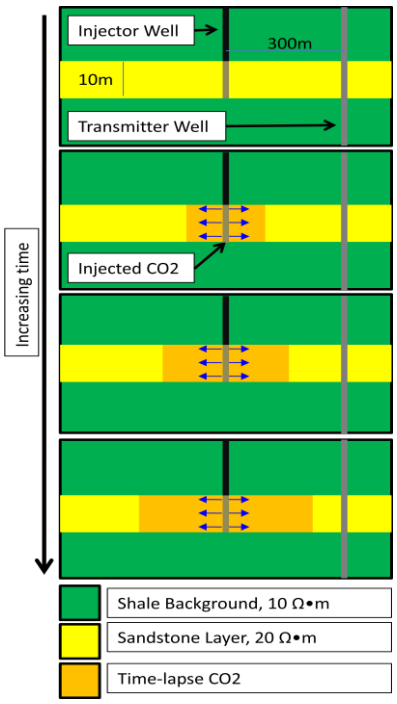

Figure 1 - Time lapse model of CO2 injection. Injected CO2 is expected to travel further out into the formation as the period of injection increases over time.

The time lapse CSEM changes that might be recorded can be represented in a number of ways. One method is to show the normalized electric field as presented below in equation 1:

$$Nomralized\ electric\ field = \frac{Total\ E\ Field - Background\ E\ Field}{Background\ E\ Field} * 100\ (eq\ 1)$$

The normalized electric field is simply the percent change in electric field after CO2 injection with reference to the pre-injection electric field.

We would note that it is always important to represent the actual amplitude changes and with EM normalized fields can shift attention away from where the largest total change in electric field amplitude has occurred.

RESULTS AND DISCUSSION

We compute many simulations to illustrate the time lapse response for a range of transmitter types and frequencies. The electric and magnetic fields generated by the transmitter are always computed for the full 3D volume around the injector well. Electric and magnetic fields from all transmitter positions are preserved such that the electric or magnetic fields for any arbitrarily located well (i.e. at any distance from the injector well) can be retrieved. We compute examples for a full range of transmitter positions and frequencies and illustrate one example in plan and section view provided as Figures 3 and 4. We use the normalization described (i.e. *eq* 1) to highlight the time-lapse response. An injection rate of 100 tonnes of CO2 per day is used in the time-lapse calculations. We include simulations at a total injected CO2 volume of:

(i) 0.1 kT (i.e. 1 day of injection)
(ii) 1 kT (i.e. 10 days of injection)
(iii) 10 kT (i.e. 100 days of injection)

As we cannot be sure exactly what the associated change in resistivity will be with the injected CO2 we will simulate a range of possibilities including (see figure 4 and 5):

(i) Resistivity will increase by 10 % to 22 Ohm.m
(ii) Resistivity will increase by 25 % to 25 Ohm.m
(iii) Resistivity will increase by 50 % to 30 Ohm.m

Our simulations reveal a normalised total electric field of the order 2% when 0.1 kT of CO2 is assumed to result in resistivity of 22 Ohm.m is injected into the sandstone layer. At the other extreme when resistivity increases to 30 Ohm.m and injected CO2 tonnage is at 10 kT (i.e. 100 days of injection) a change of greater than 100% in normalized total electrical field is modelled.

The borehole response 200m from the injector well shows a large spike in the normalised Ex and Ez components (Figure 2).

In section view a change in the normalised total electric field can be measured approximately 100m from the injection site at the lower limit of the simulation (Figure 3, upper left). Upper limit calculations show a change in normalisation is able to be measure at more than 300m from the injection site (Figure 3, lower right).

In plan view (Figure 4) the depth slice is taken at 1480m depth, 5m above the target layer. These simulations show that not only can the change in normalised amplitude be measured in one dimension but out in any direction from the injector well.

The predicted simulations are only of practical significance if the changes after signal-to-noise are considered. For that reason it is helpful to understand the factors affecting noise that may exist for the cross-well CSEM method. At the transmitter and receiver depths simulated high frequency noise (i.e. spherics) is attenuated and almost insignificant after 1km depth. Measurements are expected to be less than 100nV, above the expected noise floor for the simulated CO2 injection scenarios. Basically cross-well CSEM measurements should be readily repeatable to great accuracies with modern instrumentation. The type and arrangement of monitoring wells and inversion may be of more importance.

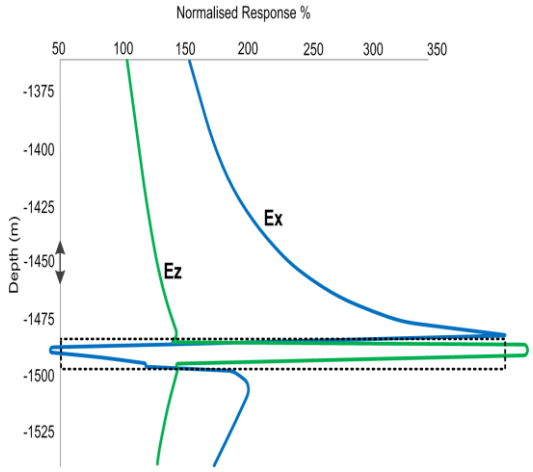

Figure 2 - Normalised receiver borehole response of Ex, Ez at 200m offset from the injector well. The background injection layer is 20 Ohm.m and the injected CO2 is 30 Ohm.m. Clearly Ex is not practical as a receiving antenna, however Ez is certainly a reasonable proposition.

CONCLUSIONS

We find that suitably configured in-hole CSEM methods should be highly sensitive to time lapse changes in electrical resistivity associated with CO2 injection into a brackish or saline formation.

Simulations show that CO2 injection into a brackish or brine filled water saturated sandstone reservoir can be detected with the time lapse cross-well CSEM methods even if the CO2 injection is associated with relatively small changes in electrical resistivity. We show that changes of less than 10% should be readily detectable for high volume CO2 sequestration. Success with practical application of cross well CSEM methods is highly dependent on selection of a suitable survey configuration (i.e. transmitter type, frequency, monitoring well separation and location relative to the injection well).

Yes, cross-well CSEM works however considerable due diligence is required prior to design of both the acquisition system and type/arrangement monitoring wells.

ACKNOWLEDGMENTS

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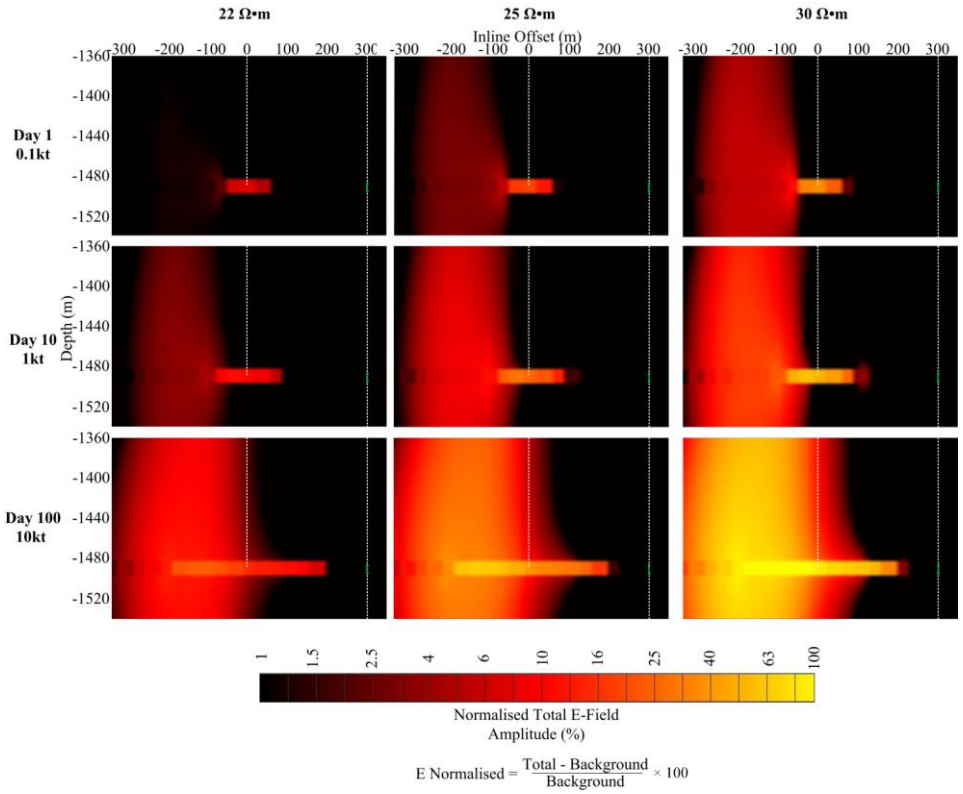

Figure 3 - Cross section view of the Normalised Total Electric field at various stages of CO2 injection. The background injection layer is 20 Ohm.m. The simulations compares set the change in resistivity resulting injected CO2 injection at 22, 25 and 30 Ohm.m. The actual change in resistivity will be far more complex than the simple expanding block suggests (Nakatsuka, 2009). However the change would certainly be expected to fit within the ranges shown.

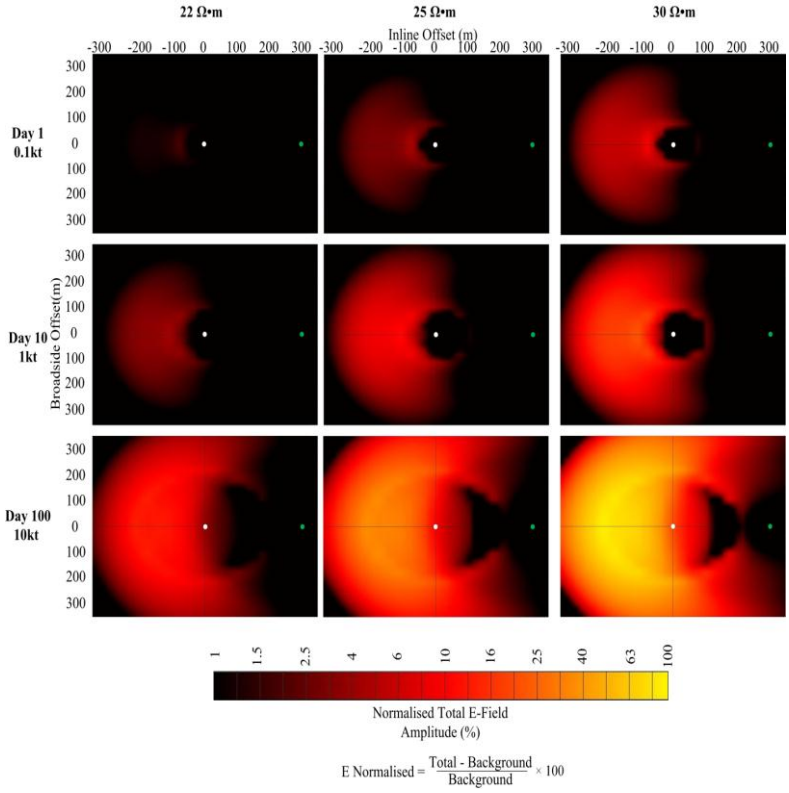

Figure 4 - Plan view of the Normalised Total Electric field at various stages of CO2 injection. The depth slice is located at 1480m, 5m above the CO2 injection. The green and white dots represent the vertical electrical dipole and injection well respectively.