Monitoring CCS/CCUS using charged wellbore CSEM

Trevor Irons[1]; Rich Krahenbuhl[2], Yaoguo Li[2], Jiajia Sun[2], Nathan Moodie[1], Ben Bloss[3]

[1]University of Utah, Energy & Geoscience Institute, Dept. of Civil & Environmental Engineering
[2]Colorado School of Mines, Center for gravity eletrical and magnetic studies, Dept. of Geophysics
[3]United States Geological Survey, Crustal Geophysics and Geochemistry Science Center

Summary

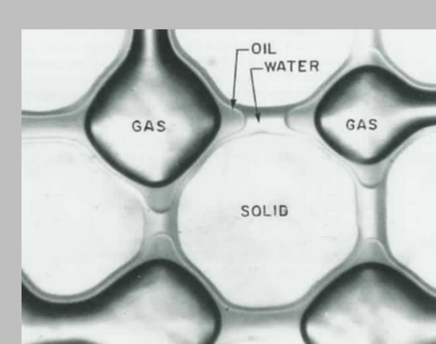
Monitoring CCS/CCUS projects is of critical importance in order to verify plume migration and sweep for hydrocarbon production as well as meet regulatory monitoring requirements. Geophysical imaging methods could greatly enhance well based point observations. However, geophysical monitoring of CCS projects is often challenging due to the depths involved and relatively modest change in fluid densities. Additionally, many imaging techniques are not sensitive to fluid phase, which is of primary importance in a CCUS monitoring project. Electrical and electromagnetic methods are promising techniques as the CO_2 phase will present as a large resistive body within a depleted reservoir of conductive saline water. Additionally, dissolved CO_2 in the oil phase will also be resistive. The depths involved place a high cost on drilling and traditional electrical resistance tomography methods can easily become cost-prohibitive in a CCUS project. However, many CCUS projects contain a large number of legacy boreholes which have been used for production, injection, or monitoring over the life of the field. We propose using these legacy borehole casings as long deep electrodes in a controlled source electromagnetics survey which penetrate the reservoir of interest, as well as the overburden. Measurements of the electrical and magnetic fields on the surface can be used to reconstruct the electrical conductivity of the subsurface; which, when combined with reservoir simulations, can be used to monitor changes in fluid phase within a CCUS project.

Fundamentals of relative permeability

matrix properties
- pore geometry
- wetting characteristics

fluid properties
- density (ρ)
- viscosity (μ)
- interfacial tension

scale dependent
- continuum scale measure of pore scale phenomenon
- secondary porosity effects



Two-phase Darcy equations

$$q_{nw} = -\frac{\kappa_{rnw}\kappa}{\mu_{nw}}\left(\frac{\partial P}{\partial z} + \rho_{nw} g\right)$$
$$q_{w} = -\frac{\kappa_{rw}\kappa}{\mu_{nw}}\left(\frac{\partial P}{\partial z} + \rho_{nw} g\right)$$

Resistivity to saturation relations

Phase saturations are a manifestation of reservoir conditions: geometry, injection, production, relative permeability, capillarity, etc. Resistivity relations to (e.g. Glover et al., 2006; Berg, 2012).

Archie's Law $R_t = a\phi^{-m}S_w^{-n}R_w$

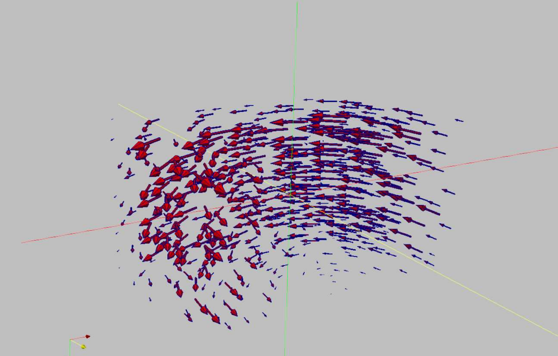
Waxman-Smits $\phi_t^m S_{wt}^n \left(\frac{1}{R_w} + \frac{BQ_V}{S_{wt}}\right)$

- R_t saturated rock resistivity
- a tortuosity factor
- ϕ porosity
- m cementation factor
- S_w saturation of water
- R_w brine resistivity

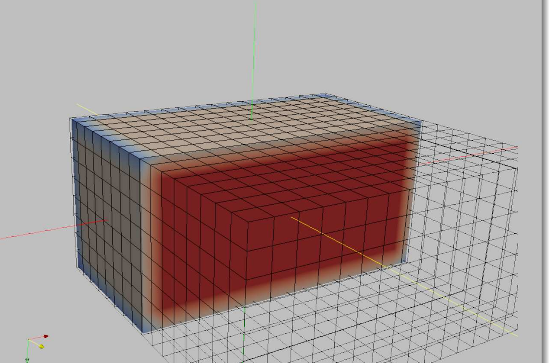
Electromagnetic methods

Maxwell's equations (1-4) describe the interconnected relationship between electrical **E** and magnetic (**B** $= \mu$**H**) fields. Incident fields (a) on conductive anomalies (b) will result in charge acccumulation on the boundaries (c) and a secondary electrical field (d).

$$\nabla \times \mathbf{E} = -\jmath\omega\underline{\mu}\mathbf{H} \quad (1)$$
$$\nabla \times \mathbf{H} = (\underline{\sigma} + \jmath\omega\underline{\epsilon})\mathbf{E} + \mathbf{I}_E \quad (2)$$
$$\nabla \cdot \mathbf{B} = 0 \quad (3)$$
$$\nabla \cdot \mathbf{E} = \frac{\rho_f}{\underline{\epsilon}} \quad (4)$$



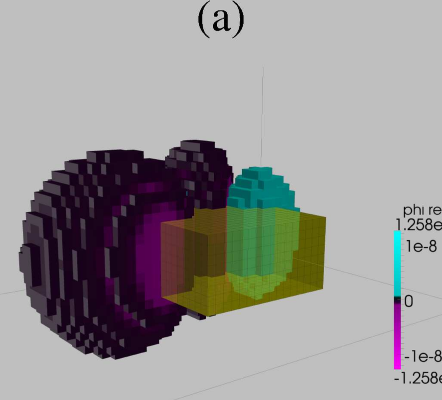
(a)



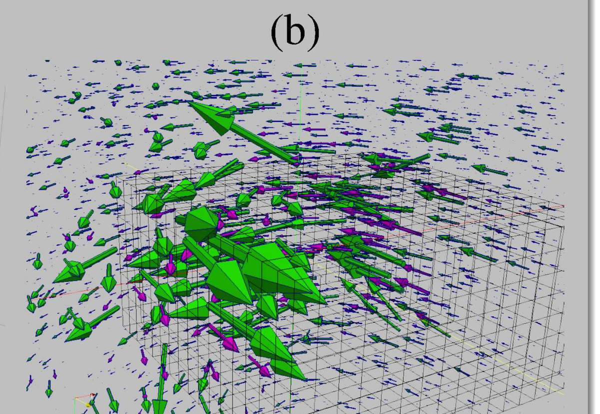
(b)

Which can be reformulated in terms of a vector and scalar potential (**A** and ϕ) (Irons et al., 2012; Irons and Li, 2013) which has several attractive attributes including improved numerical properties and memory efficiency.

$$\nabla^2\mathbf{A} - \jmath\omega\mu_0\underline{\sigma}\mathbf{A} - \mu_0\underline{\sigma}\nabla\phi = -\mathbf{s}_E$$
$$\nabla\cdot\mathbf{A} = 0$$
$$\mathbf{s}_E = \mu_0\underline{\sigma}'\mathbf{E}_0.$$

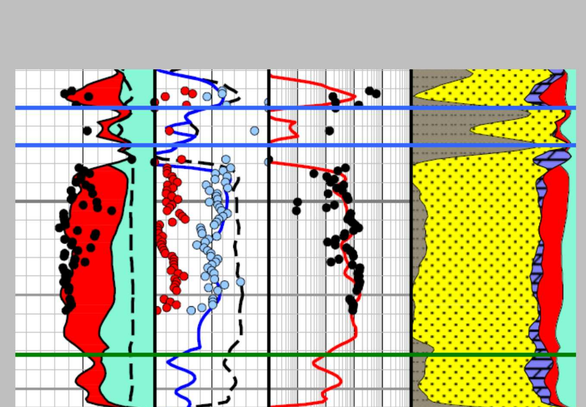


(c)

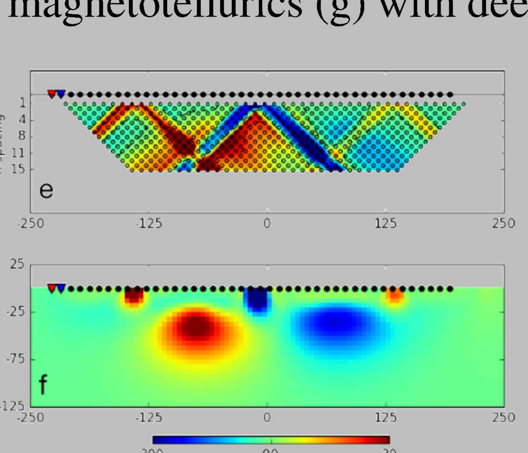


(d)

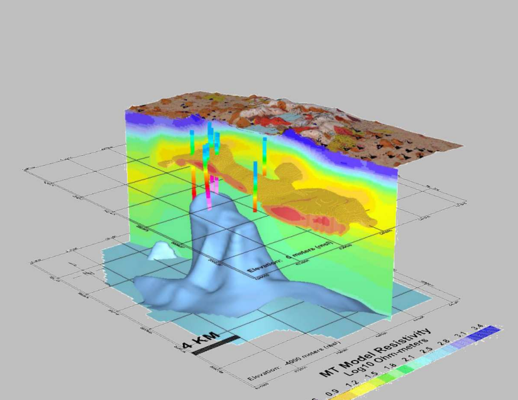
Electrical and EM methods commonly used for subsurface characterisation include wireline logs (e) that do not probe deeply into the formation and require drilling, electrical resistance tomography (f) with shallow depth of resolution, and magnetotellurics (g) with deep investigation but low resolution.



https://www.spec2000.net
(e)



http://gpg.geosci.xyz
(f)

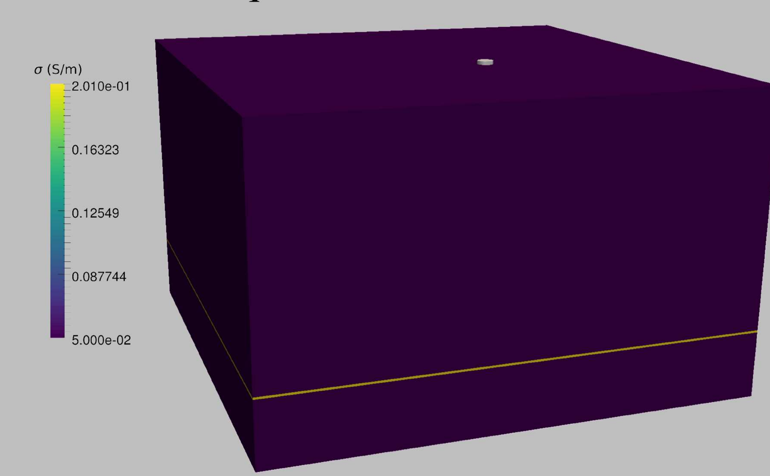


https://www.spec2000.net
(g)

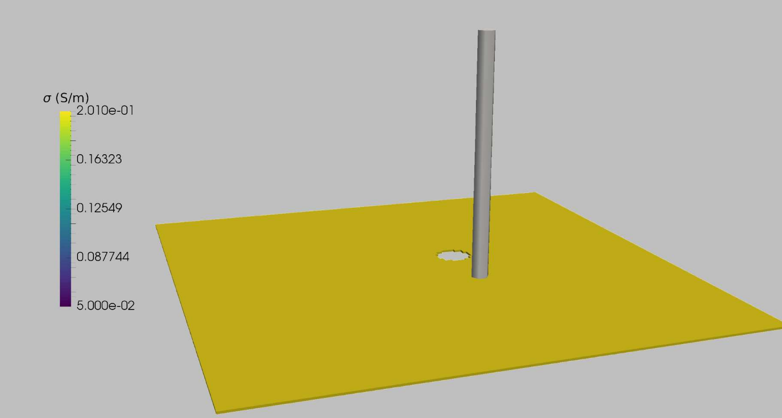
CWC-CSEM

Legacy boreholes can be used as long galvanically coupled electrodes allowing for much deeper current injection providing much greater depth of investigation and resolution. CCUS operations on depleted oilfields often have many legacy wellbores that are not active in production or injection

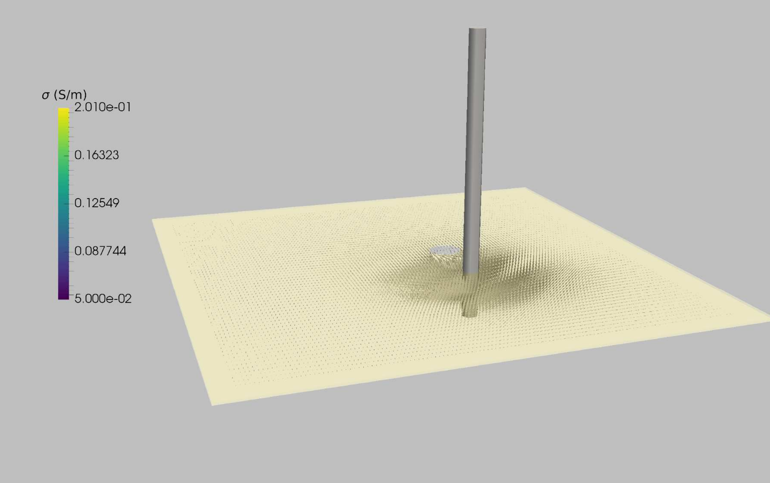
- CWC-CSEM avoids prohibitive drilling costs needed for crosswell ERT methods
- CWC-CSEM requires no access to wellbore internals



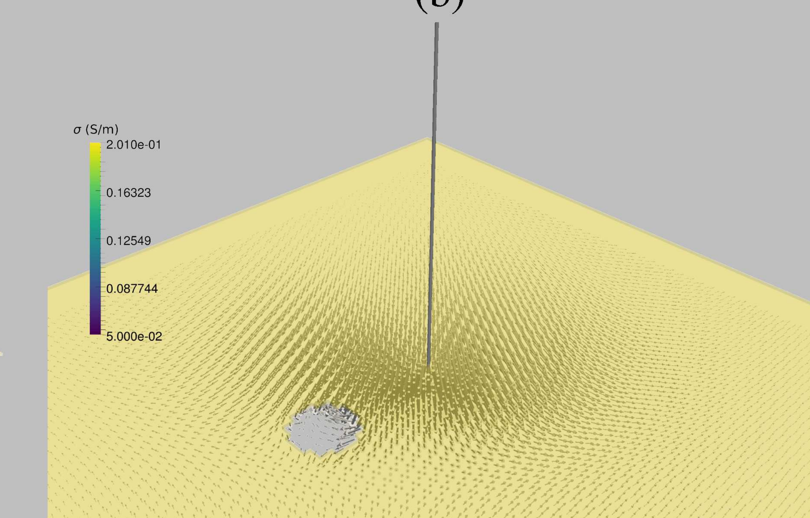
(a)



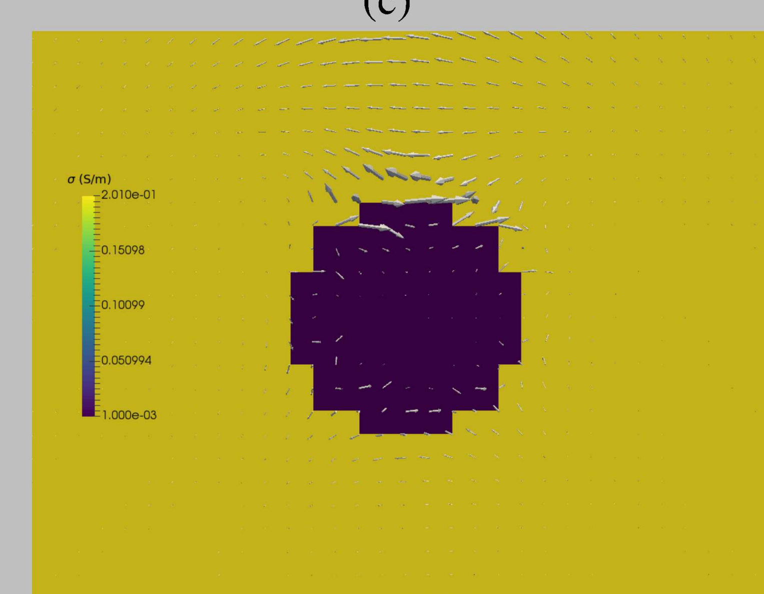
(b)



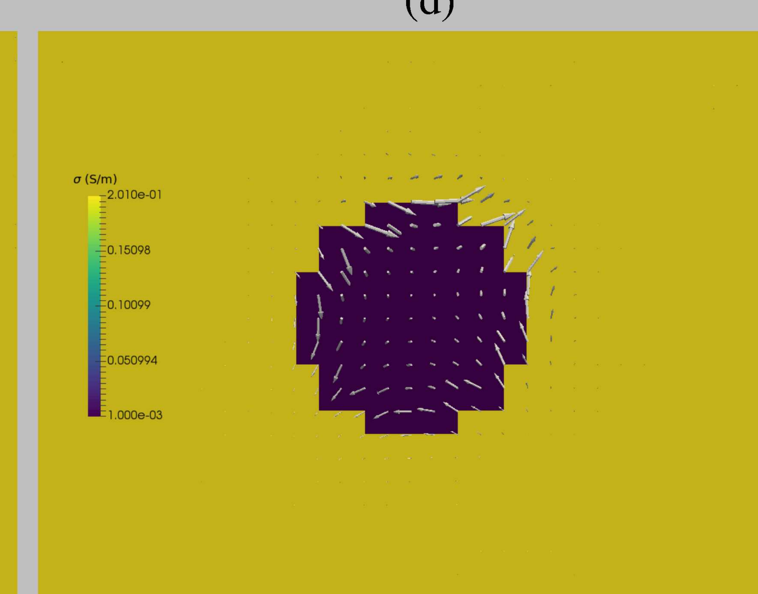
(c)



(d)



(e)



(f)

Current injection utilizing existing borehole as a deep electrode (a-d). A simplified CO_2 is modeled as a resistive body. Inphase (e) and quadrature (f) **E** fields preferentially flowing around resistor.

Field measurements

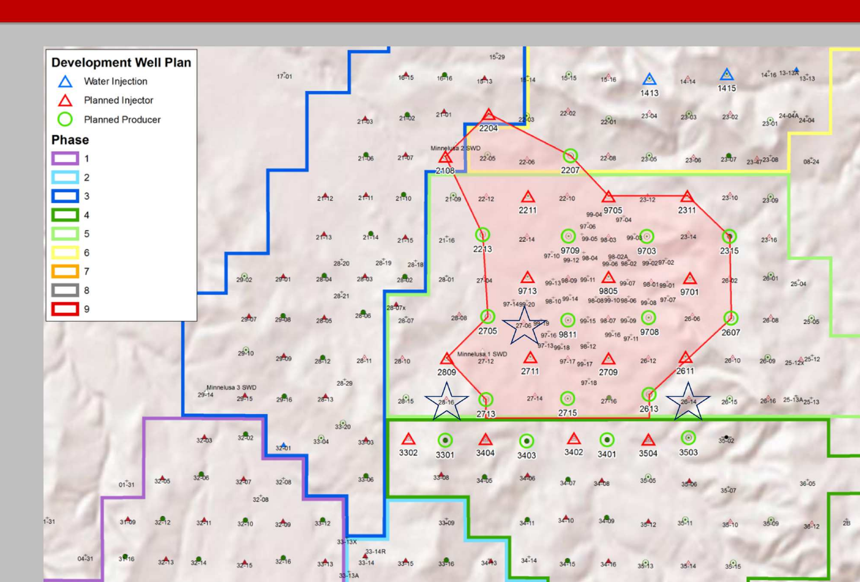
Surface activities are minimally invasive and require the temporary installation of non-polarizable electrodes which differentially measure the **E** field as well as magnetic field coils which measure $\partial H/\partial t$.

H sensor

electrode

Belle Creek, MT

- in field from 14-18 August 2017
- baseline survey
- Phase 5 operations at the Bell Creek site operated by Denbury Resources, Inc
- CO_2 injections to begin shortly
- additional time-lapse monitoring surveys
- inversions constrained and coupled with reservoir simulations



Acknowledgements

The authors gratefully acknowledge funding for this work through DOE/NETL award number FE-0028320. Collaborative partnership with Denbury Resources Inc. and the University of North Dakota Energy & Environmental Research Center are further acknowledged.

References

Berg, C. F., 2012, Re-examining archie's law: Conductance description by tortuosity and constriction: Phys. Rev. E, **86**, no. 4, 046314.

Glover, P., I. Zadjali, and K. Frew, 2006, Permeabiltiy prediction from MICP and NMR data using an electrokinetic approach: Geophysics, **71**, F49–F60.

Irons, T., and Y. Li, 2013, 3D frequency-domain electromagnetics modeling using decoupled scalar and vector potentials: 6th international AEM Conference and Exhibition, 1–5.

Irons, T., Y. Li, and J. R. McKenna, 2012, 3D frequency-domain electromagnetics modeling using decoupled scalar and vector potentials: SEG Technical Program Expanded Abstracts 2012, 1–6.