Integrated Model Construction for CO_2-EOR Monitoring via Charged-Wellbore Casing Controlled-Source Electromagnetics

Richard A. Krahenbuhl†, Yaoguo Li†, W. Andy McAliley†, Nathan Moodie‡, Trevor Irons‡, & Benjamin R. Bloss§*
Center for Gravity, Electrical & Magnetic Studies (CGEM), Colorado School of Mines†
Energy and Geoscience Institute, University of Utah‡
United States Geological Survey§

SUMMARY

We present a method for the integrated development of 3D electrical conductivity models for CO_2-EOR monitoring with charged wellbore casing controlled-source electromagnetics (CWC-CSEM). The model is constructed through the multiphysics integration of reservoir simulation, seismic, borehole resistivity, and transient EM (TEM) data. The process is performed in two stages. First, a large background conductivity model is constructed from the combination of seismic, borehole, and TEM data. Second, a more detailed and dynamic component of the model is created within the production interval by converting the reservoir simulation parameters to conductivity through Archie's equation. In this presentation, we demonstrate the complete workflow for building these 3D conductivity site models that can be updated throughout production using the Bell Creek oil field as an example. We then show application of the developed site model to simulating the predicted CWC-CSEM data as one step in the larger problem of reservoir imaging and monitoring of injected CO_2 during enhanced oil recovery.

INTRODUCTION

Carbon dioxide (CO_2) injection for enhanced oil recovery (EOR) extends the life of an oil field through production of otherwise inaccessible resources. The CO_2-EOR hydrocarbon recovery process also inherently results in associated storage of CO_2 incidental to the oil production process. Utilizing anthropogenic CO_2 beneficially results in simultaneously keeping CO_2 out of the atmosphere. A critical component to the CO_2-EOR process is developing reliable and cost-effective techniques for monitoring the CO_2 migration during EOR operations. Reservoir models are generally relied upon in order to optimize field production choices. These models are inherently simplified, and a great deal of uncertainty exists due to non-uniqueness of physical properties with respect to simulated production outputs. As such, there exists an acute need for improved means by which to validate and reduce the uncertainty of these models.

DOE-NETL Project DE-FE0028320 is a multi-faceted study focused on the use of charged wellbore casing controlled source electromagnetics (CWC-CSEM) for reservoir imaging and monitoring of injected CO_2 during enhanced oil recovery. A crucial aspect of the project is to understand and reproduce the link between reservoir simulation models and geology to the physical property distributions at the site. Such a link has the ability to guide the CWC-CSEM field surveys at the front end, and act as a feedback mechanism into the reservoir simulations at the back end. Within this project, we have developed a practical method for establishing such a link between the reservoir simulation models of the CO_2-EOR field site, the large-scale 3D conductivity variations above and below the reservoir, and the 3D and time-varying distributions of electrical conductivity from production activities. In this presentation, we provide details into the underlying workflow developed to create such a 3D and time-varying conductivity site model and demonstrate its application to the simulation of predicted CWC-CSEM data.

SITE BACKGROUND

The Bell Creek field is located along the northeastern flank of the Powder River Basin in south-east Montana (McGregor and Briggs 1968). The producing formation is the Muddy Sandstone (Figure 1), a low angle westward dipping high permeability and porosity sandstone that pinches out to the east (Berg and Davies, 1968; Weimer *et al.*, 1988). The formations above and below are oil rich shale formations that provide the source rock, as well as create an ideal stratigraphic trap for the Muddy (Berg and Davies, 1968; McGregor and Briggs, 1968).

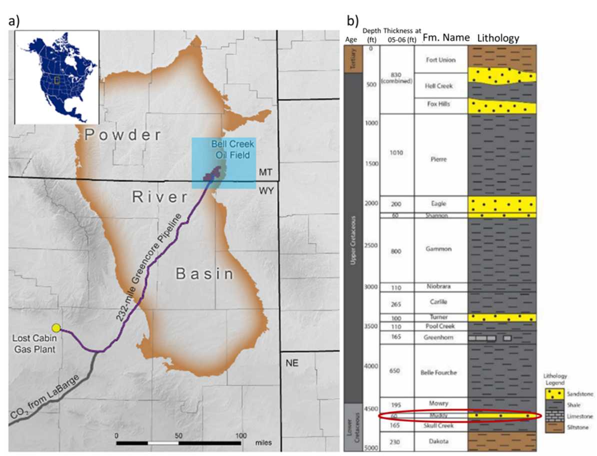

Figure 1: a) Location of the Bell Creek field the Powder River Basin in south-east Montana. b) General stratigraphic column for the site. Gorecki *et al*., 2014.

CWC-CSEM METHOD

Controlled-source electromagnetics are established in marine exploration as a de-risking technology as the method is sensitive to the presence of resistors at depth (e.g. Constable and Cox, 1996). Similar needs present themselves in terrestrial CO_2-EOR operations where supercritical CO_2 is injected into a mature oilfield in order to produce residual oil which remains after primary production and water floods. At this stage in production, the electrically-conductive brine saturation is high. However, supercritical CO_2 as well as oil are resistive, and techniques which are sensitive to the subsurface distribution of the fluid phases are welcome. Electrical methods are well suited toward this end as bulk conductivity can be related to saturation through relations such as Archie's Law in many settings (e.g. Kennedy and Herrick, 2012).

Conventional surface EM surveys have difficulties investigating the conductivity changes in the reservoir at large depths. However, in CO_2-EOR oil fields, there are generally numerous legacy boreholes with steel casings that extend into the reservoir. There has been growing interest in exploiting this legacy infrastructure using the casing as long deep CSEM electrodes (e.g., Tietze *et al.*, 2015). In this configuration, current flows outwards from the casing and into the formation, and surface observations of the electrical and magnetic field are made using commodity CSEM/MT sensors (Figure 2).

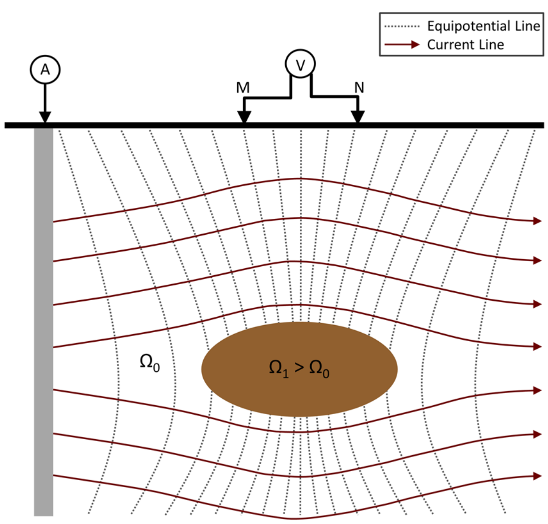

Figure 2: Illustration of CWC-CSEM survey configuration. Electrical current flows out from the borehole casing and into the formation. Resistors distort the field lines and can be observed through surface measurements of the electrical potential and magnetic fields.

BUILDING A 3D CONDUCTIVITY SITE MODEL

The construction of a representative 3D and time-varying conductivity model of the Bell Creek field site must start at the ground surface, drop through the significant geologic sequences, incorporate the detailed reservoir simulation data within the injection/production interval, and continue to extend below the reservoir to depth. To accomplish this, the complete site models are developed in two primary stages. The first is the creation of detailed time-varying conductivity models of the dynamic production interval as reservoir simulations are updated over time. The second is building the larger background model for the Bell Creek field site through the multiphysics integration of seismic, borehole resistivity, and field TEM data. To accomplish these two overarching objectives for building the full site model, the complete process can be divided into a sequence of five interrelated tasks as presented here.

1) Reservoir simulation modeling: A dynamic reservoir model consistent with current field conditions is critical to design field surveys and interpret the resulting CSEM data. To accomplish this, a geological model previously developed by North Dakota Energy & Environmental Research Center (EERC) was leveraged to create an up-to-date 3D dynamic model of the reservoir interval. The porosity field, Figure 3, was constructed from the collection of well logs at the site, calibrated to core data, and distributed stochastically across the reservoir interval by a facies model.

Simulations are then run using historical production and injection data, and model parameters such as the fluid model and relative permeability model are varied to provide a suite of plausible solutions. Given that history matching provides a non-unique solution, having multiple realization that match field data is a desired outcome. These results are then used as initial conditions for predictive simulation covering the dates of the project's field work. The final result of the reservoir modeling step is the generation of fluid saturation distributions over time, water in particular, that can then be converted to conductivity in step 2.

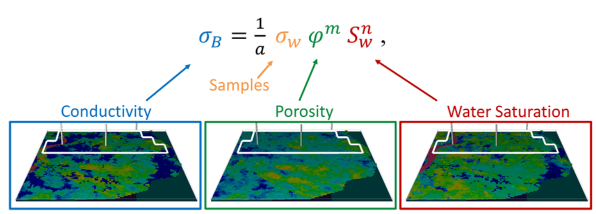

Figure 3: Application of Archie's Law to convert 3D static and time-varying reservoir simulation data, specifically porosity and water saturation, into conductivity.

2) Conversion to electrical conductivity: To construct a sequence of conductivity models for Bell Creek, we apply Archie's equation (Archie, 1942) with the 3D reservoir porosity model and dynamic saturation models (e.g., Figure 3). We implement Archie's equation as:

$$\sigma_B = \frac{1}{a}\sigma_w \varphi^m S_w^n \,, \quad (1)$$

where a is a tortuosity factor [= 0.6], σ_w is the conductivity of injected water measured on site [= 0.733 S/m], φ is the 3D porosity model (Figure 3), m is cementation factor [= 1.9], S_w are the 3D time-varying saturation models (Figure 3), and n is Archie's saturation exponent [= 2.0]. One of the resulting conductivity models for Bell Creek is illustrated in Figure 3 and Figure 6 for a single time-state of the field.

3) Seismic horizons: The first two steps focus on the task of updating the dynamic reservoir model within the production interval and converting those simulations to conductivity. The remaining steps focus on building the larger background conductivity model and integrating the two into complete and representative site models that would be consistent with the timing of each CWC-CSEM field survey. To accomplish this, the first step is to build the complete over- and under-burden for the site. For this we use seismic horizons from previous site investigations as structural data to delineate the significant stratigraphic layers and formation boundaries within the larger geologic model. A subset of the horizons are presented in Figure 4 along with the surface topography and reservoir interval.

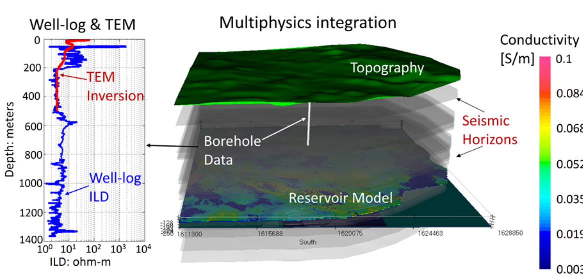

Figure 4: Multiphysics integration of geology, seismic, reservoir simulation, and borehole data into a complete 3D site conductivity model.

4) Borehole ILD and inversion of TEM data: Once the significant formation boundaries have been defined within the over- and under-burden, the next step is to incorporate representative conductivities for each of the stratigraphic layers. To accomplish this, we integrate the resistivity data from a collection of boreholes throughout the site with the inversion results of TEM field data collected during each CWC-CSEM field campaign. An example of the overlapping borehole ILD and TEM data used to define the background conductivity model are presented in Figure 4 (left panel), and Figure 5. The resulting 3D conductivity site model, prior to incorporating the detailed reservoir interval from step 2, is presented in Figure 5 along with one of the ILD borehole logs from the field site.

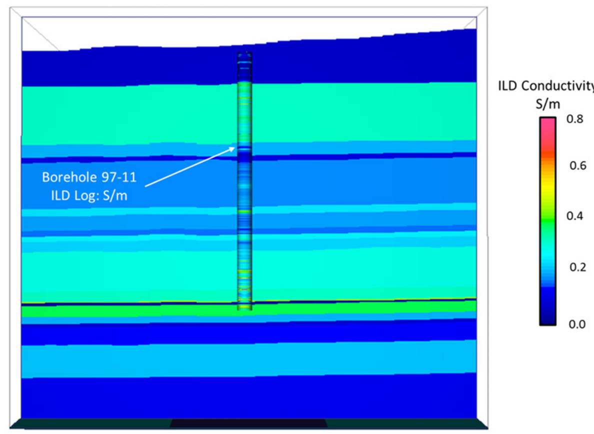

Figure 5: The large-scale 3D conductivity site model after filling in the horizons with borehole resistivity and TEM inversion data.

5) Merge the background and reservoir models: The final step to build the complete site model is to bring the two previously constructed models together. To accomplish this, the detailed reservoir model, at any time, is inserted into the larger background model at the appropriate depth interval. An important component to this step is allowing the reservoir model to be updated independently over time, converted to conductivity, and incorporated into the full site model without the need to rebuild the complete background. Results of the final 3D conductivity site model for one time-state, including the over-burden, under-burden, and detailed reservoir data, are illustrated in Figure 6.

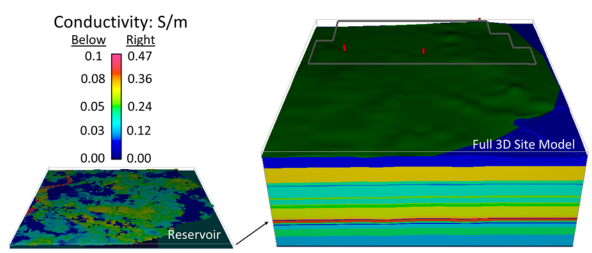

Figure 6: Final 3D conductivity site model including the relevant geological sequences and the reservoir interval at one time-state inserted at the appropriate depth. The gray lines on the topography define the Phase 5 production area where the project is currently focused, and the three red points on the topography are the locations of three legacy wells utilized for the CWC-CSEM field surveys.

CWC-CSEM SIMULATIONS

To close, we briefly demonstrate the application of the developed site model (Figure 6) to simulating the predicted CWC-CSEM responses as one step in the larger problem of reservoir imaging and monitoring of injected CO_2 during enhanced oil recovery.

Simulations of the CWC-CSEM surveys are carried out in a two-step process: 1) determining the current distribution in the casings, and 2) combining this response into a 3D numerical solution of Maxwell's equations. The current in the borehole casing is calculated using a method of moments approach (Schenkel and Morrison 1990). Within this formulation, the response of the casing is calculated using a superposition of Dyadic Green's Functions in the presence of an active transmitter source (Tang *et al.*, 2015). Once the response of the borehole has been determined, the 3D Maxwell's equations are solved using a decoupled vector and scalar potential formulation called EMSchur3D (Irons *et al.*, 2012).

Performance of the 3D EM solver is greatly influenced by the choice of sparse matrix solver which is called repeatedly. The underlying system is complex-symmetric but not Hermitian. As a result, many solvers are not optimized for this system. Benchmarks suggest that the complex symmetric variant PARDISO (Kourounis *et al.*, 2018) is the best performing solver when sufficient memory is available (Table 1). Iterative and hybrid solvers are less memory intensive, but run significantly slower (Guennebaud *et al.*, 2010).

Table 1: Timing examples using EMSchur3D on a test problem of dimensionality 50x50x25 cells. All times were on twin socket featuring Xeon(R) CPU E5-2670 CPU's and utilizing up to 28 physical cores. The PARDISO direct solver (D) had the best performance, but also the greatest memory requirements. The BiCGSTAB iterative solver (IS) was less performant, but also had a much lower memory footprint.

Solver	Solution error	Setup Time (min)	Solve time (min)	Total time (min)
SuperLU (D)	4.9e-30	4.6	0.43	5.02
PARDISO (D)	5.2e-30	0.18	0.34	0.52
BiCGSTAB (IS)	2.6e-29	0.0	2.17	2.17
BiCGSTAB w/ILU (IS+D)	8.3e-30	0.57	1.92	2.48

Field electromagnetic data collected at the surface may then be compared to electromagnetic simulations based on reservoir model realizations and Archie relations (Figure 7). This workflow allows for validation and/or reduce uncertainty in reservoir modeling parameters. Formal incorporation in a history matching workflow is forthcoming.

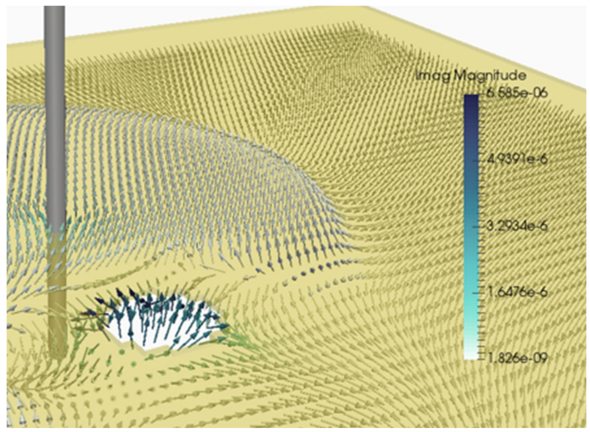

Figure 7: EM simulation data using the presented workflow. Electric field lines flowing around a resistive CO_2-plume is shown.

CONCLUSION

We have developed a method for the integrated development of 3D electrical conductivity models of an oil field for CO_2-EOR monitoring with charged wellbore casing controlled source electromagnetics (CWC-CSEM) and presented its application at the Bell Creek Oil Field. Such developments are critical for understanding and reproducing the link between reservoir simulation models and geology to the physical property distributions at the site. They additionally provide an ability to guide the CWC-CSEM field surveys at the front end, and act as a feedback mechanism into the reservoir simulations at the back end.

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 (EERC) are further acknowledged.

REFERENCES

Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Petroleum Transactions of AIME, **146**, 54–62, doi: https://doi.org/10.2118/942054-G.

Berg, R. R., and D. K., Davies, 1968, Origin of lower cretaceous muddy sandstone at bell creek field, Montana: AAPG Bulletin, **52**, 1888–1898.

Constable, S., and C. S., Cox, 1996. Marine controlled source electromagnetic sounding: 2. The PEGASUS experiment: J. Geophys. Res., **101**, 5519–5530, doi: https://doi.org/10.1029/95JB03738.

Gorecki, C. D., E., Steadman, and J., Harju, 2014, Plains CO2 reduction (PCOR) partnership - phase III: 2014 Carbon Storage R&D, Project Review Meeting.

Gaël, G., B., Jacob, and M., Lenz, 2010, Eigen v. 3, https://doi.org/http://eigen.tuxfamily.org, accessed 28 March 2019.

Irons, T., Y., Li, and J. R., McKenna, 2012, 3D frequency domain electromagnetics modeling using decoupled scalar and vector potentials: 82nd Annual International Meeting, SEG, Expanded Abstracts, 1–6, doi: https://doi.org/10.1190/segam2012-0896.1.

Kennedy, W. D., and C. H., David, 2012, Conductivity models for Archie rocks: Geophysics, **77**, no. 3, WA109–WA128, doi: https://doi.org/10.1190/geo2011-0297.1.

Kourounis, D., A., Fuchs, and O., Schenk, 2018, Towards the next generation of multiperiod optimal power flow solvers: IEEE Transactions on Power Systems, **33**, 1–10, doi: https://doi.org/10.1109/TPWRS.2017.2789187.

McGregor, A. A., and C. A., Biggs, 1968, Bell Creek Field, Montana: A rich stratigraphic trap: AAPG Bulletin 52, **10**, 1869–1887, doi: https://doi.org/10.1306/M14368C5.

Schenkel, C. J., and H. F., Morrison, 1990, Effects of well casing on potential field measurements using downhole current sources: Geophysical Prospecting, **38**, 663–686, doi: https://doi.org/10.1111/j.1365-2478.1990.tb01868.x

Tang, W., Y., Li, A., Swidinsky, and J., Liu, 2015, Three dimensional controlled source electromagnetic modelling with a well casing as a grounded source: a hybrid method of moments and finite element scheme: Geophysical Prospecting, **63**, 1491–1507, doi: https://doi.org/10.1111/1365-2478.12330.

Tietze, K., O., Ritter, and P., Veeken, 2015, Controlled source electromagnetic monitoring of reservoir oil saturation using a novel borehole to surface configuration: Geophysical Prospecting, **63**, 1468–1490, doi: https://doi.org/10.1111/1365-2478.123222478.12322.

Weimer, R. J., C. A., Rebne, and T. L., Davis, 1988, Geologic and seismic models, Muddy Sandstone, Lower Cretaceous, Bell Creek-Rocky Point area, Powder River Basin, Montana and Wyoming: 39th Annual Field Conference Guidebook, AAPG, 161–177.