2021 FALL TOPICAL CONFERENCE
UNCONVENTIONAL PETROPHYSICS

SOCIETY OF PETROPHYSICISTS AND WELL LOG ANALYSTS

Upscaling borehole resistivities to 3D anisotropic models for CCUS applications

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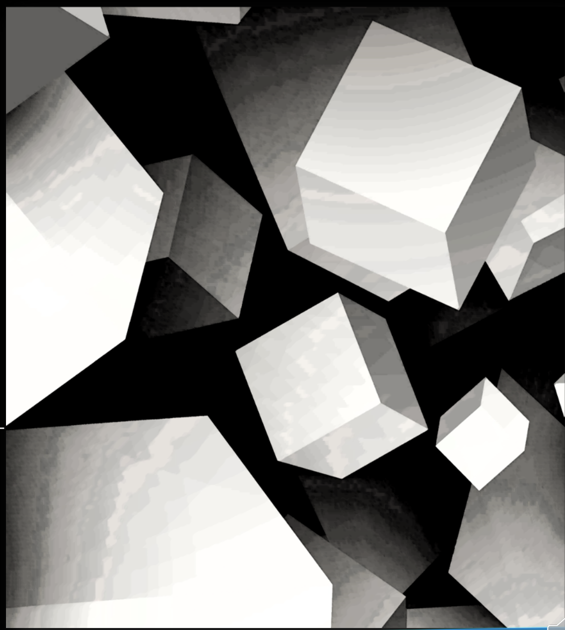

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Introduction

- Monitor CO_2 reservoir fluid movement
- Fluid sensitivity asses with 3D models
- Workflow to upscale from borehole to surface
- Derived CO_2 resistivity from petrophysics
- Field examples, validation

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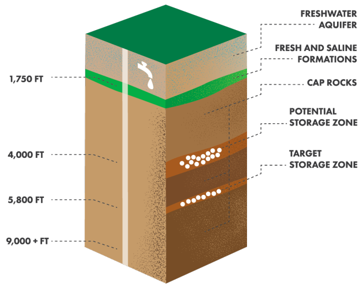
Workflow

A priori: Logs, geology, seismic horizons; additional surveillance → Build 3D anisotropic model → CO_2 fluid substitution → Define reservoir variations → Link data with variations → FEASIBIILITY → Evaluate / decide → **Baseline survey**

Field noise measurement → Link data with variations → FEASIBIILITY



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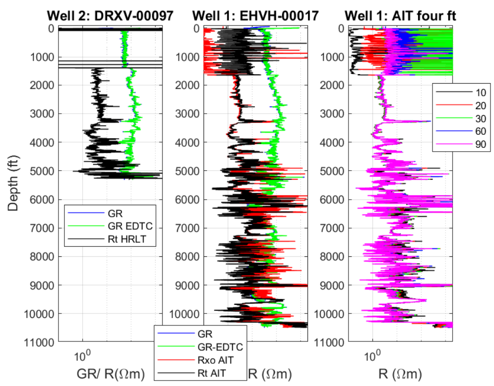
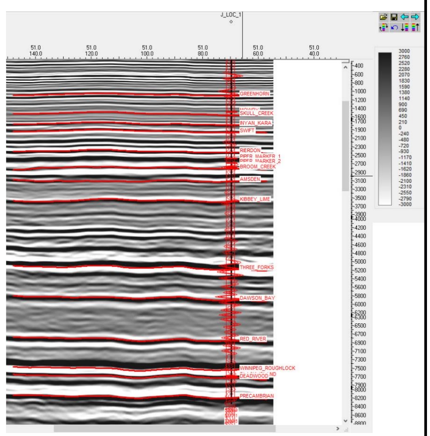
A priori data

- Inyan Kara Fm.
  - Sandstones, silty sandstone & shale
  - 180 ft thick
  - 4,000 ft deep
- Brook Creek Fm.
  - Eolian & nearshore marine sandstone-carbonate cycles: sandstone, dolomite & anhydrite
  - 280 ft thick
  - 5,000 ft deep
- Deadwood Fm.
  - Marine siltstones, sandstones & shales on top of Precambrian basement
  - 9,000 ft deep

Logs



Seismic horizons



After Barajas-Olalde et al., 2021

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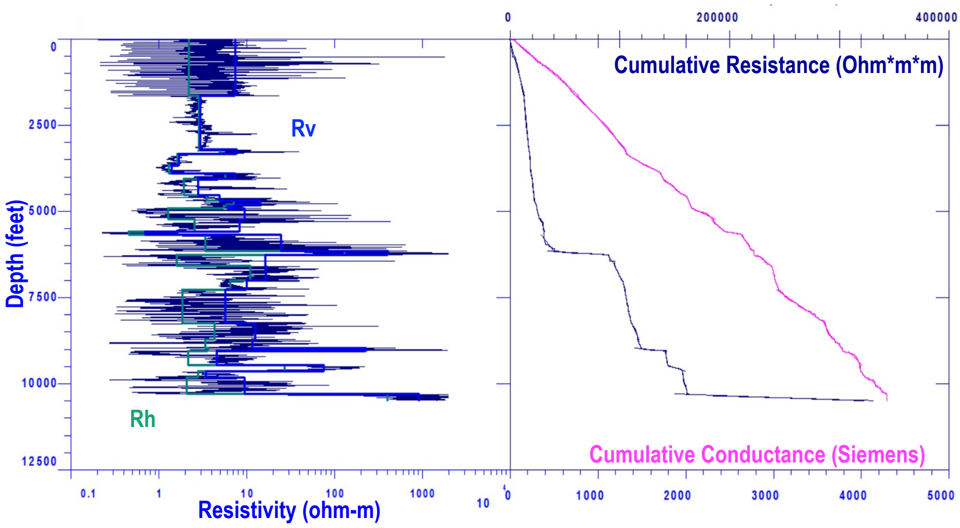
Anisotropic model



- 31 layers
- Use
  - Rv for CSEM – E field
  - Rh for CSEM – H field
  - Rh for MT

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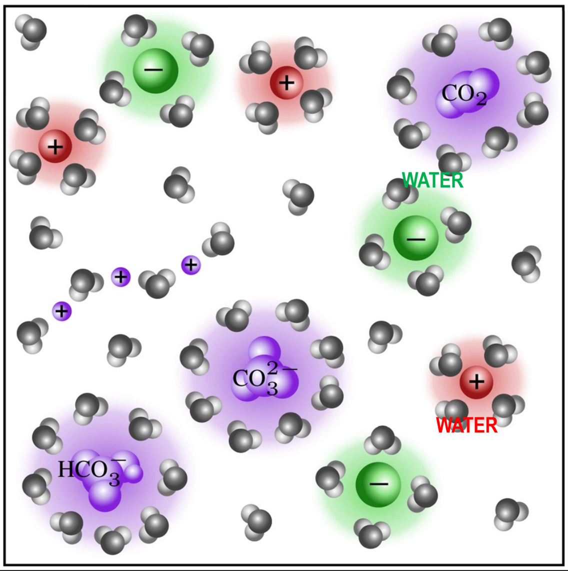
Dissolved CO_2 – how does it influence rock resistivity?

- @ normal brine salinity → fluids are more resistive (6 -50 times)
- @ low salinity (≤ 5,000 ppm) → more conductive



After Boerner et al., 2015

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CO_2 fluid substitution

Know petrophysical parameters:

Inyan Kara Fm.: Average porosity: 20 %, average permeability: 200 mD

Broom Creek Fm.: Average porosity sandstone: 23 %, average permeability sandstone: 222 mD

Deadwood Fm.: Average porosity sandstone: 11 %, average permeability sandstone: 70 mD

Assumptions:

Brine salinity: 20,000 ppm for all reservoirs

CO_2 density: ~ 1000 kg/m3

Geothermal gradient 1.82 °C/100 m

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CO_2 fluid substitution - continued

Estimate formation temperature for each reservoir

R_w calculated from Schlumberger chart of temperature & NaCl concentration

Using the formula:

$$F = \frac{a}{\emptyset^m}$$

Where a = 1 & m =2

Then using

$$R_0 = F \times R_w$$

we determine the formation resistivity for the sandstone.

If shaly sand, the one can use

$$\frac{1}{R_t} = \frac{1 - V_{sh}}{R_0} + \frac{V_{sh}}{R_{sh}}$$

Formation resistivity was compared to average resistivity (Rh) from well data, values were consistent, validate selected a & m constants

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CO_2 formation resistivity

Given CO_2 is 10 times more resistive than brine →

$$R_{CO2} = F \times (10 \times R_w)$$

Average resistivity for brine volume and CO_2 volume, we calculate the resistivity change ratio for 100 % water saturation → vertical resistivity

Reference: resistivity 6 to 50 times higher than fresh water (*10 for brine) (Capobianco et al, final version 071814, contract No. DE-AC05-00OR22725)

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3D modeling scenarios

Reservoir	Years of injection	Radius of injection area (m)	Ratio of increase of resistivity by saturation of CO_2			Resistivity by saturation of CO_2 R_h & R_v (Ωm)			Brine saturated resistivity (Ωm)
			90 %	60 %	30 %	90 %	60 %	30 %	
Broom Creek (5,000 ft)	1	200	16.4	4.2	2.7	R_h: 22.46 R_v: 251.74	R_h: 5.75 R_v: 64.47	R_h: 3.69 R_v: 41.44	R_h: 1.37 R_v: 15.35
	5	500							
	15	860							
Deadwood (9,000 ft)	1	150	7.5	2.3	1.5	R_h: 17.62 R_v: 186.75	R_h: 5.4 R_v: 57.27	R_h: 3.52 R_v: 37.35	R_h: 2.35 R_v: 24.9
	5	230							
	15	610							
Inyan* Kara (4,000 ft)	1	300	10	2.6	1.5	R_h: 57 R_v: 72.9	R_h: 14.82 R_v: 18.95	R_h: 8.55 R_v: 10.93	R_h: 5.7 R_v: 7.29
	5	660							
	15	1150							

Volume of injection of 3 million tons for reservoir Brook Creek and 0.5 million for Deadwood

Inyan Kara Fm. is just backup for injection

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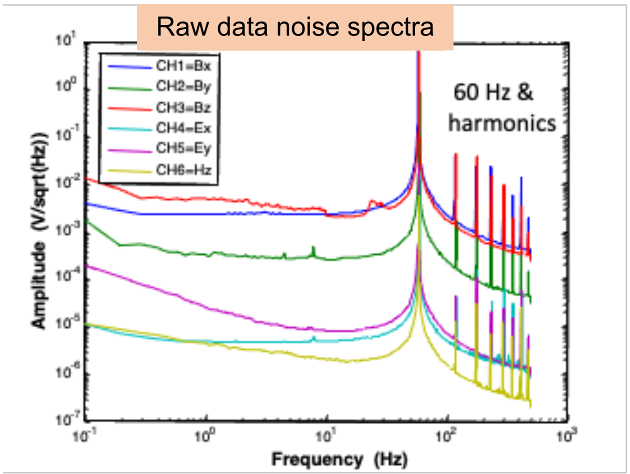
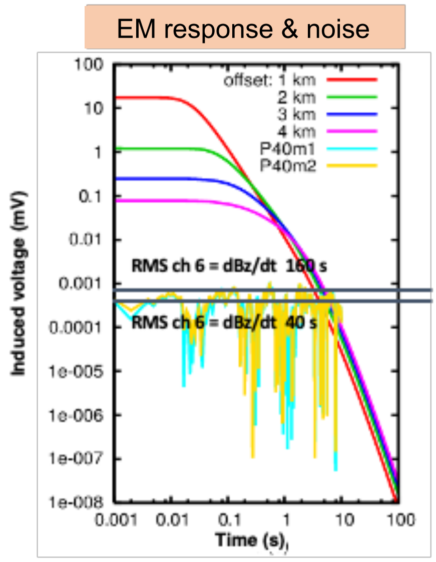
Field noise measurements





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EM sensitivity & field data results

- EM sensitivity
  - Broom Creek Fm. (5,000 ft deep) – detectable in 5% range
  - Deadwood Fm. (9,000 ft deep) – around 1%
  - Inyan Kara Fm. (4,000 ft deep) - > than 5 %
- CSEM signal > noise level to 4-6 s.
- 1D & 2D MT inversion
- CSEM inversion

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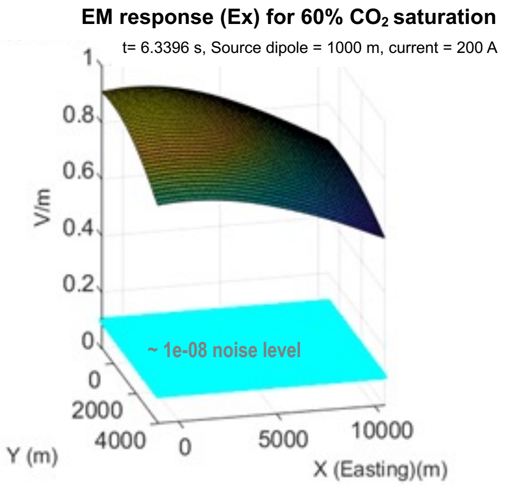
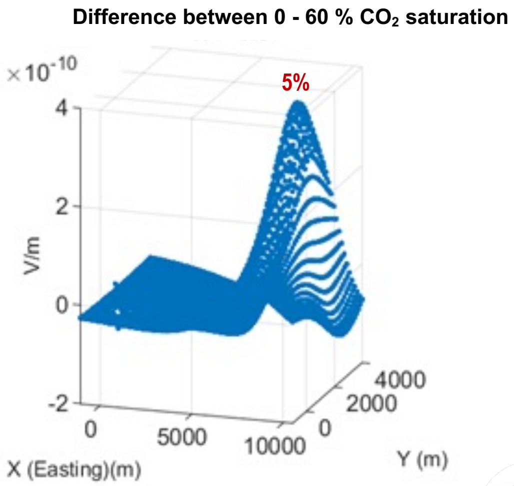
Example modeled CSEM response





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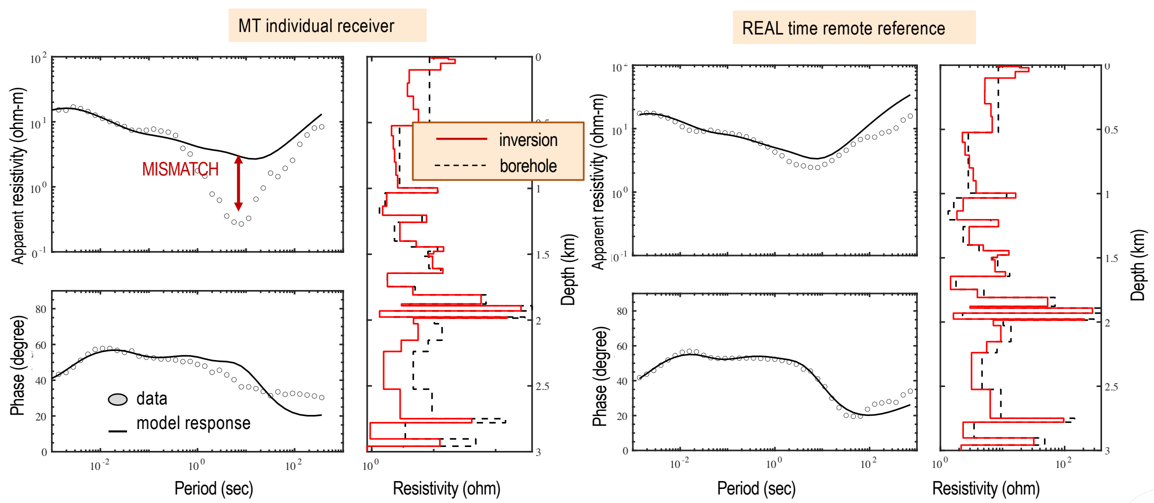
Cloud-based quality assurance: MT

DATA



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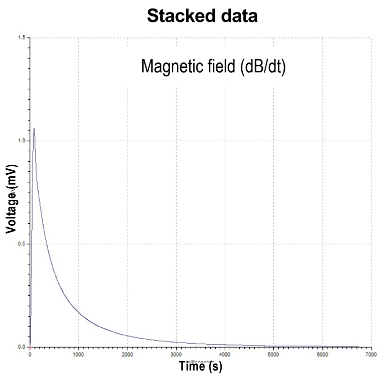
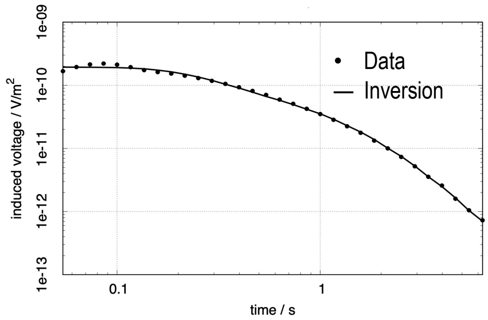
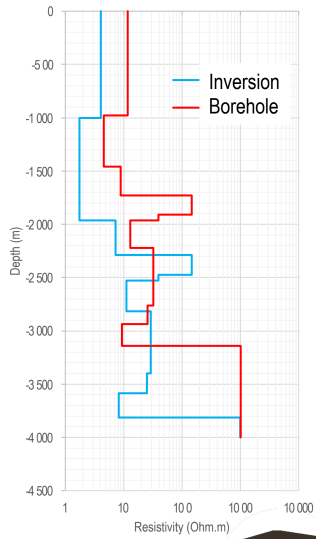
Cloud-based quality assurance: CSEM







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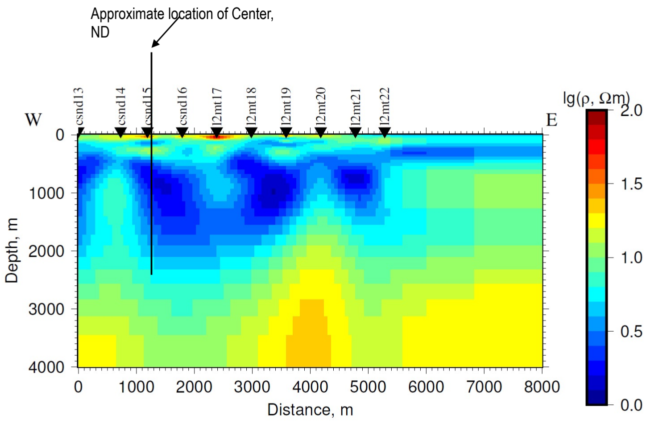
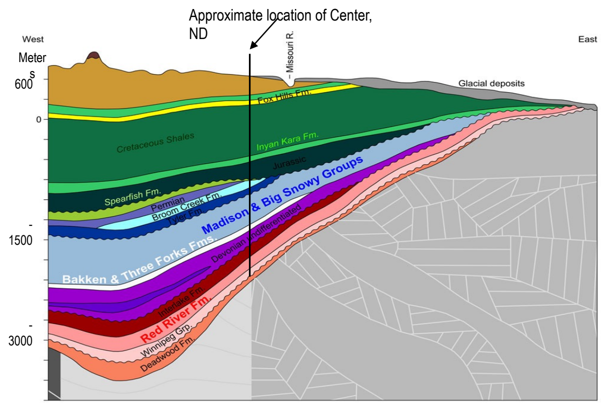
Cloud-based quality assurance: 2D MT





After Barajas-Olalde et al., 2021

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Conclusions

- EM monitors fluid movements
- CO_2 flooding provides resistivity contrast → EM anomaly
- CSEM preferred method
- MT & CSEM QA inversion results match anisotropic log model
- Upscaling workflow validated
- Future: CO_2 injection & time-lapse measurements

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Thank you!

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