Joint inversion of crosswell seismic and EM data for CO_2 saturation

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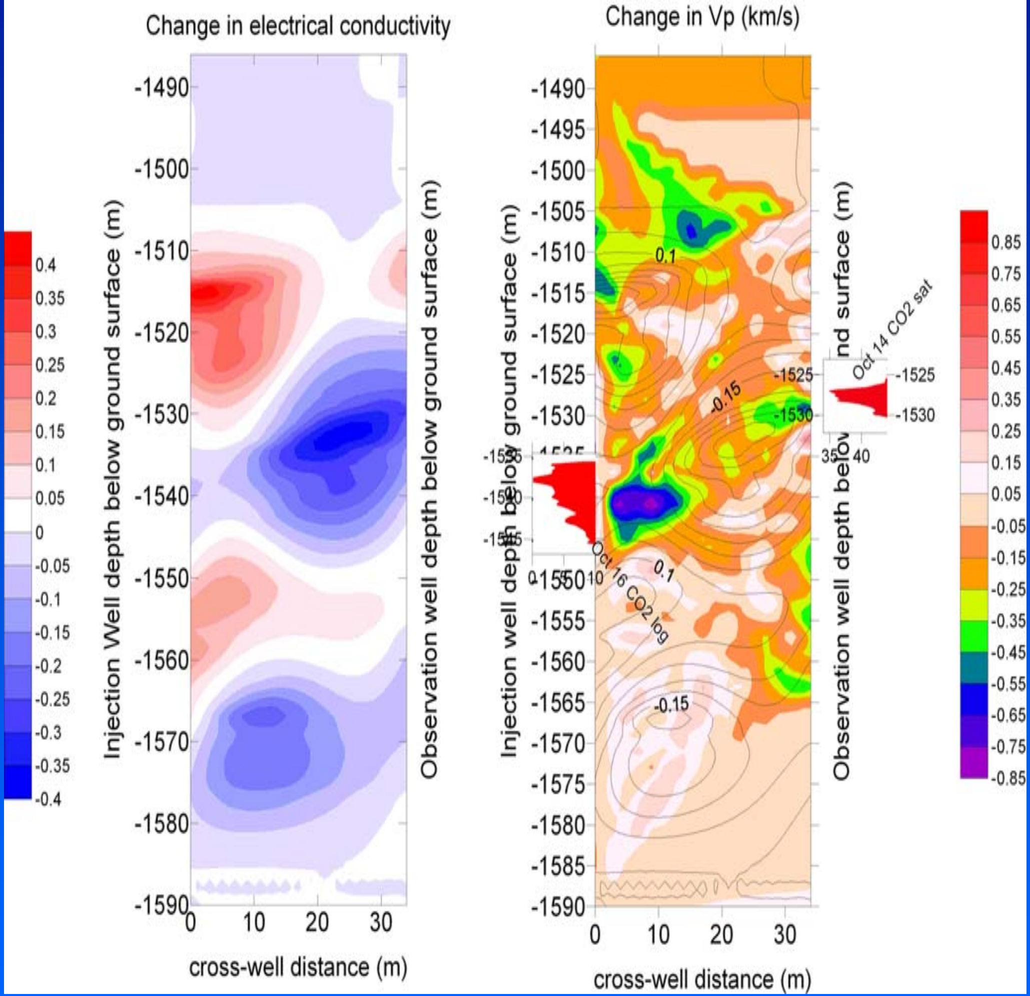
Outline

- Input Geophysical Data
- Process
- Rock-physics models
- Individual estimation of S_w
- Joint inversion
- Discussion
- Conclusions

Cross Well Data

- V_p travel-time tomography
  - Contours of $\Delta\sigma$ are overlaid
  - Large ΔV_p @ -1510 coincides with large $+\Delta\sigma$
- EM inversion
  - $+\Delta\sigma$ could be movement of brine or noise
- Further work to tie to VSP and logs is required to interpret
  - Possible fault induces upward migration
  - Possible movement of CO2 &/or brine up annulus of injection well

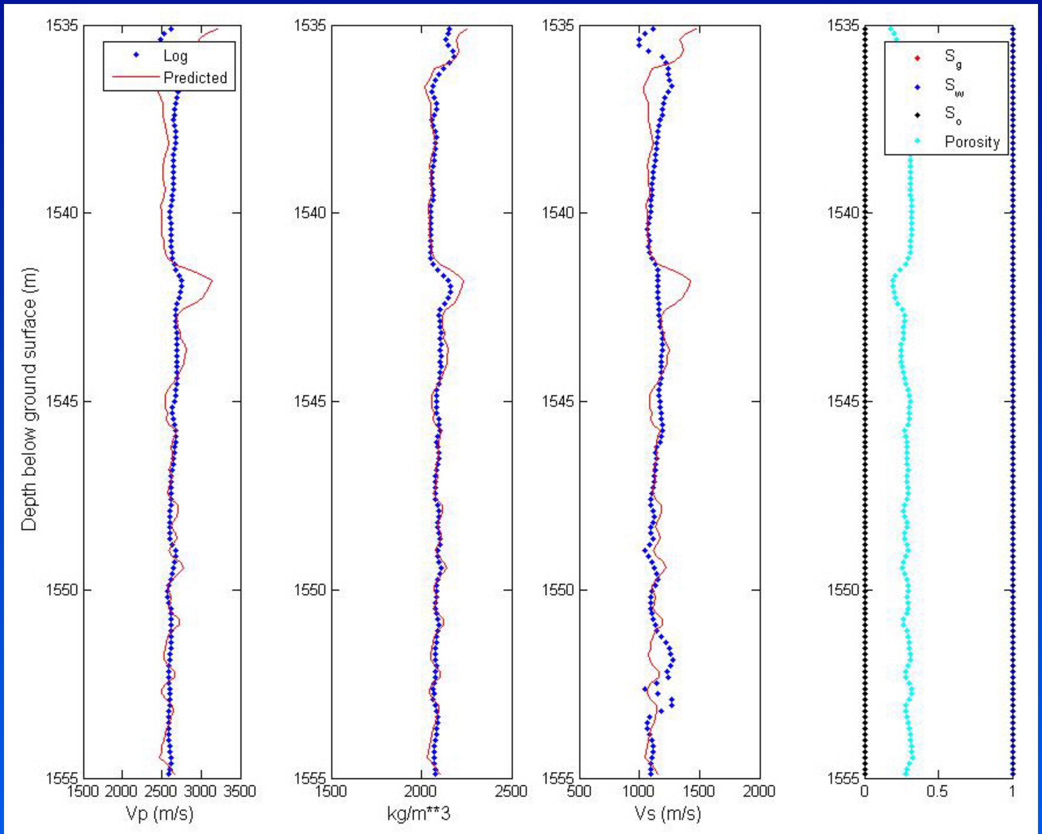


Path from geophysics to reservoir

- Geophysical estimates of V_p, V_s, and σ
- Rock-physics model that relates geophysical parameters to reservoir parameters
- Two approaches taken
  - Rock-physics transform (V_p, V_s, s) -> (S_w, ϕ)
  - Bayesian inversion

Rock-Physics

- Velocity
  - Hertz-Mindlin & Hashin-Strikman (effective dry rock bulk modulus)
  - Dry frame $K(P_{eff})$
  - Gassmann (fluid substitution)
- Density
  - Mixing law
- Simplex inversion for model parameters
  - Input (ϕ, S_g, S_w, P,T,oil API, brine salinity)
  - Output (grain - υ,ρ,K, critical ϕ, gas density)

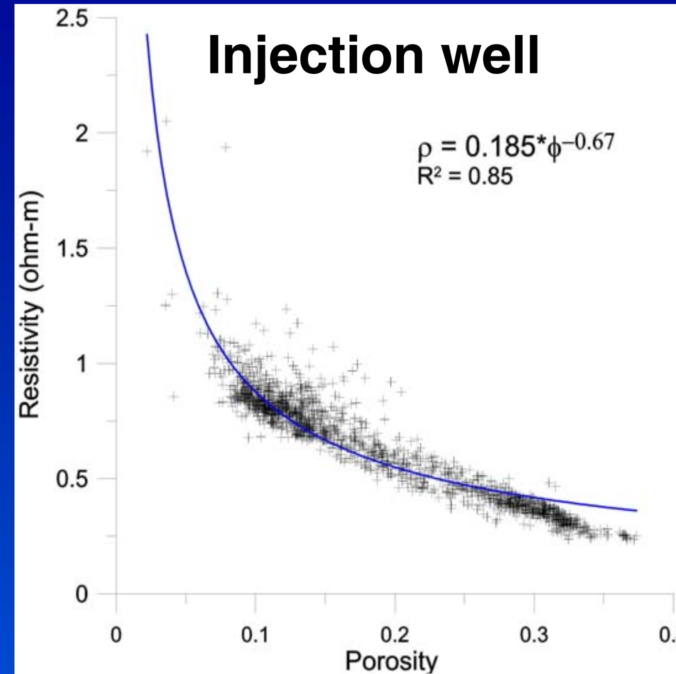


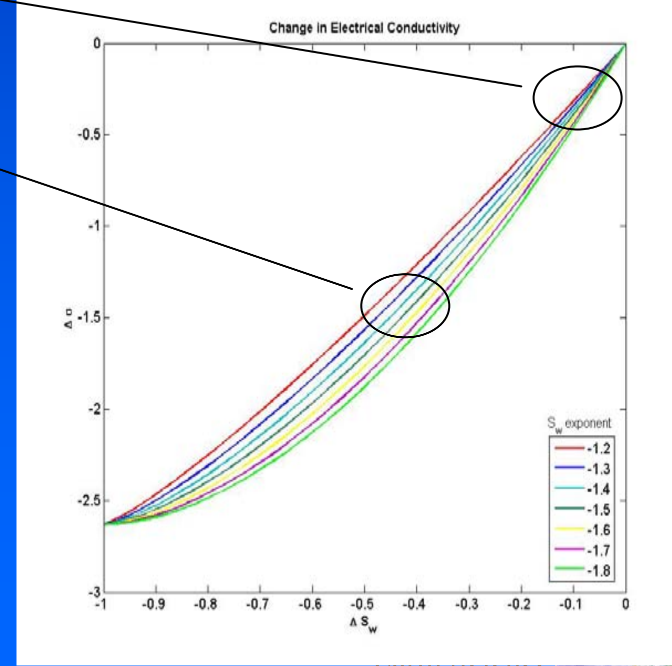
Fixed Parameters	
Critical Porosity	0.38
Oil API	28.5
Brine Salinity	0.07
Gas Gravity	0.59
Temperature©	67.7

Regression Fit	
Grain Shear Mod.	44.5
Grain Poisson	0.26
Grain Density	2512
# Contacts/grain	4.1

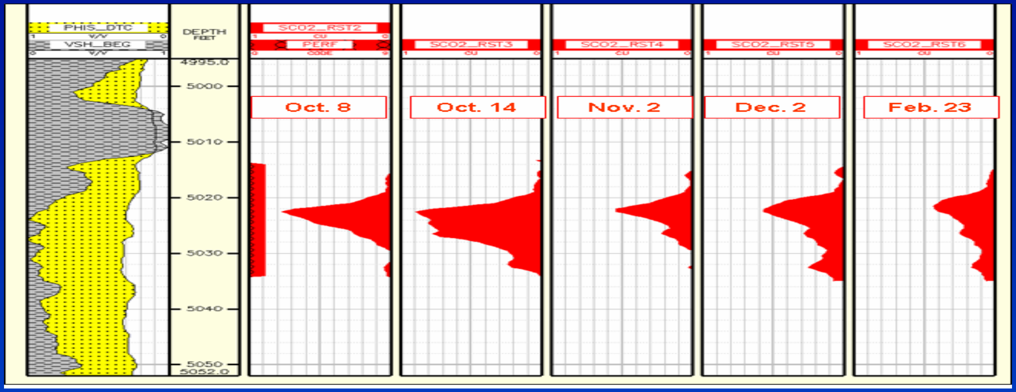
Archie's Law

- Logs determine porosity exponent
- No variable S_w, so S_w exponent is unknown
  - Limited sensitivity to S_w exponent at small ΔS_w
  - At higher ΔS_w unknown exponent -> 10% variation in estimate
- Inversions run at $S_w^{-1.8}$

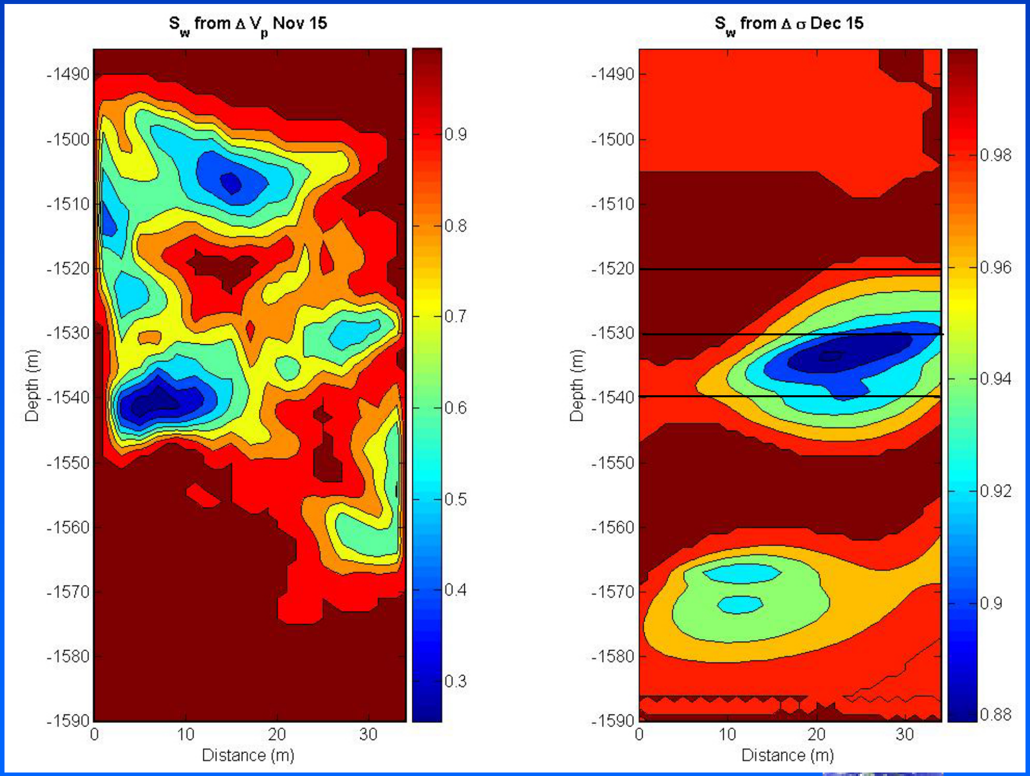




Prediction from Rock-Physics transform



- V_p, V_s, ρ model used to convert ΔV_p to ΔS_w
- Archie's Law used to convert $\Delta\sigma$ to ΔS_w
- Seismic result
  - 50% S_w at Obs. well
  - Nov 2 log average S_w = 83%
- EM result
  - 90% S_w at Obs. Well
  - Dec 2 log average S_w = 80%



Bayesian Estimation Model

Posterior PDF | Likelihood function

$$f(\phi,S_w,S_o,P\,|\,k_b,k_s,\rho,\sigma) \propto f(k_b,k_s,\rho,\sigma\,|\,\phi,S_w,S_o,P) \times f(\phi,S_w,S_o,P)$$

Prior PDF

Likelihood can be simplified

$$f(k_b,k_s,\rho,\sigma\,|\,\phi,S_w,S_o,P) = f(k_b\,|\,\phi,S_w,S_o,P) \times f(k_s\,|\,\phi,P) \times f(\rho\,|\,\phi,S_w,S_o) \times f(\sigma\,|\,\phi,S_w)$$

where $k_b = g_1(\phi,S_w,S_o,P) + \varepsilon_b$ $\quad k_s = g_2(\phi,P) + \varepsilon_s$

$\rho = g_3(\phi,S_w,S_o) + \varepsilon_\rho$ $\quad \sigma = g_4(\phi,S_w) + \varepsilon_\sigma$

For example, if we assume ε_σ has the Gaussian distribution;

$$f(\sigma\,|\,\phi,S_w) = \frac{1}{\sqrt{2\pi D}} \exp\left\{-\frac{(\sigma - g_4(\phi,S_w))^2}{2D^2}\right\}$$

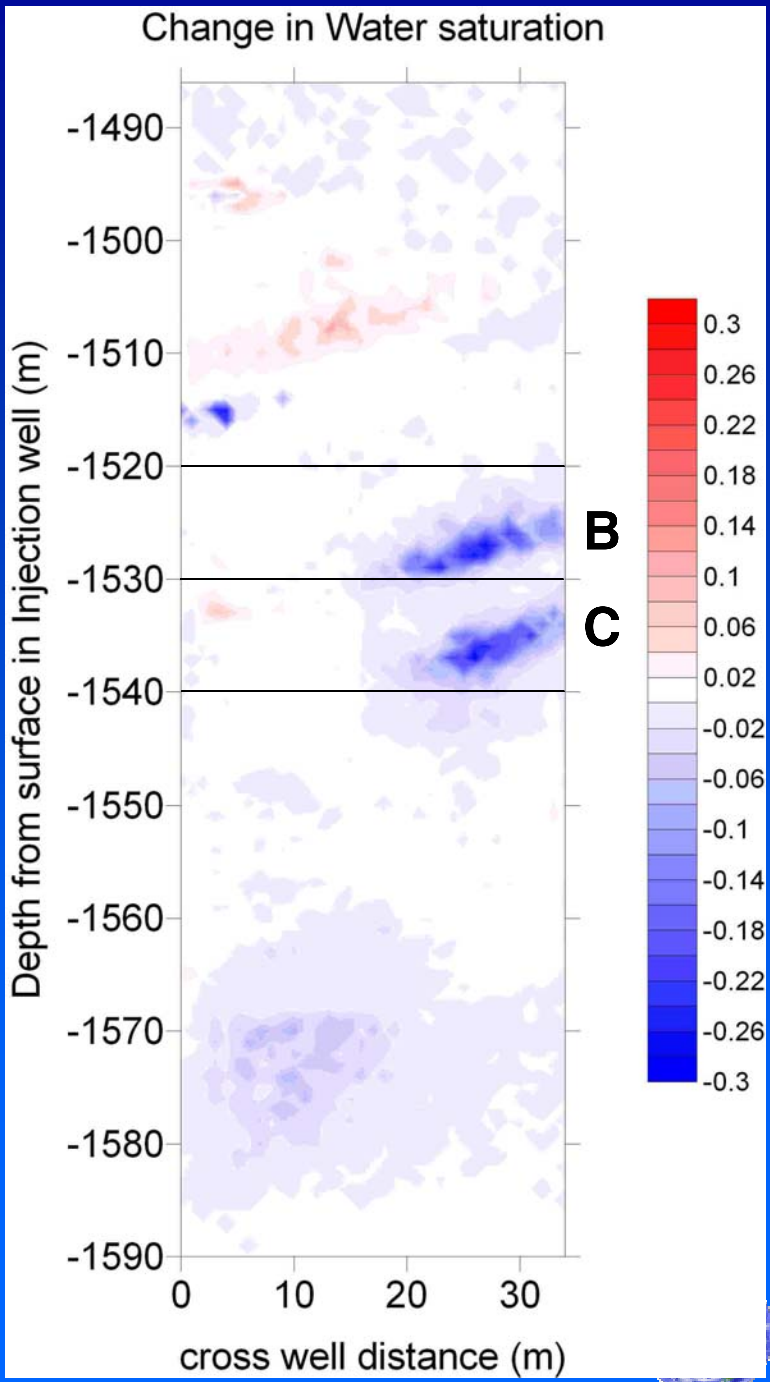
where, D is the standard deviation of the errors

MCMC Sampling Method

- MCMC methods use a variety of algorithms to update Markov chains, which are convergent to the true distribution
  - chains are irreducible and aperiodic.
- Traditional Monte Carlo (MC) methods (e.g., Bachrach et al. [2004]) draw samples uniformly in entire feasible space, but MCMC methods sampling density is proportional to the true probability density function.
- For example, in Bachrach's paper, the traditional MC methods need to draw 100,000 or more samples, but MCMC methods only need to draw 2,400 samples with the first 400 as burn-in.

Joint inversion

- Estimated V_p and σ at the two times are used to estimate Sw
- Joint estimation removes artifacts not common to both
- Predicted has a time smear of 1 month due to time lag in surveys
- C-sand S_w = 75-85%
  - Log ~ 80%
- Indication of CO_2 reaching the B sand above
  - S_w = 75-85%



Discussion

- Processing is not complete
  - Refinement on seismic picks and sensor rotation
- EM inversions have not been exhaustive
  - Data sensitivity analysis and further editing may imporve
- Both seismic and EM inversions could benefit by cross-iterations where models are transformed to each other and used as starting points
- Input from Final VSP models has not been incorporated

Conclusions

- Both time-lapse EM and seismic see changes realated to CO_2 movement
  - Noise levels need to be reduced
- Both techniques suggest possible movement of fluids (CO_2 and/or brine) up the injection well annulas and into upper formations
- Transformation of seismic alone via rock-physics model yields lower S_w estimate in November
- Transformation of EM alone via rock-physics model yeilds higher S_w estimates in December
- Joint inversion estimates of S_w in C sand are very close to logged value
- Joint inversion estimates of S_w indicate chane in B sand
- Further work will improve all estimates