Subsurface Imaging of CO_2 Plumes Using Multiple Data Types and Bayesian Inference

A.Ramirez, J. Friedmann, W. Foxall, B. Kirkendall and K. Dyer

Lawrence Livermore National Laboratory

This Approach was Developed to Improve Prediction of Subsurface Systems

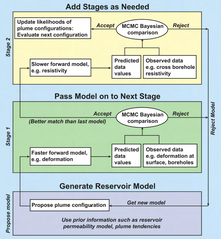
- Stochastic inversion tool was developed with internal LLNL funds:
  - Developed - 2001 - 2003
  - 8 FTE effort
  - Approximately $4M continued investment and application
- Specifically addresses subsurface uncertainty
  - Due to: poor spatial coverage, noisy data, non-unique inversions
  - Provides a robust, data-driven measure of the uniqueness of a subsurface characterization
  - Generates a suite of possible results that are statistically significant
- Useful for a variety of CCS applications
  - Geophysical inversion, data fusion
  - Oil reservoir fluid flow monitoring: e.g., monitor water floods, CO_2, or steam injection
  - Reservoir characterization: determine lithologic framework using multiple data types
  - Environmental applications: detection of tank leaks, mapping contaminant flow paths
  - Atmospheric/surface detection

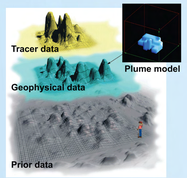
Our MCMC Approach Offers Significant Benefits

- Good for joint reconstructions of disparate data:
  - Examples: reservoir permeability models, measurements of injected plume CO_2 volume, ground deformation measurements, and cross-borehole electrical resistivity measurements
  - Good for formal information on fusion
  - Uses insight and prior information
  - Combines geophysical measurements, geophysical forward models and prior knowledge
- Produces realistic plume models
  - Inversion is typically ill-posed, requiring stabilization
  - We can incorporate existing data (e.g. , well logs, cores, reservoir permeability model)
  - Conventional approaches often use unrealistic regularization techniques (e.g. smooth models)
  - Produces likely plume models that are consistent with all available data (- models show plume location, shape, and CO_2 content)
- Finds alternative models that are readily tested
  - Produces robust models of 3D fluid distributions
  - Non-uniqueness treated explicitly: alternative models identified
  - Provides measures of model uncertainty
- Directs next inquiry or survey

Joint Reconstructions of Disparate Data Types

Disparate data are jointly reconstructed using a staged approach





MCMC Bayesian search uses the robust Metropolis-Hastings algorithm to guide the search

Misfit function:

$$S(m) = \sum_i \left\{ \frac{\left(d_{i,cal} - d_{i,obs} \right)}{\sigma_i} \right\}^2$$

Likelihood function:

$$L(m) = k e^{-S(m)}$$

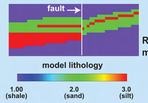
Metropolis Hastings algorithm:

if $\frac{L(m_{t+1})}{L(m_t)} \geq 1$ Accept proposed transition to m_{t+1}

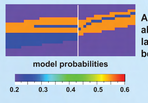
if $\frac{L(m_{t+1})}{L(m_t)} < 1$ Make random decision to move to m_{t+1} with probability $p = L(m_{t+1})/L(m_t)$

- Search tends to hover in regions with higher likelihoods
- Does not get stuck in local minima
- Samples solution space at a rate proportional to posterior probabilities

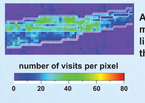
Reservoir model is used as prior data: CO_2 plumes are more likely to be proposed in the permeable layers



Reservoir model

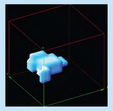


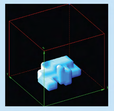
Analyst assigns probabilities that a particular location is likely to be a CO_2 pathway



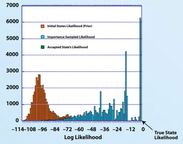
Approach proposes model that are more likely to be located in the permeable layers

"Plume tendencies" prior assumes a CO_2 body embedded within a volume



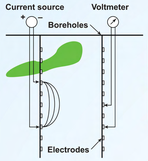


- Assume that:
  - Shape, location and volume of the zone are unknown
  - Range of possible CO2 saturation is 0.0 - 1.0
  - Segments of the plume are contiguous
- Can constrain models with other data such as:
  - Total injected volume (e.g. steam or CO2 injection)
  - Production history
  - Water sample analyses or borehole temperature data



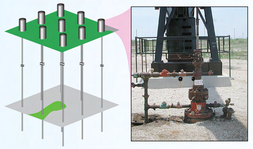
We consider several measurement techniques that sense different attributes associated with the CO_2 plume

Electrical resistance measurements detect changes in pore fluid resistivity



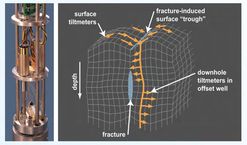
- Measures resistance between electrodes
- Short electrodes attached to casing surface - production/injection wells

Borehole casings used as long electrodes to do cross-well electrical resistivity surveys



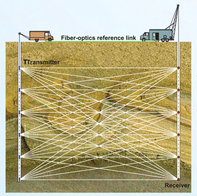
- Detect changes in fluid resistivity due to CO_2
- Fast, low-cost, non-intrusive
- Horizontal resolution only

Deformations caused by plume pressure gradients are detected by - downhole or surface tiltmeters



- Detects nano-radians of tilt
- Real-time, low cost
- Non-intrusive

EM induction measurements offer high resolution locally

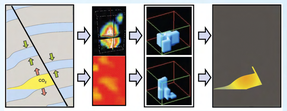


- Measures induced current between transmitter-receiver (active)
- Requires either open or non-conductive casing
- Hi-res, low cost, fast

Pending capabilities

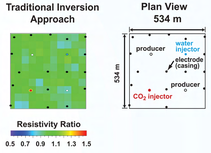
- Pressure, temperature, pH
- Seismic (4D, VSP, cross-well)
- Micro-seismic
- Gravity
- Production/Injection data
- Atmospheric detection

Detection and mapping of the CO_2 plume is the goal



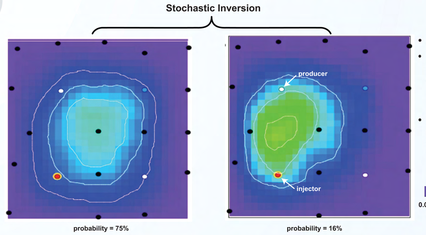
MCMC framework is compatible with other types of data such as seismic reflection, 3D fluid flow simulations

We have monitored CO_2 injection at the Salt Creek Field, Wyoming



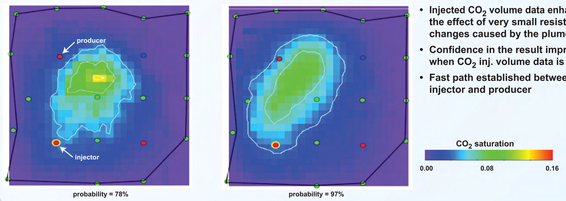
- Used abandoned well casings as long electrodes
  - ~ 710 m deep
- Time-lapse results using traditional approach were discouraging
- Poor signal to noise
  - ~4% of casing length in contact with reservoir

Time-lapse stochastic inversions suggested that the CO_2 caused small changes in resistivity



- Alternative models were identified
- Most probable result is radially symmetric
  - Modeling suggests that this is consistent with poor signal to noise data
- Second most probable result shows a plume that spans the region between injection and extraction

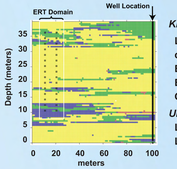
Time-lapse inversions show a growing plume when resistivity and injected CO_2 volume are combined



- Injected CO_2 volume data enhances the effect of very small resistivity changes caused by the plume
- Confidence in the result improves when CO_2 inj. volume data is used
- Fast path established between injector and producer

Experiment where disparate data types were used to infer the most likely lithologic model

We tested MCMC with real data from the Savannah River Site A/M Outfall Area



Knowns:

Lithology at distal well
ERT Data in two wells (poor quality)
Electric logs
Overall site lithologic characteristics

Unknowns:

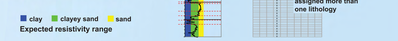
Local lithology within ERT domain
Locations of clay and silt layers

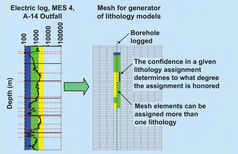
Shown is one possible lithology realization

Geophysical logs can be combined with in-process information such as pump tests to constrain the lithology models

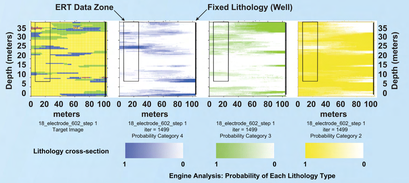
Bayesian time-series analysis is applied to establish confidence levels for given lithology types

This type of "soft" conditioning allows many kinds of data to be incorporated in the analysis





The search was guided by core data, geostatistical trends and cross-well geophysics



- Lithology sampler constrained using geostatisics developed by core and outcrop studies
- Resistivities 650 (blue) 1900 (green) 4200 (yellow) ohm-m

Future Efforts

- FY06: Conduct field test
- Expand capabilities:
- Other non-CO_2 applications:
  - Heavy oil recovery
  - Oil shale, tight sands
  - Water/steam floods

Acknowledgements

This work was funded by the Laboratory Directed Research and Development Program at Lawrence Livermore National Laboratory. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48. We wish to acknowledge the support provided by the Rocky Mountain Oil Technology Center and Anadarko Petroleum Co.