Evaluating time-lapse borehole gravity for CO2 plume detection at SECARB Cranfield

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Susan Hovorka
Kevin Dodds
Richard Krahenbuhl
Anya Reitz
Yaoguo Li

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Evaluating time-lapse borehole gravity for CO_2 plume detection at SECARB Cranfield

Susan Hovorka (BEG/UT)*

Kevin Dodds (BP)**, Richard Krahenbuhl (CSM)***, Anya Reitz (CSM)***, Yaoguo Li (CSM)***

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* BEG/UT Bureau of Economic Geology University of Texas

** BP Alternative Energy

*** CSM/CGEM Colorado School of Mines – Center for Gravity, Electrical & Magnetic Studies

Context

- Monitoring of CO2 storage processes provides a renewed challenge for re-evaluation of deep reading measurements besides seismic, such as gravitational and electromagnetic technologies which are respectively sensitive to density and electrical properties of the fluids

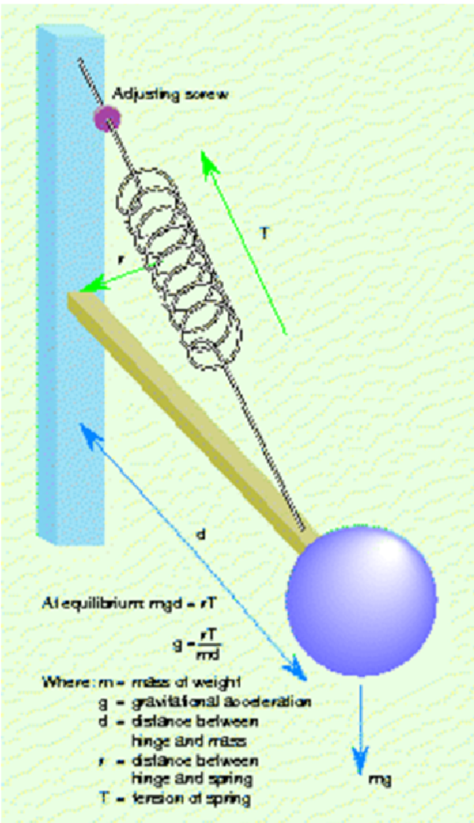
- These measurements need to be evaluated in their ability to
  - Support an understanding of safe containment of the CO_2 plume, and
  - Inform evidence that injected CO_2 remains in the storage complex
  - Provide means to assess green house gas accounting.

- In particular this paper explores the operational and interpretational challenges of borehole microgravity in a CO_2 time-lapse survey in two wells at the SECARB Cranfield injection site.

- The objective was twofold;
  - Understand the survey design and operational aspects
  - To assess the ability of the surveys to detect the injected CO_2.

- The baseline acquisition occurred in October 2009 and the repeat survey in September 2010.

Borehole Gravity Challenges



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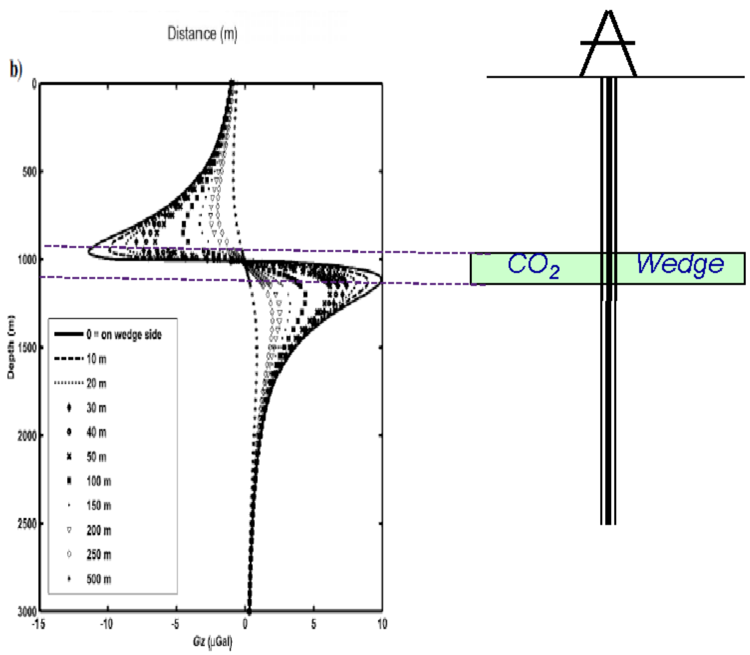
- Sensitive to variations in acceleration resolution to 3-5 μgals
    - 1 billionth of gravitational acceleration at the earth's surface
- Environmental noise exceeds the signal in size
    - cyclical earth-tides
    - influence of nearby masses
    - air pressure effects
    - vibration and electronic noise
- Borehole Instrument Limitations
    - Highly sensitive 'weight-on-spring' device,
    - Fragile, temperature sensitive, drift sensitive
    - Limited to 7 inch vertical wells only one technology* in world
    - New technology 2013 slimhole deviated and horizontal ability
    - (Micro-g LaCoste/Scintrex Colorado and Canada)
- Surface Measurements
    - Surface gravimeters have measured water floods (Prudhoe B
    - Sea-bed gravimeter deployed in Sleipner
    - Most instances surface response not detectable

Importance of modelling time-lapse survey

- Time-lapse response equivalent to a slab of density difference of water and CO_2 (0.027 gm/cm^3)
- All other lithology effects subtracted out in differencing the two logs



Gasperikova 2008

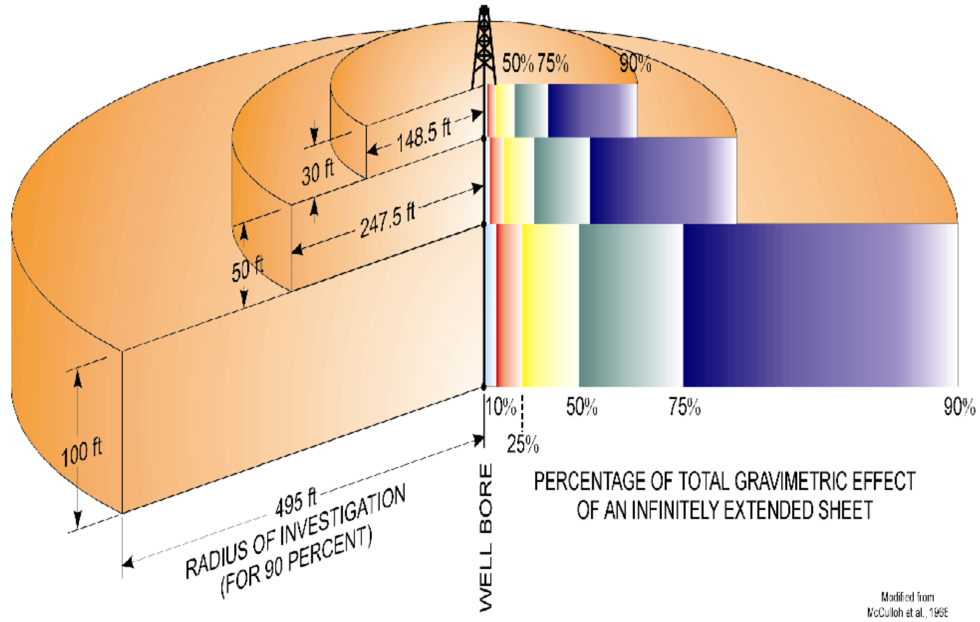
- It is important for borehole gravity, that the response of the problem is modelled providing
  - Expected response
  - survey design how to sample the response
  - manage the timing and costs of the operation
- We model the difference in fluid density post injection in the reservoir interval ie CO_2 replacing water (- 0.027 g/cm^3)
- The model consisted of two slabs, one 15 feet thick and a second 7 feet thick separated by 23 feet, each 400 feet on a side
- Each slab density calculation
  - Density difference - 0.027 g/cc
  - With saturation 30%
  - With porosity 0.2 p.u.

Deep Reservoir Monitoring - Place of Gravity

Physical Parameters	Property	Technology	Shallow Reading	Deep Reading
Elastic Response	$\upsilon_{p,s}$	Seismic/Sonic	Borehole sonic Array sonic	3D seismic VSP Crosswell Seismic
Density	ρ	Gravimeter/ radioactivity	γ-γ log	Surface gravity *Borehole gravity*
Conductivity	σ	Electromagnetic	Induction log Through casing resistivity	Crosswell EM CSEM Borehole to Surface EM MagnetoTellurics
Pressure	P	Quartz Silicon on wire	-	Reservoir Above Reservoir
Temperature	T	Discrete Distributed Temperature	-	Temperature profile Flow Effects

Depth of Investigation

- A rule of thumb you can "see" out 5 times the downhole station spacing.
- Hence stations are spaced at 100 ft, one can see out to 500 ft.
- Second rule of thumb: when the borehole does not penetrate the plume, you can "see" out as far as twice the height of the body.



Logging Method	Radial distance investigated for 90% effect		Formation volume investigated	
	in	cm	ft^3	m^3
Conventional 5.25-in. core	2.6	6.6	1.5	0.04
Gamma-gamma log	8	20	17	0.5
Neutron log	14	36	40	1.1
Sonic log	18	46	59	1.7
Borehole Gravity log	**600**	**1,500**	**78,532**	**2,224**

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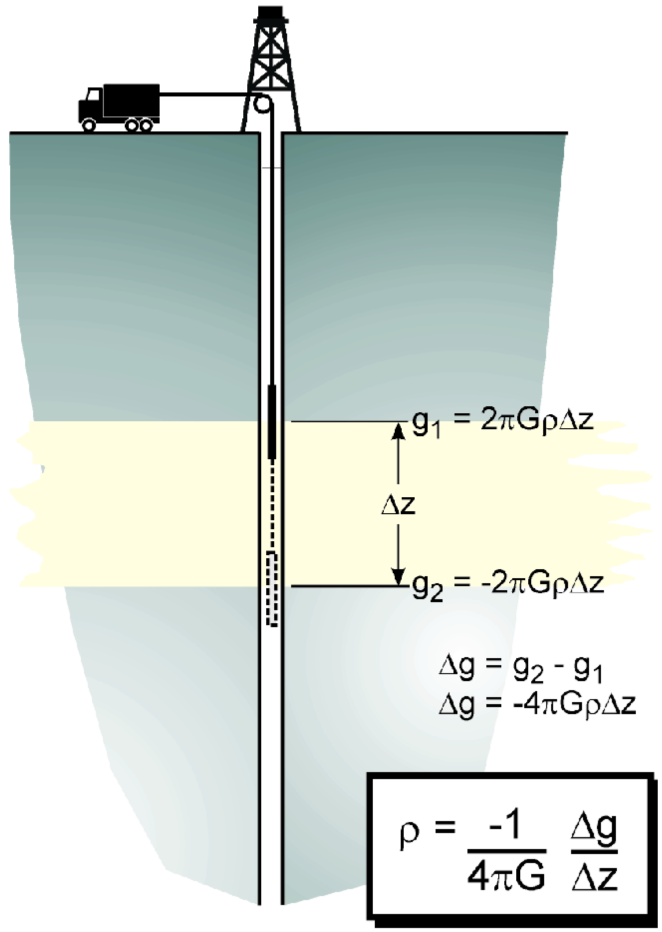
Source: Beyer, L.A. 1991, Borehole Gravity Surveys, SEG Continuing Ed. Prgm. Course Notes, p. 3-8, Table 3-1.

Gravity Acceleration Sensitivity

Scale	Units / Response
1 Gal	1 cm/sec^2
Earth's gravity field	981 Gal (cm/sec^2)
1 μGal	10^{-6} Gal
Infinite slab of water 1 inch thick	1 μGal
Lithology changes over 1000's ft	100 - 300 μGal
Plume Water/Gas contrast - 0.14 g/cm^3	~ 24 μGal @ 50 ft
Plume CO_2/water contrast - 0.03 g/cm^3	~ 10 μGal @ 50 ft

Measurement errors influence on apparent Density

- Density is derived from the difference of acceleration at two different depths
- Depth determination precision is critical
- Gravity resolution and repeatability are critical
- Especially for low contrast Water/CO^2



p = apparent density
z_1= level 1
z_2= level 2
g_1= acceleration at z_1 (equals contribution from slab between z_1 and z_2)
G= gravitational constant

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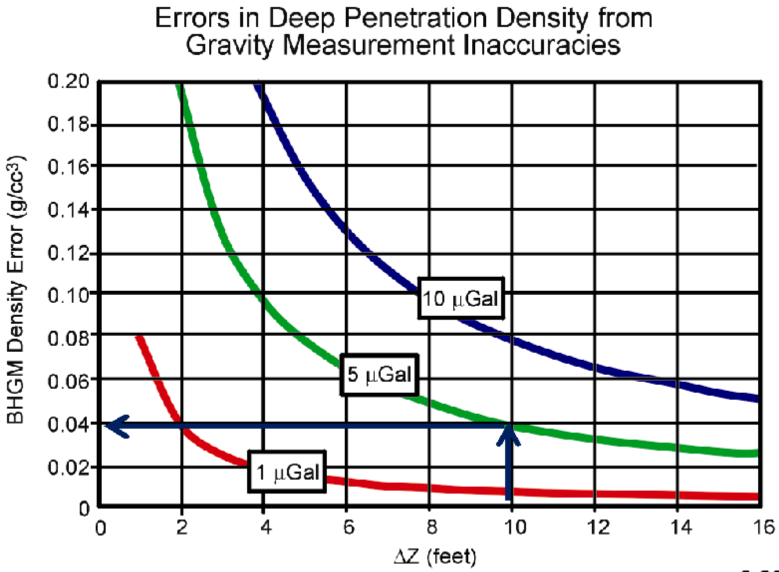
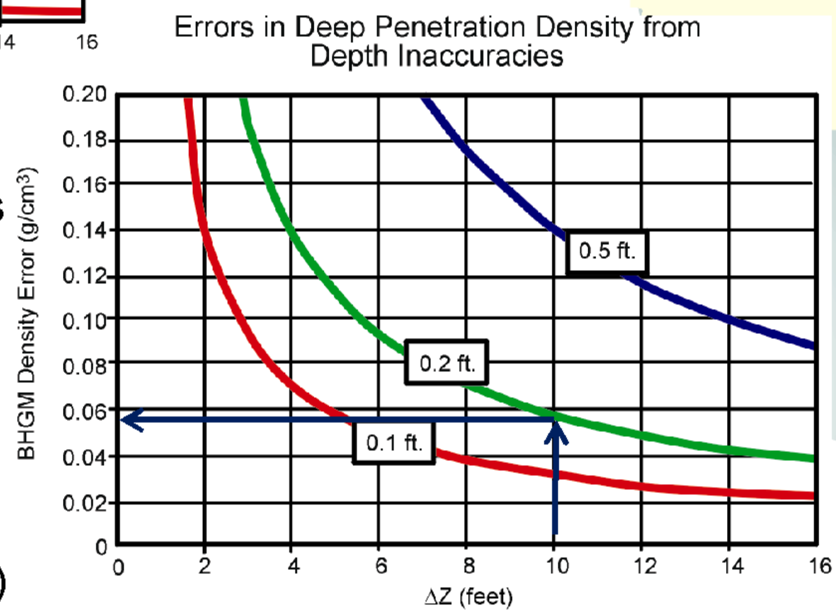
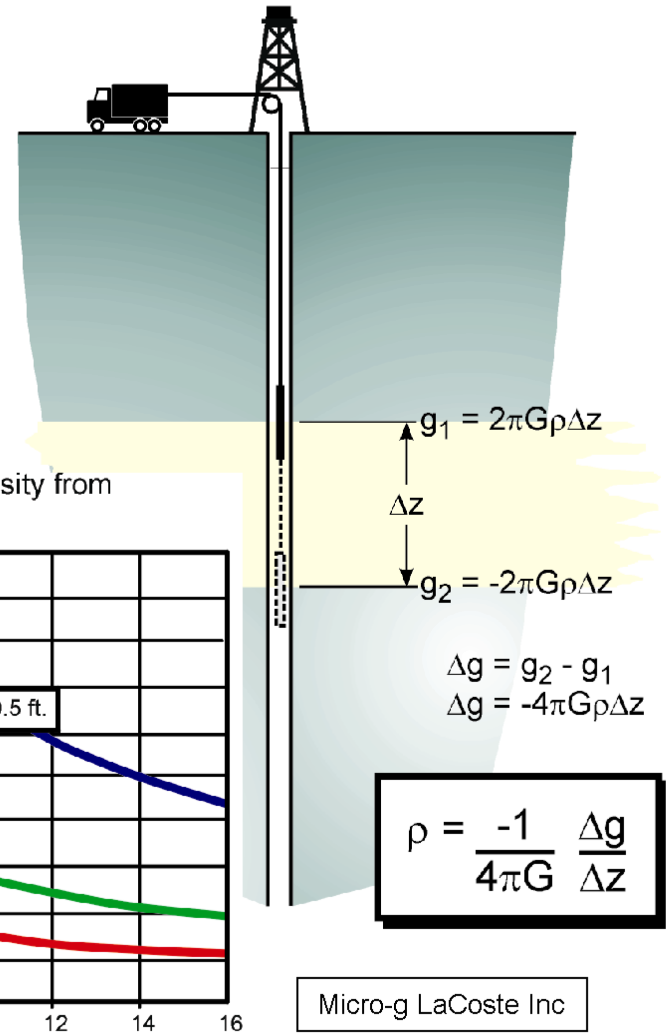
Apparent Density Error Challenges



$\Delta g/\Delta z$ ratio amplifies errors

- 10 ft spacing at 5µGal error gives 0.04 g/cm³ uncertainty
- 10 ft spacing at 0.2 ft error gives 0.06 g/cm³ uncertainty
- Where CO_2/water contrast 0.03 gm/cm³ (at 30 % S_{CO2} and 20 pu)





Cranfield SECARB Regional Partnership

SECARB Cranfield, Mississippi

Time-lapse Borehole Gravity

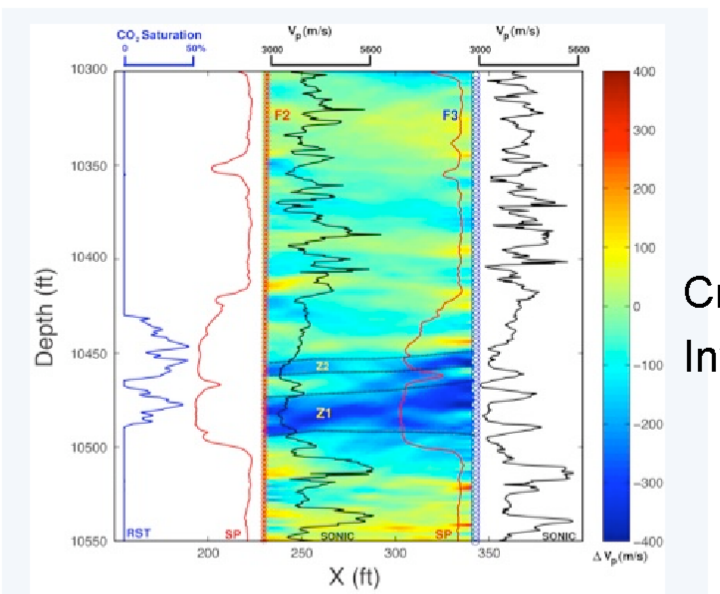
- Two well pre-injection borehole gravity acquisition in Sept 2009
- Two well post-injection borehole gravity acquisition in Sept 2010

Goals

- Evaluate design criteria
- Evaluate operational issues
- Evaluate response to CO_2 injection

Time-lapse Borehole Gravity

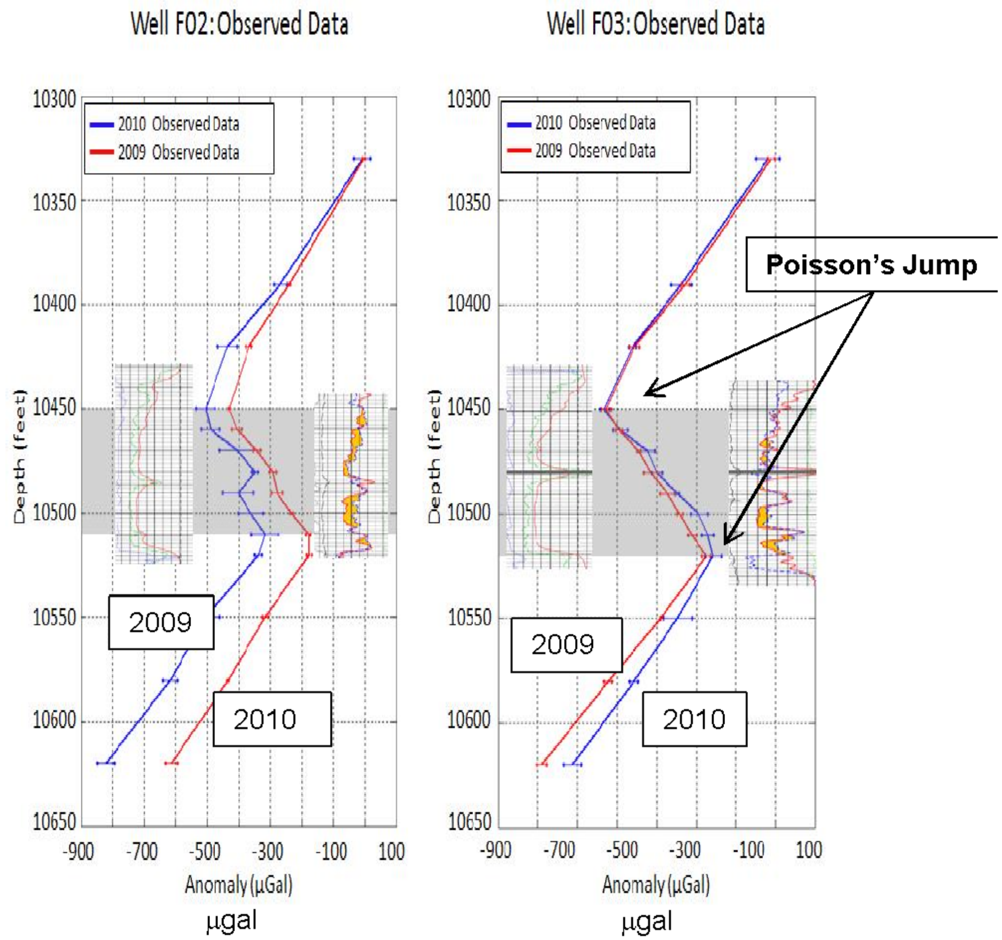
- Colorado School of Mines Gravity Magnetic consortium collaboration
- Specific project to evaluate inversion of data (completed)



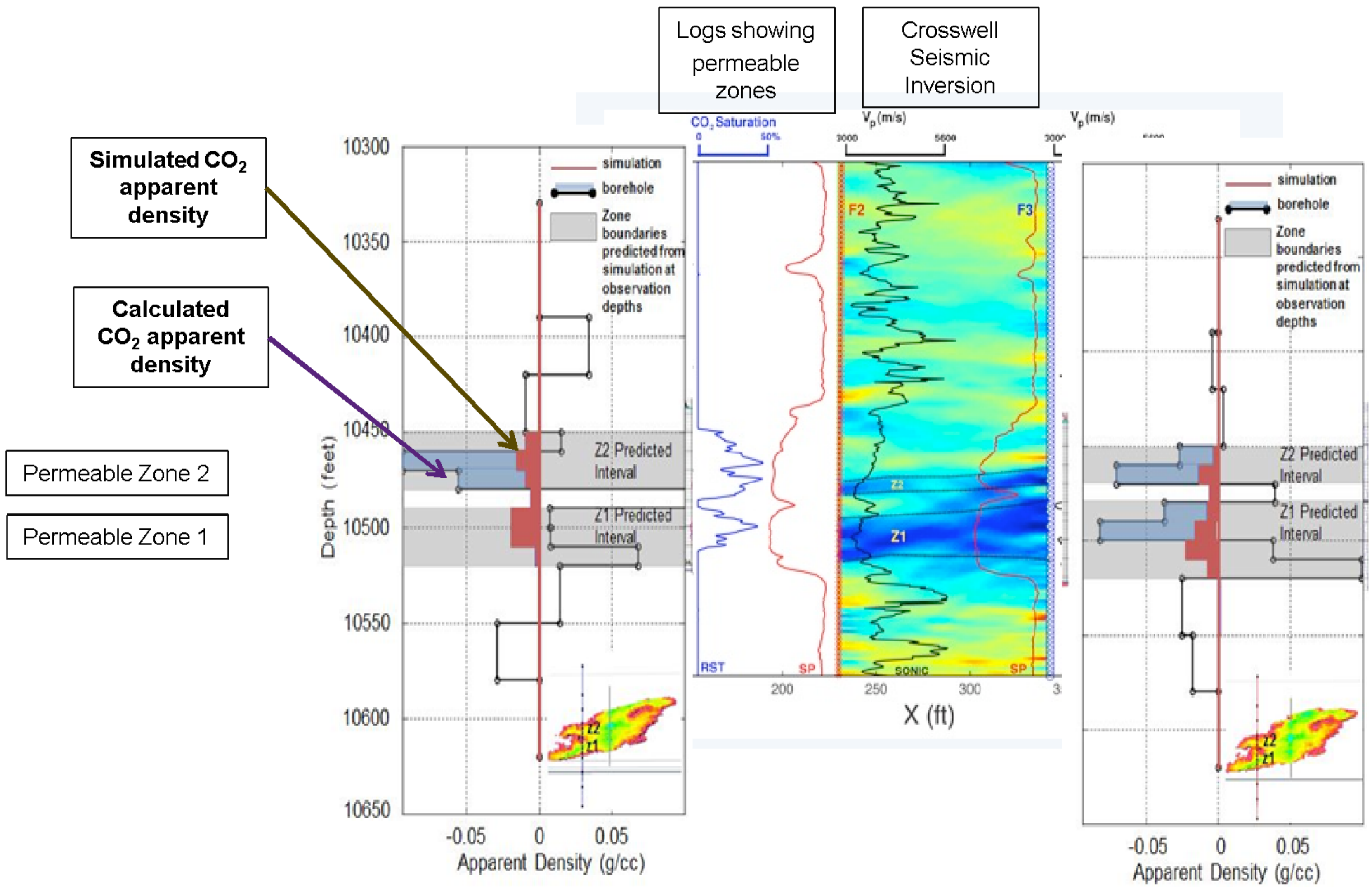
Crosswell Seismic Inversion (LBNL)

Baseline and repeat for both wells

- Red denoting 2009 data, Blue denoting 2010 data
- Bars show the statistical variation of the measurements at each level
- Reversal 'Poisson Jump ' associated with bulk density change over the permeable zones indicated by logs on each side.
- The increasing separation from top to bottom is due to the anomalous instrumental drift observed during the repeat passes.



Observed apparent density cf simulated CO_2 apparent density



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Conclusions

- The borehole gravimeter data were evaluated on several levels:
  - Sensitivity to the larger geologic response
  - Smaller time-lapse signal from injected CO_2
  - Operational constraints
- All four data sets, demonstrated distinct changes at the boundaries of the permeable zone
- It identifies the separation between upper and lower zones of the reservoir
- We observed that the apparent density change is consistent with that predicted from the reservoir simulations.
- The time-lapse borehole gravity data for sequestration monitoring at Cranfield contain meaningful but qualitative information about CO_2 saturation.
- Quantitative evaluation can be achieved by careful attention to depth measurements and introduction of new higher resolution borehole technology

Acknowledging...

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Colorado School of Mines – Center for Gravity, Electrical & Magnetic Studies (CSM-CGEM)

Denbury Resources

CO2 Capture Project, Joint Industry Partners (see at bottom)

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