Measurement, Monitoring & Verification

Dr. Lee H. Spangler, Director

Zero Emission Research and Technology Center

The Need for MMV

Demonstration / Research Stage

- Health, Safety and Environmental concerns (HSE)
- Required by regulators
- Confirm underground behavior of CO_2
- Test models
- Public Acceptance

The Need for MMV

Implementation Stage

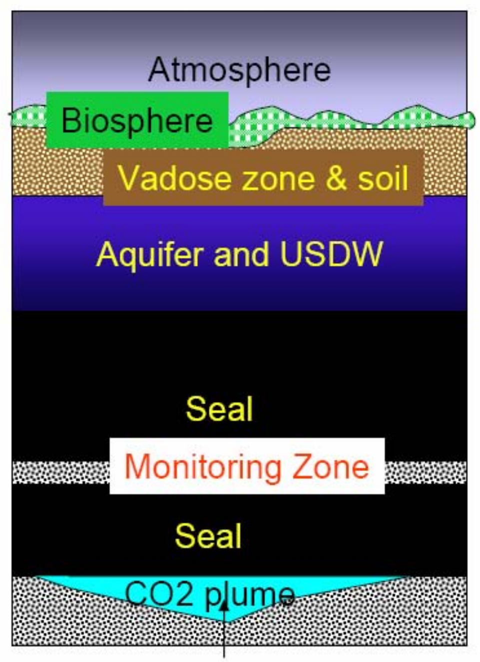
- Health, Safety and Environmental concerns
- Injection / reservoir management
- Required by regulators
- Verification for credits
- Reduction of liability
- Confirm underground behavior of CO2
- Test models
- Public Acceptance

Monitoring Zones

- Near Injection
- Near Surface
- Remote Sensing

Others classify differently (Hovorka)

Monitoring Zone Options

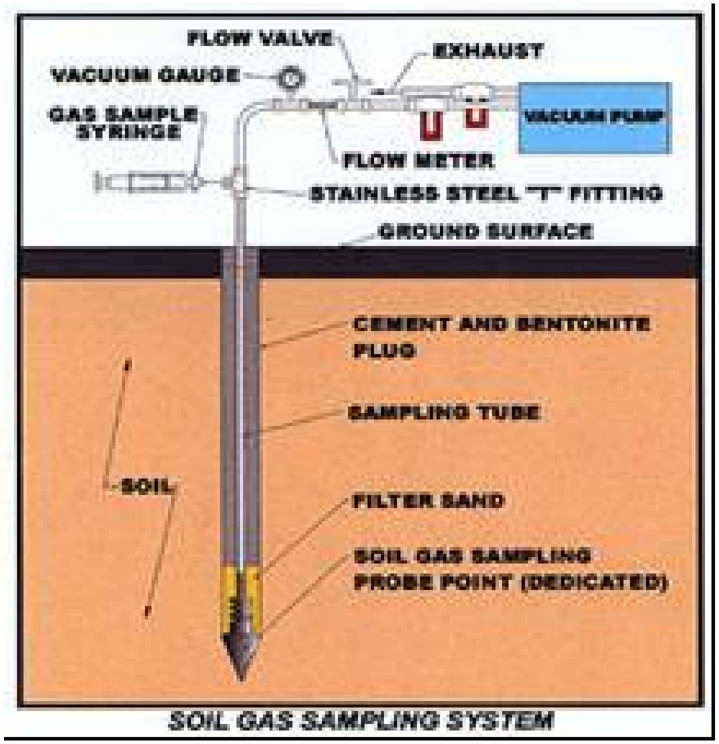


- Atmosphere
  - Ultimate integrator, dynamic
- Biosphere
  - Requires assurance of no damage, dynamic
- Soil and Vadose Zone
  - Integrator but dynamic
- Aquifer and USDW
  - Integrator, slightly isolated from ecological effects
- Above injection monitoring zone
  - First indicator, monitor small signals, more stable. May not integrate
- In-injection zone - plume
  - Oil-field type technologies. Will not find small leaks

Consider also lateral complexities, transport, focused flow paths

Soil Gas Monitoring

- Measures gases that exist within soil pore spaces in the unsaturated layer (i.e., vadose zone) between the ground surface and the groundwater table
- Soil gas can contain atmospheric gases and biologically produced gases.
- If seepage occurs it can contain gases that are introduced into the subsurface (for example CO2, or tracers).



Example Sampling Train for Soil Gas Using Vacuum Pump and Syringe (USEPA 2003).http://www/epa.gov/ttbnrml/presentations.htm

Soil Flux Monitoring

- Directly measures flux of CO2 at surface using an infrared gas analyzer
- Abnormally high fluxes are an indicator of leakage
- Measurements are complicated by daily and seasonal variations in plant and soil respiration that depend on amounts of sunlight, moisture levels and temperature.

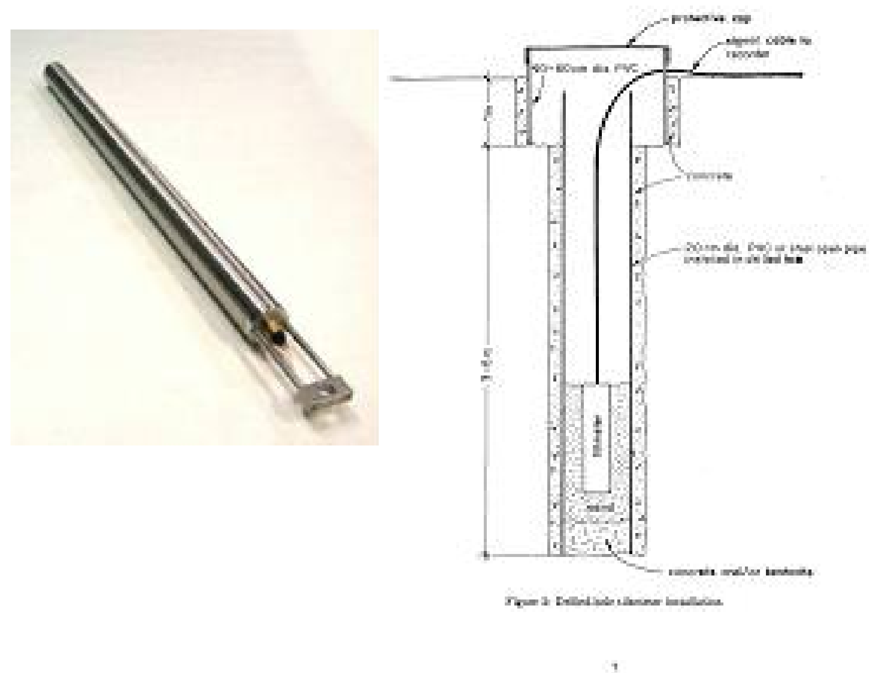
Jennifer Lewicki, LBNL

Eddy Covariance

- CO_2 flux measurement (the amount of CO_2 released per unit area per unit time)
- Determined by simultaneously measuring wind speed and direction, temperature, humidity, and the atmospheric concentrations of CO_2
- CO_2 concentrations are measured using an open-path infrared gas analyzer.
- Can have a large “Footprint”

Tiltmeters

- Monitors surface deformation caused by CO2 plume
- Use an array of tiltmeters installed in shallow boreholes (typically <10 m deep) around the injection wells in the area overlying the CO2 plume
- Tiltmeters are sensitive enough to record microradian-scale changes (which is the angle turned by raising one end of a beam one kilometer long the width of a dime), which can be caused by various surface phenomena including daily temperature variations.



Tiltmeter (left) and Installation in Shallow Borehole (Applied Geomechanics)

InSAR (Interferometric Synthetic Aperture Radar)

- Uses radar satellite images from Earth-orbiting satellites
- Maps land surface topography with accuracy of a few centimeters,
- Cannot be used in areas with vegetation.
- InSAR is a proven technique for mapping ground deformation and is commonly used to monitor ground deformation at volcanoes.

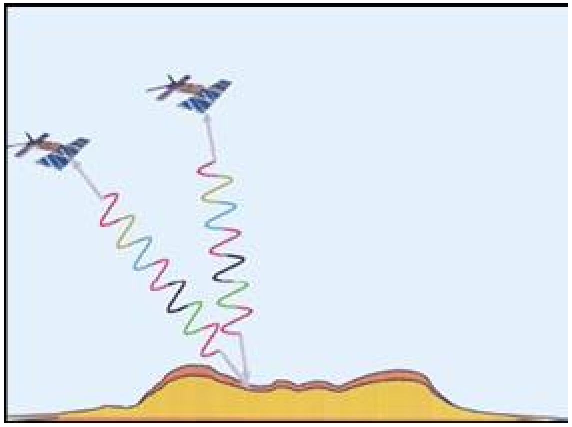
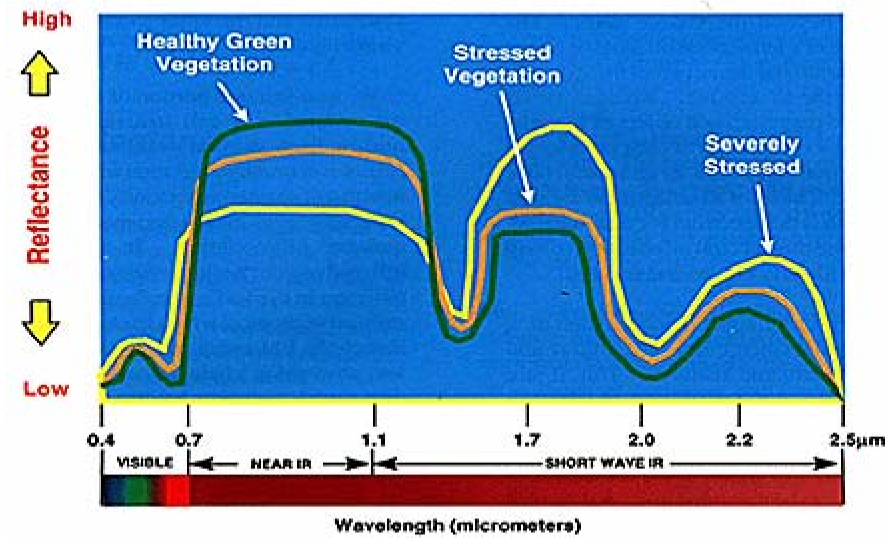


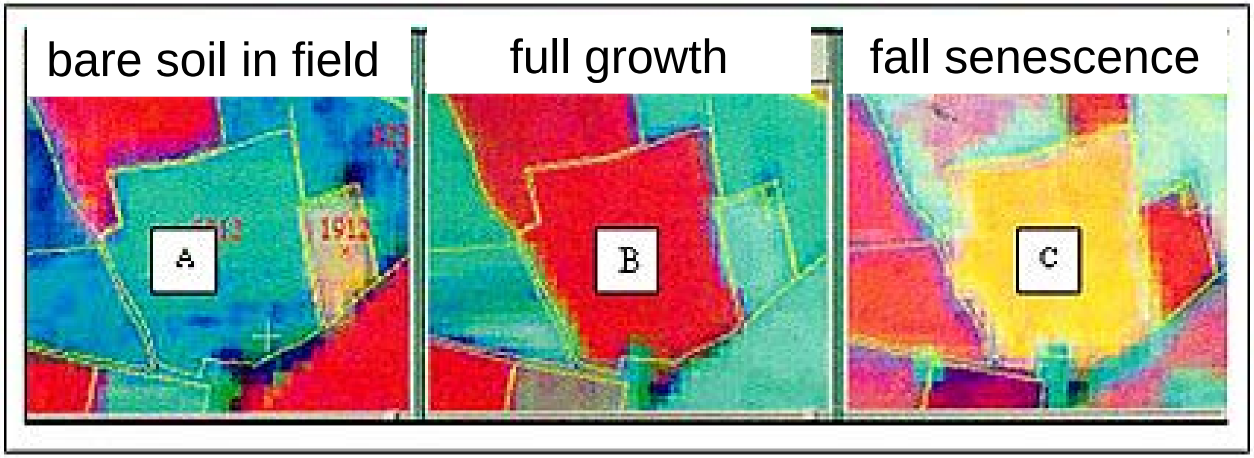
Diagram Showing how Radar Interferometry Detects Uplift of the Earth's Surface.[1]

[1]http://volcanoes.usgs.gov/insar/public_files/InSAR_Fact_Sheet/2005-3025.pdf

Hyperspectral Imaging

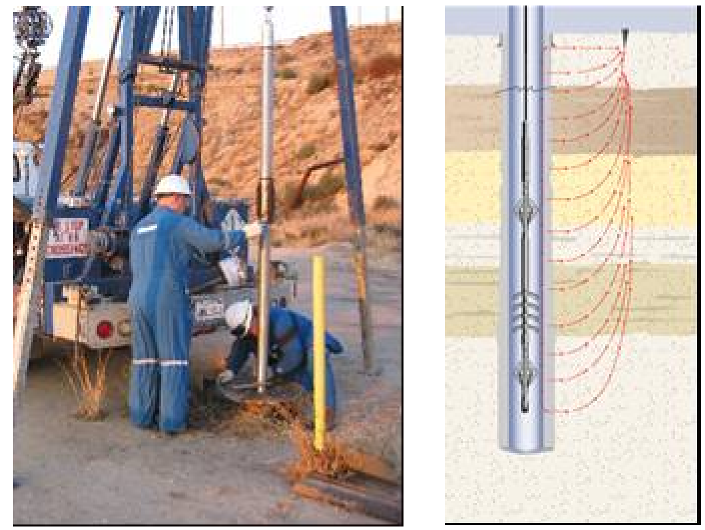
- High CO_2 levels in soil can stress or even kill plants
- Plant stress can be detected via infrared spectral imaging
- This can be land based, airborne or satellite
- Methodology will be dependent on land use





Wireline Logs

- Acquired by lowering instruments down the well and making a measurement profile of various physical properties along its length.
- Sonic, density, neutron, NMR and the various induction and resistivity logs are potentially suitable for CO2 storage monitoring
- The Reservoir Saturation Tool (RST), a through-casing pulsed neutron tool designed to measure water and hydrocarbon saturations, is well suited to CO2 monitoring. Work at Frio (Muller et al.) has demonstrated successful CO2 saturation logging with the RST tool.

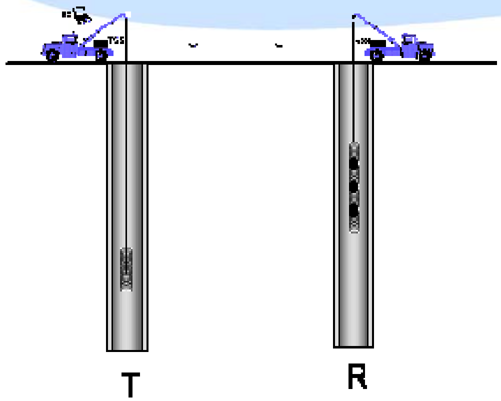


Lowering a Wireline Assembly into a Well (left) and Schematic of CHFR Tool Showing Current Flow (Schlumberger)

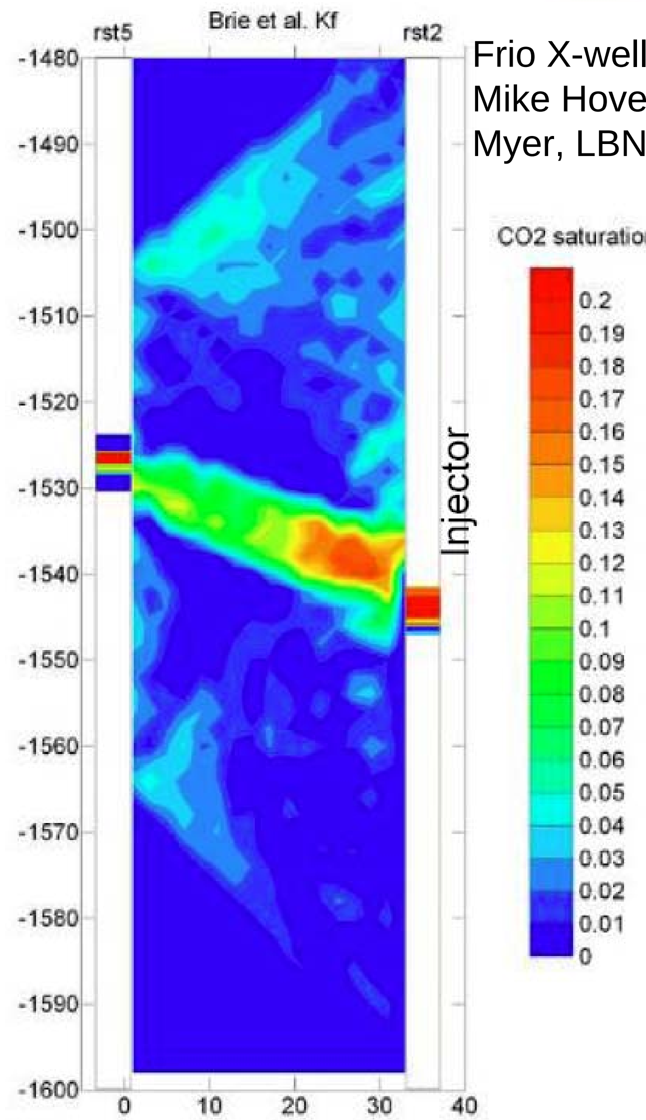
Direct Fluid Sampling

- Dissolved CO2
- Other chemistry
- U-tube sampling (LBNL) allows sample extraction at correct T & P conditions

Cross-well seismic



Schematic of Cross-Well Seismic Survey (Schlumberger)



Frio X-well Tom Daley, Mike Hoversten, L. Myer, LBNL

- Monitors distribution of CO_2 in the injection reservoir.
- Requires a minimum of two wells that extend to the base of the injection reservoir.
- Seismic sources suspended on a cable are lowered down one well and a cable containing a set of receivers is lowered down the other well.
- Provides data for the 2-dimensional vertical “slice” between the two wells containing the sources and receivers.

Microseismic Sensors

- Pressure changes caused by the CO_2 plume generate subsurface vibrations.
- Receivers placed down a borehole continuously record a seismic signal from the injection reservoir.
- These events are due to the small changes in pore pressures.

Microseismic Downhole Sensors and Surface Completion with Solar Power (ESG)

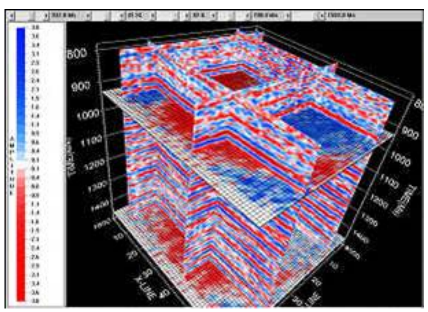
Vertical Seismic Profiling (VSP)

***VSP reflection section at Frio showing pronounced enhancement of reflectivity at the reservoir level after CO2 injection** (Images courtesy of Tom Daley (LBNL), Christine Doughty (LBNL) and Susan Hovorka (University of Texas)).*

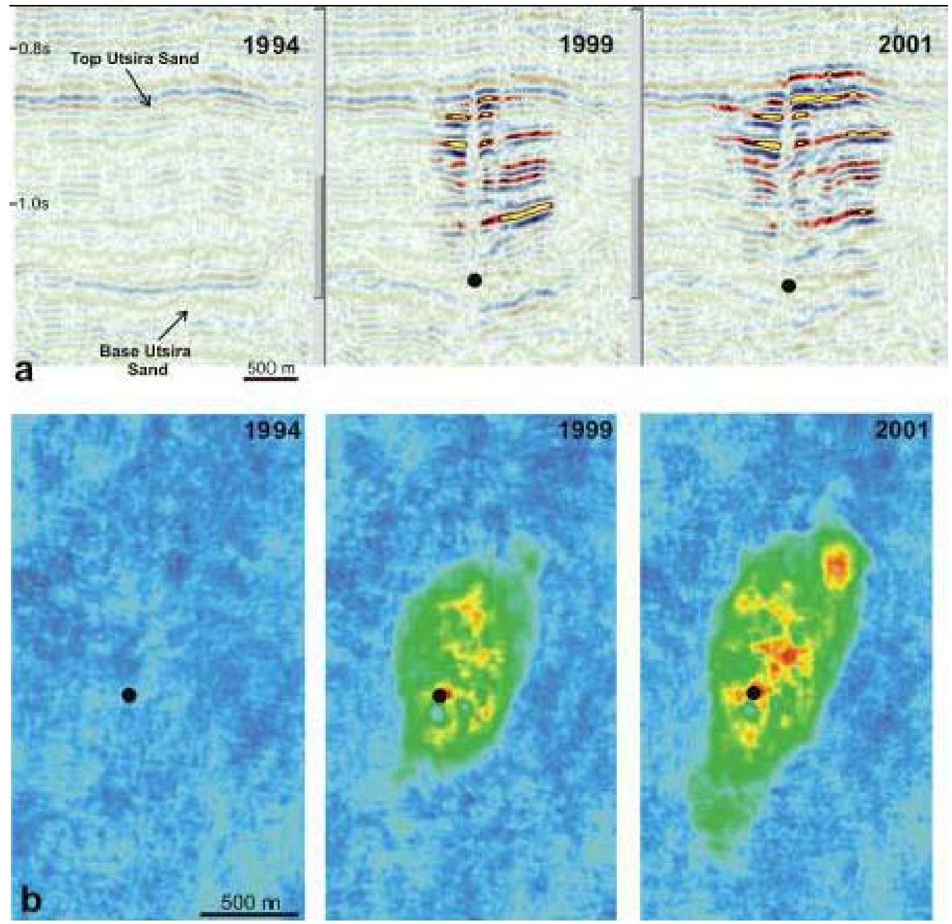
- Requires that a well is situated in close proximity to the CO2 plume.
- Surface seismic sources are deployed around the well installation,
- Sensors deployed downhole.
- Conventional VSP with sources close to the wellhead gives quite narrow subsurface coverage around the wellbore.
- Walkaway VSP where sources are arranged on a radial profile provides 2D subsurface coverage away from the well.
- Compared to surface seismic, VSP data can offer improved resolution and formation characterization around the well.
- VSP data also offers the potential for providing early warning of migration from the well into the surrounding caprock.

3-D Seismic

- Uses multiple seismic sources and receivers.
- Produces full volumetric images of subsurface structure in both reservoir and overburden.
- Very powerful but expensive method



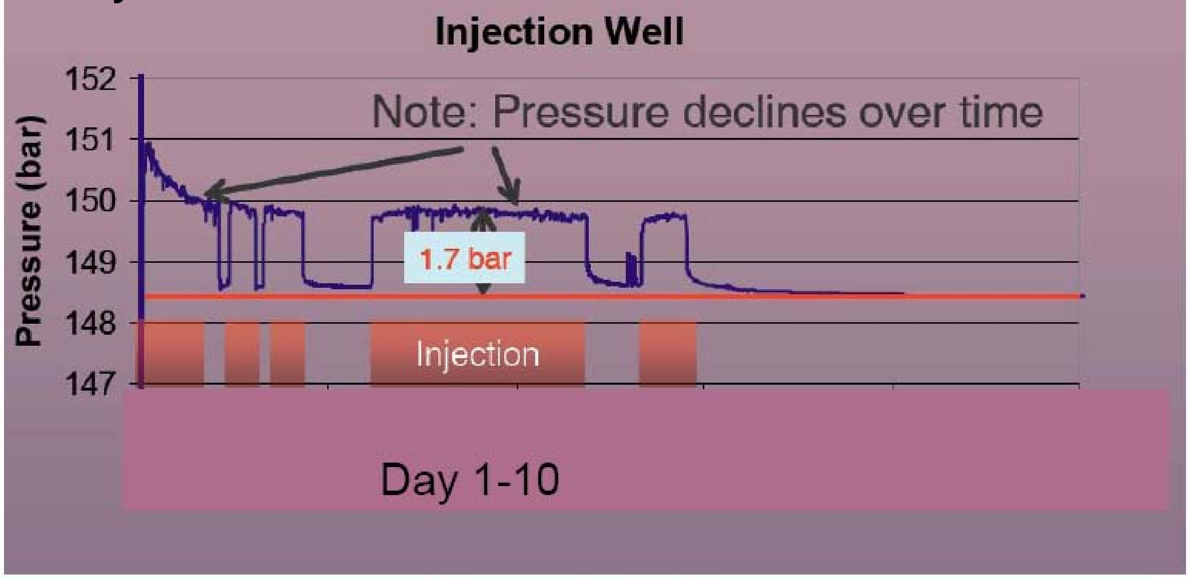
Vibroseis Trucks Acquiring Surface Seismic Data (Tesla Exploration) and 3D Seismic Data Volume (Gedco)
http://www.teslaoffshore.com

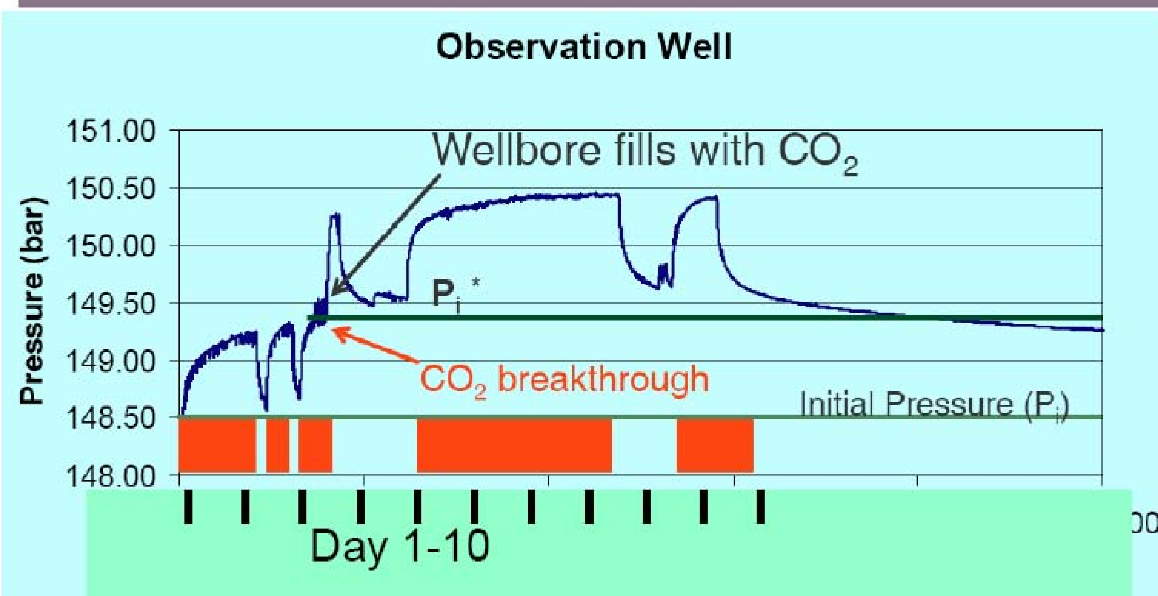


4-D seismic (time lapse 3-D seismic) at Sliepner (from Chadwick, 2004)

Pressure Monitoring

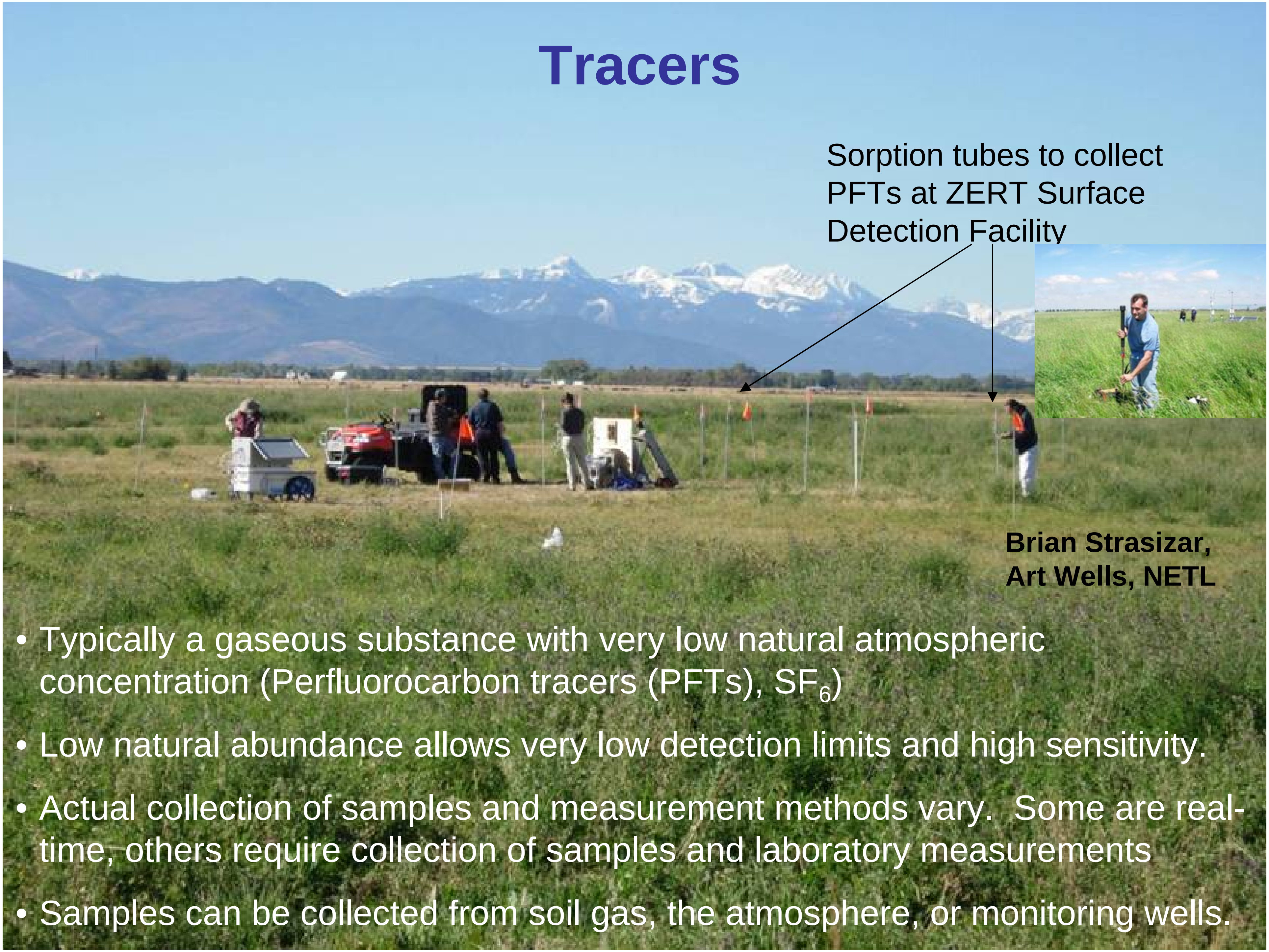
Sally Benson, LBNL





- Wellhead, bottom-hole and annular pressure can be monitored
- Provides information about injectivity
- Provides feedback useful to protecting reservoir, caprock integrity
- Sudden changes provide early evidence of problems
- Relatively inexpensive

Tracers



- Typically a gaseous substance with very low natural atmospheric concentration (Perfluorocarbon tracers (PFTs), SF_6)
- Low natural abundance allows very low detection limits and high sensitivity.
- Actual collection of samples and measurement methods vary. Some are real-time, others require collection of samples and laboratory measurements
- Samples can be collected from soil gas, the atmosphere, or monitoring wells.

Frio Tracer Data

•Introduced materials that travel with CO2can uniquely fingerprint migration

–Nobel gasses

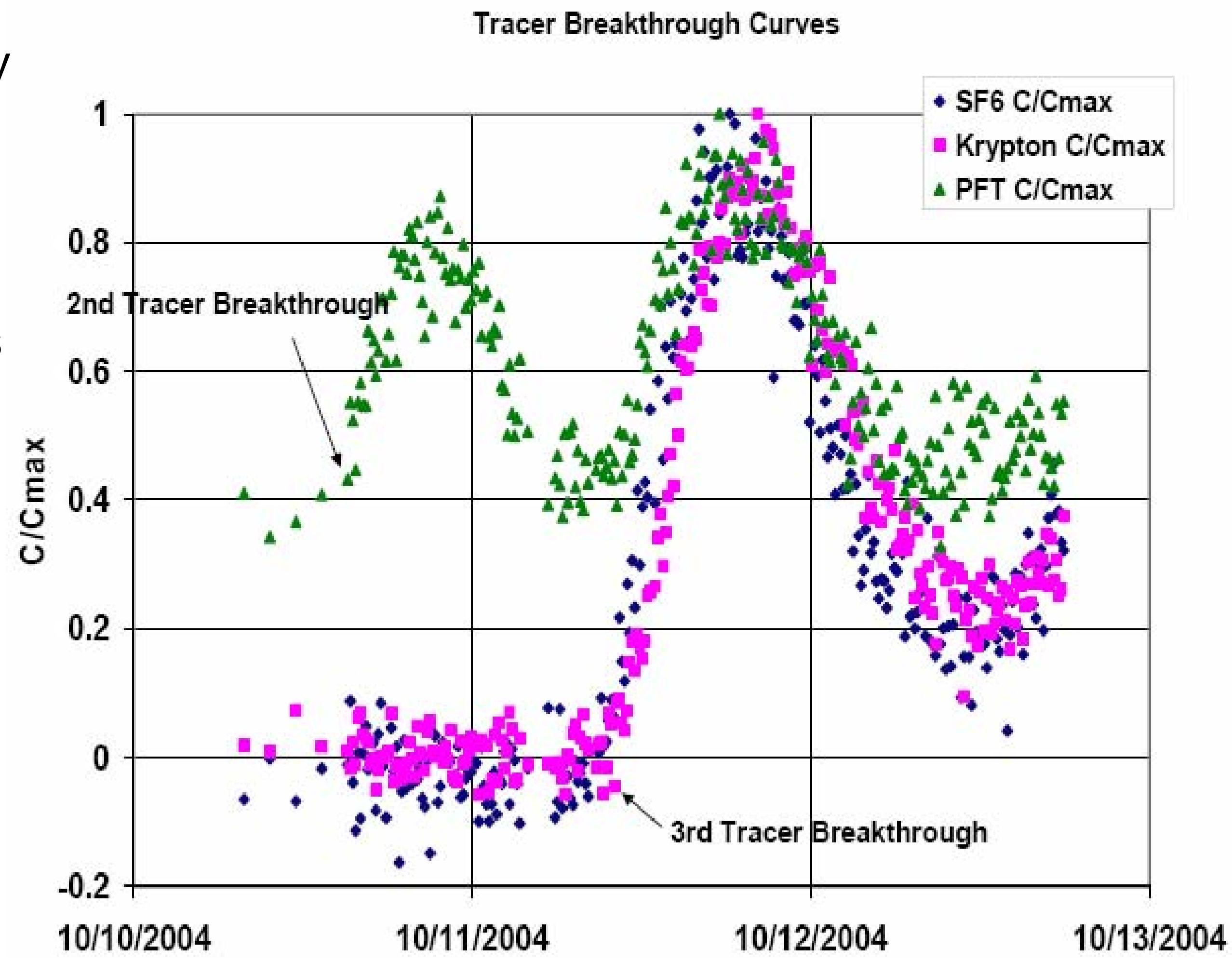
–PFT's and other chemically unique materials

–Detection at very low concentrations

•CO2can be geochemically unique

–C isotopes

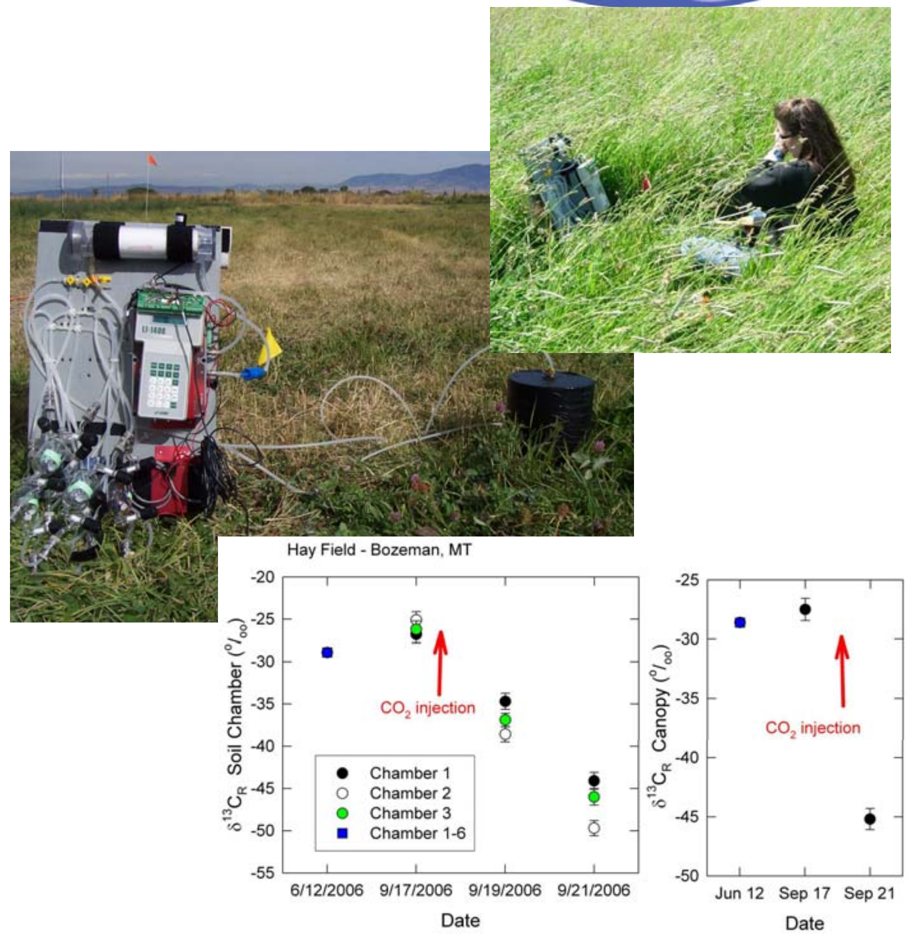
–Impurities



Frio noble gas and PFT analysis, Barry Freifeld (LBNL) and Timmy Phelps (ORNL)

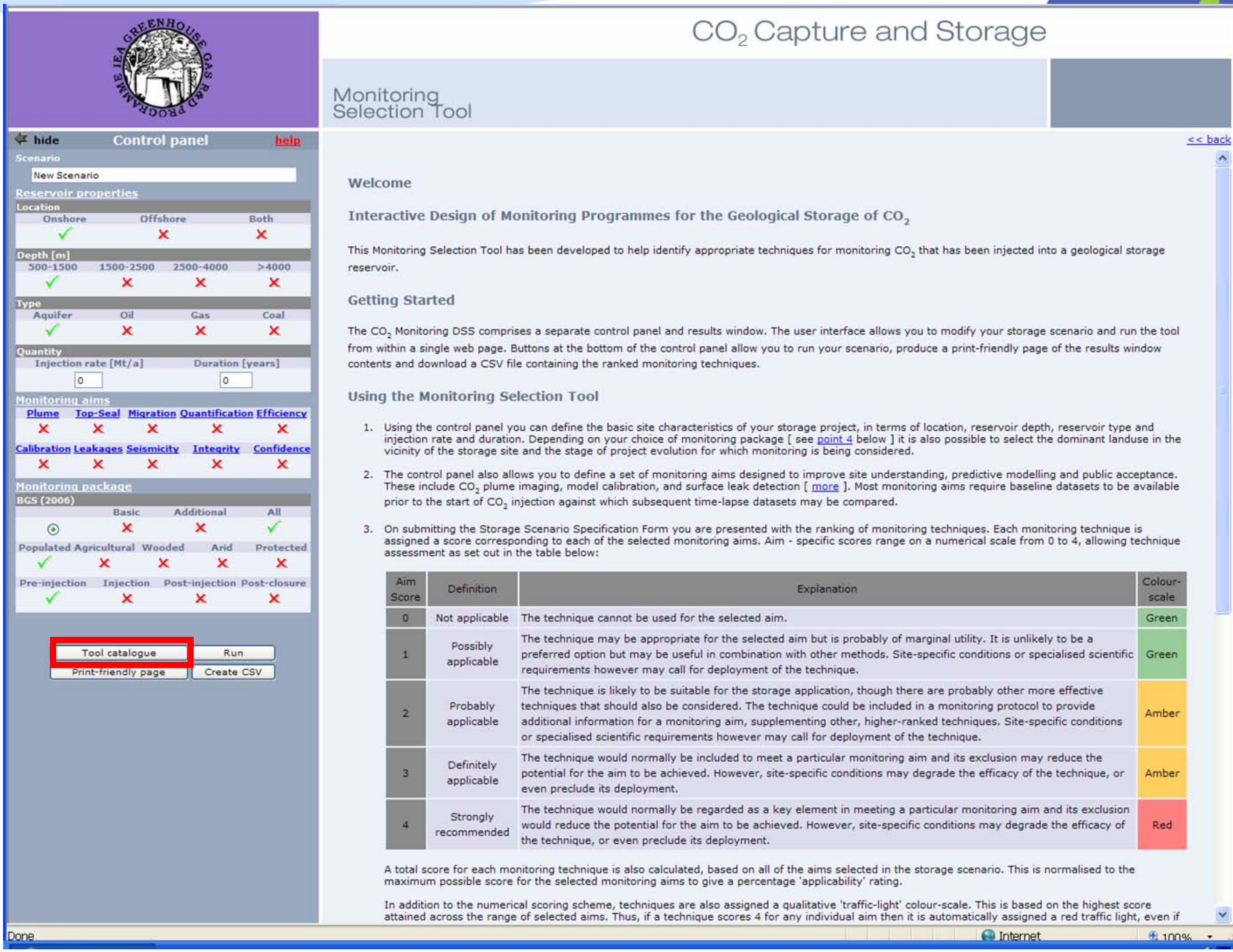
Isotopic Analysis

- The ^{13}C content of CO_2 varies depending on the source of CO_2.
- Fossil fuel generated CO_2 typically has a different ^{13}C to ^{12}C ratio than soil gas or the atmosphere
- Measurement of the isotopic ratio can be a more sensitive method than measuring flux or concentration
- Different types of sampling can be used (soil gas, atmospheric, vegetation, ground water).

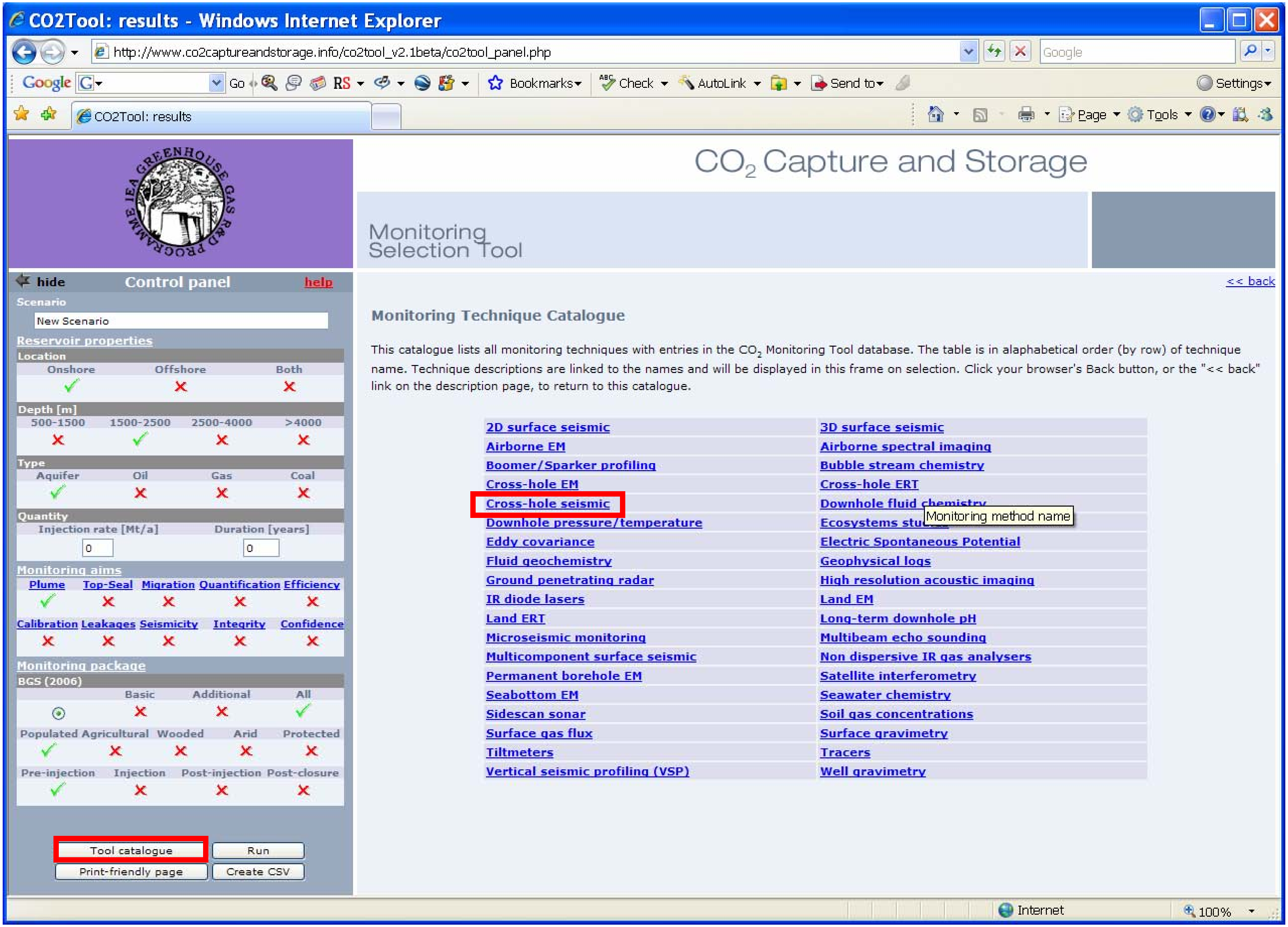


Julianna Fessenden, LANL

A Useful, Interactive MMV Website



http://www.co2captureandstorage.info/co2monitoringtool/index.php


CO2Tool: results - Windows Internet Explorer
http://www.co2captureandstorage.info/co2tool_v2.1beta/co2tool_panel.php
CO2Tool: results
CO2 Capture and Storage
Monitoring Selection Tool
hide
Control panel
help
Scenario
New Scenario
Reservoir properties
Location
Onshore
Offshore
Both
Depth [m]
500-1500
1500-2500
2500-4000
>4000
Type
Aquifer
Oil
Gas
Coal
Quantity
Injection rate [Mt/a]
Duration [years]
Monitoring aims
Plume
Top-Seal
Migration
Quantification
Efficiency
Calibration
Leakages
Seismicity
Integrity
Confidence
Monitoring package
BGS (2006)
Basic
Additional
All
Populated
Agricultural
Wooded
Arid
Protected
Pre-injection
Injection
Post-injection
Post-closure
Tool catalogue
Run
Print-friendly page
Create CSV
<< back
Monitoring Technique Catalogue
This catalogue lists all monitoring techniques with entries in the CO2 Monitoring Tool database. The table is in alaphabetical order (by row) of technique name. Technique descriptions are linked to the names and will be displayed in this frame on selection. Click your browser's Back button, or the "<< back" link on the description page, to return to this catalogue.
2D surface seismic
3D surface seismic
Airborne EM
Airborne spectral imaging
Boomer/Sparker profiling
Bubble stream chemistry
Cross-hole EM
Cross-hole ERT
Cross-hole seismic
Downhole fluid chemistry
Monitoring method name
Downhole pressure/temperature
Eddy covariance
Electric Spontaneous Potential
Fluid geochemistry
Geophysical logs
Ground penetrating radar
High resolution acoustic imaging
IR diode lasers
Land EM
Land ERT
Long-term downhole pH
Microseismic monitoring
Multibeam echo sounding
Multicomponent surface seismic
Non dispersive IR gas analysers
Permanent borehole EM
Satellite interferometry
Seabottom EM
Seawater chemistry
Sidescan sonar
Soil gas concentrations
Surface gas flux
Surface gravimetry
Tiltmeters
Tracers
Vertical seismic profiling (VSP)
Well gravimetry
Internet
100%

CO_2 Capture and Storage

Monitoring Selection Tool

hide **Control panel** help

Scenario

New Scenario

Reservoir properties

Location

Onshore	Offshore	Both
✓	✗	✗

Depth [m]

500-1500	1500-2500	2500-4000	>4000
✗	✓	✗	✗

Type

Aquifer	Oil	Gas	Coal
✓	✗	✗	✗

Quantity

Injection rate [Mt/a]	Duration [years]
0	0

Monitoring aims

Plume	Top-Seal	Migration	Quantification	Efficiency
✓	✗	✗	✗	✗

Calibration	Leakages	Seismicity	Integrity	Confidence
✗	✗	✗	✗	✗

Monitoring package

BGS (2006)

	Basic	Additional	All
⊙	✗	✗	✓

Populated	Agricultural	Wooded	Arid	Protected
✓	✗	✗	✗	✗

Pre-injection	Injection	Post-injection	Post-closure
✓	✗	✗	✗

Tool catalogue | Run | Print-friendly page | Create CSV

<< back

Cross-hole seismic

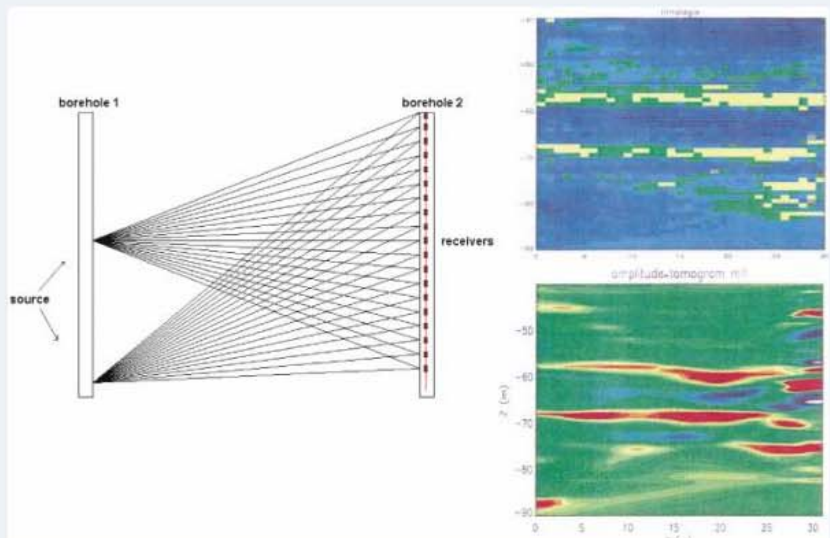
Overview

The cross-hole seismic technique measures velocity and attenuation characteristics in a 2D profile between wells, to measure CO_2 saturations and/or pressure changes during CO_2 injection. In time-lapse mode this can provide information on how the CO_2 is moving, as well as fine-scale data to help calibrate surface seismic data.

Full Description >> | Case Studies >> | Bibliography >>

Full Description

The cross-hole seismic technique measures velocity and attenuation characteristics in a 2D profile between wells using seismic sources and receivers, to model CO_2 saturations and/or pressure changes during CO_2 injection. In time-lapse mode this can provide information on how the CO_2 is moving, as well as fine-scale data to help calibrate surface seismic data. The method requires two or more wells that pass through or close to the storage reservoir with energy sources mounted in one borehole and receivers mounted in the other.



Basic configuration for a cross-hole seismic survey (left) with velocity and amplitude tomograms (right) showing seismic structure between the wells. *(Courtesy of R. Arts, TNO).*

By measuring changes in travel-time and signal amplitude between the wells, tomographic techniques can be used to map velocity and attenuation variations in the section between the wells. These can be used to model CO_2 saturations and/or pressure changes. In addition, cross-hole data can be useful for assessing how effectively the pore

Done | Internet | 100%

CO_2 Capture and Storage

Monitoring Selection Tool

hide **Control panel** help

Scenario

New Scenario

Reservoir properties

Location		
Onshore	Offshore	Both
✓	✗	✗

Depth [m]			
500-1500	1500-2500	2500-4000	>4000
✗	✓	✗	✗

Type			
Aquifer	Oil	Gas	Coal
✓	✗	✗	✗

Quantity	
Injection rate [Mt/a]	Duration [years]
0	0

Monitoring aims

Plume	Top-Seal	Migration	Quantification	Efficiency
✓	✗	✗	✗	✗
Calibration	Leakages	Seismicity	Integrity	Confidence
✗	✗	✗	✗	✗

Monitoring package

BGS (2006)	Basic	Additional	All
⊙	✗	✗	✓

Populated	Agricultural	Wooded	Arid	Protected
✓	✗	✗	✗	✗

Pre-injection	Injection	Post-injection	Post-closure
✓	✗	✗	✗

Tool catalogue | Run | Print-friendly page | Create CSV

Cross-hole seismic

Overview

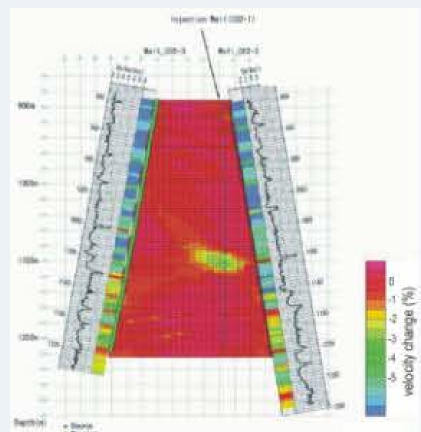
The cross-hole seismic technique measures velocity and attenuation characteristics in a 2D profile between wells, to measure CO_2 saturations and/or pressure changes during CO_2 injection. In time-lapse mode this can provide information on how the CO_2 is moving, as well as fine-scale data to help calibrate surface seismic data.

Full Description >> | Case Studies >> | Bibliography >>

Case Studies

Nagaoka

Roughly 10000 tonnes of CO_2 have been injected into a 12 m thick sandstone reservoir at a depth of about 1100 m at Nagaoka in Japan, some 200 km north of Tokyo (Kikuta et al. 2005). Monitoring is based on an array of three observation wells situated within 120 m of the injection well. Crosshole seismic data were recorded along a 160 m long section between two of the monitoring wells. A baseline survey was acquired prior to injection with a number of repeat surveys thereafter. A tomographic ima from the first repeat survey, with about 3200 tonnes of CO_2 in the reservoir, clearly shows the CO_2 plume as an area of reduced velocity around the injection well.

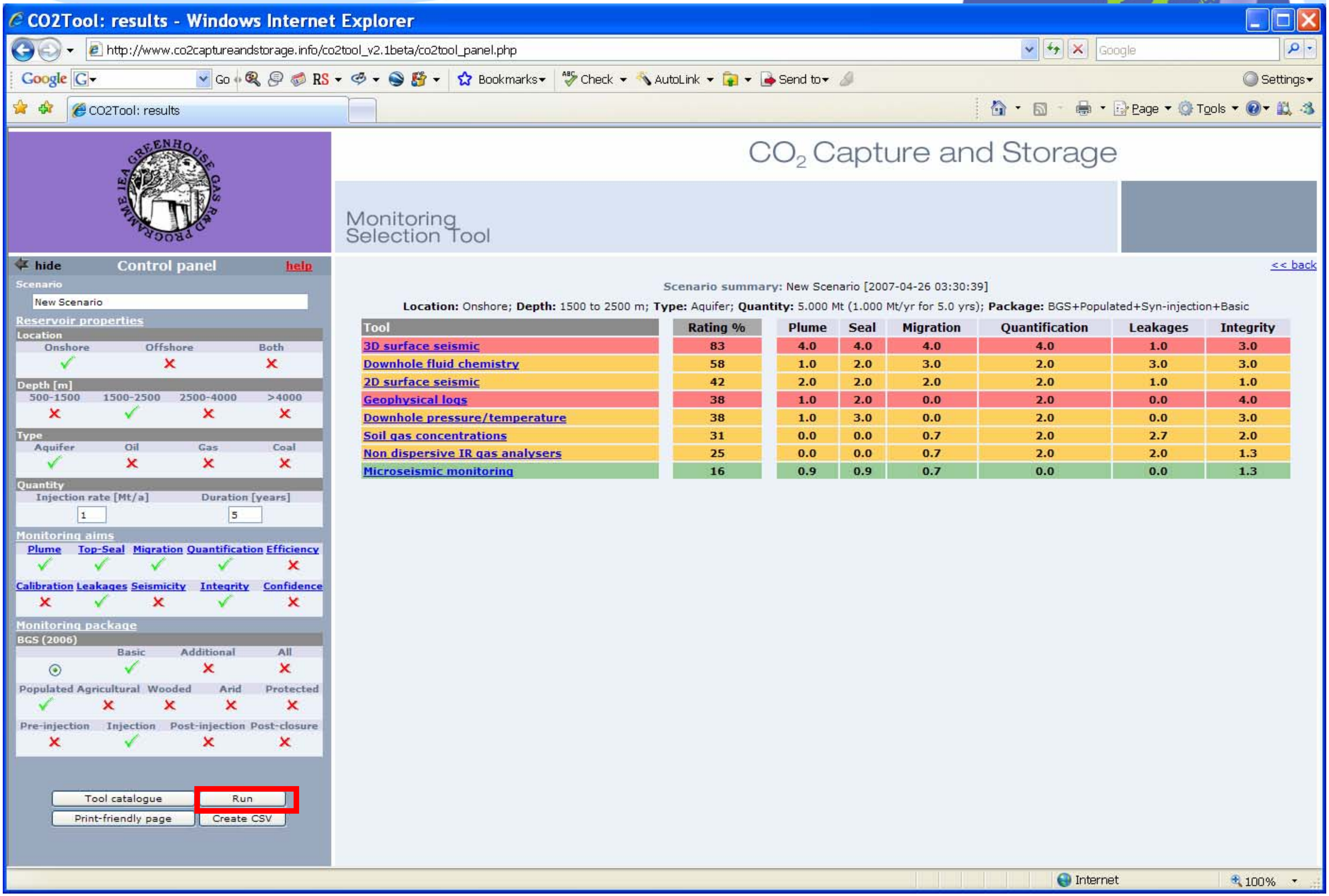


Cross-hole seismic at Nagaoka: tomographic image of velocity change due to 3200 tonnes of CO_2 in situ *(Adapted from Kikuta et al. (2005) and courtesy of Ziqui Xue, R.I.T.E).*

Frio Brine Pilot, Texas

The Frio Brine Pilot study (Hovorka & Knox 2002) involved injecting some 1600 tonnes of CO_2 into a well-characterised, relatively homogeneous, sandstone aquifer. A ra of surface and downhole monitoring technologies have been deployed including multicomponent cross-hole seismic. Preliminary results show that a velocity anomaly corresponding to the CO_2 plume has been successfully imaged on the cross-hole dataset.

A Useful, Interactive MMV Website



CO2Tool: results - Windows Internet Explorer

http://www.co2captureandstorage.info/co2tool_v2.1beta/co2tool_panel.php

CO_2 Capture and Storage

Monitoring Selection Tool

hide Control panel help

Scenario: New Scenario

Reservoir properties

Location: Onshore ✓; Offshore ✗; Both ✗

Depth [m]: 500-1500 ✗; 1500-2500 ✓; 2500-4000 ✗; >4000 ✗

Type: Aquifer ✓; Oil ✗; Gas ✗; Coal ✗

Quantity: Injection rate [Mt/a] 1; Duration [years] 5

Monitoring aims: Plume ✓; Top-Seal ✓; Migration ✓; Quantification ✓; Efficiency ✗; Calibration ✗; Leakages ✓; Seismicity ✗; Integrity ✓; Confidence ✗

Monitoring package: BGS (2006)

Basic ✓; Additional ✗; All ✗

Populated ✓; Agricultural ✗; Wooded ✗; Arid ✗; Protected ✗

Pre-injection ✗; Injection ✓; Post-injection ✗; Post-closure ✗

Tool catalogue | Run | Print-friendly page | Create CSV

<< back

Scenario summary: New Scenario [2007-04-26 03:30:39]

Location: Onshore; **Depth:** 1500 to 2500 m; **Type:** Aquifer; **Quantity:** 5.000 Mt (1.000 Mt/yr for 5.0 yrs); **Package:** BGS+Populated+Syn-injection+Basic

Tool	Rating %	Plume	Seal	Migration	Quantification	Leakages	Integrity
3D surface seismic	83	4.0	4.0	4.0	4.0	1.0	3.0
Downhole fluid chemistry	58	1.0	2.0	3.0	2.0	3.0	3.0
2D surface seismic	42	2.0	2.0	2.0	2.0	1.0	1.0
Geophysical logs	38	1.0	2.0	0.0	2.0	0.0	4.0
Downhole pressure/temperature	38	1.0	3.0	0.0	2.0	0.0	3.0
Soil gas concentrations	31	0.0	0.0	0.7	2.0	2.7	2.0
Non dispersive IR gas analysers	25	0.0	0.0	0.7	2.0	2.0	1.3
Microseismic monitoring	16	0.9	0.9	0.7	0.0	0.0	1.3

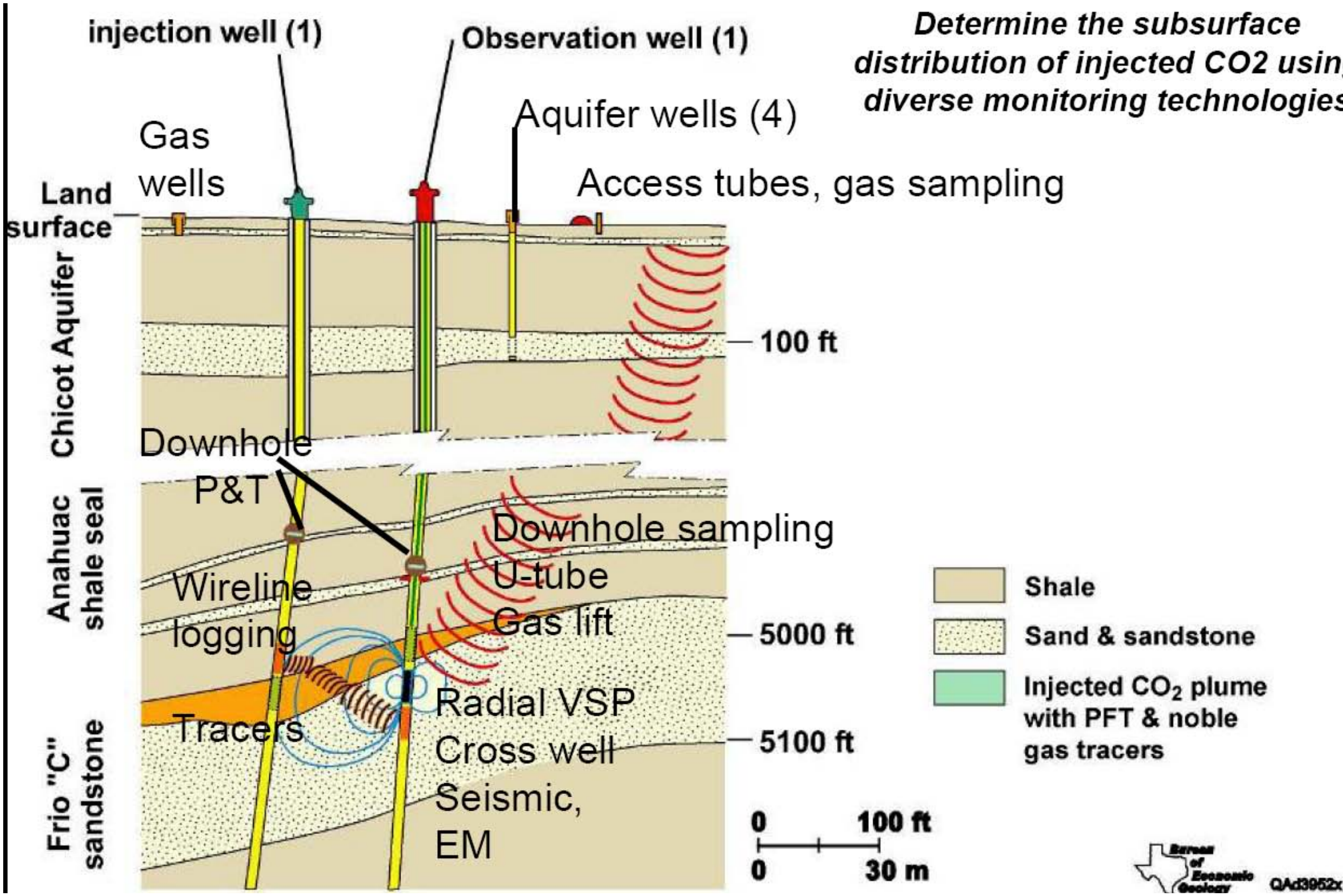
What MMV Should Be Used?

Project and Site Dependent

Category	Method	Use at CO_2 Sequestration Sites			
		Weyburn, Canada	Frio, TX	Lost Hills, CA	Vacuum Field, NM
Remote Sensing	LIDAR	√			
	INSAR			√	
	Hyperspectral Imaging				
Atmospheric Monitoring	Eddy Covariance		√		
Methods for Monitoring Processes at Surface and Near Surface	Soil Gas Sampling	√			
	Surface Flux Emissions	√	√		
	Vehicle Mounted CO_2 Leak Detection System				
	CO_2 Wellhead Monitoring				
	Borehole Tiltmeters				
	Ecosystem Studies		√		
Methods For Monitoring Subsurface Phenomena	In-Situ P/T Monitoring	√	√	√	√
	Fluid Sampling	√	√	√	
	Crosswell Seismic	√	√	√	
	Wireline Tools	√	√	√	
	Downhole Microseismic	√		√	
	3-D Time Lapsed Seismic	√	√	√	√
	2-D Time Lapsed Seismic				
	Vertical Seismic Profiling	√	√		
	Crosswell Resistivity		√	√	√
	Long Electrode Electrical Resistivity Tomography				
	Permanent Seismic Sources/Receivers				

Monitoring at Frio Pilot

Determine the subsurface distribution of injected CO2 using diverse monitoring technologies



What MMV Should Be Used?

Project, Site, and Stage Dependent

- Consistent with project goals and site properties
  - Some sites have inherently different HSE factors
  - Research intensive projects may utilize more MMV to improve understanding of CO_2 behavior
- Different stages may require different methods
  - Site characterization
  - Pre-injection background measurements
  - During injection
  - Post injection monitoring

What MMV Should Be Used?

Most projects should have:

- Some near injection component to ensure CO_2 and reservoir are behaving as expected
- Some near surface components for HSE and public assurance
- Integration of the MMV techniques so data is shared
- Pressure monitoring because it can give a very early indication of problem issues