Optical Spectroscopy and Microseismicity Tools for EOR and Coal Bed MVA Analyses

FWP FE-10-0001

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 16-18, 2016

Presentation Outline

- Project Overview
  - Goals and Objectives
- Benefit to the Program
- Technical Status
  - Remote and in situ Surface MVA with Stable Isotopes
  - Subsurface MVA – Advanced Microseismic Imaging
  - Probing the Earth’s Stress State in CO_2 Injection Reservoirs
- Summary

Project Overview: Goals and Objectives

- Surface MVA – Frequency Modulated Spectroscopy
  - Quantitatively identify CO_2, H_2S and CH_4 seepage from geologic sequestration sites
    - Distinguish anthropogenic from natural emissions
  - Real-time *remote and in situ* CO_2, H_2S and CH_4 monitoring
- Subsurface MVA – Advanced Microseismic Imaging
  - Reduce uncertainty of focal mechanism inversion of microseismic data.
  - Using focal mechanisms of microseismic data to distinguish fluid-induced and pressure/stress-induced microseismic events.
- Subsurface MVA – Analysis of Earthquakes Induced by Gas/Fluid Injection.
  - Probe ‘critical state’ of faults preceding failure in C02 storage scenarios, applying new seismological techniques

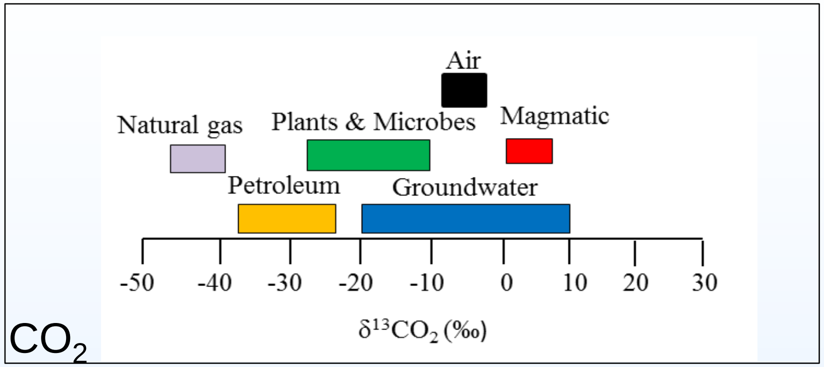
Benefit to the Program

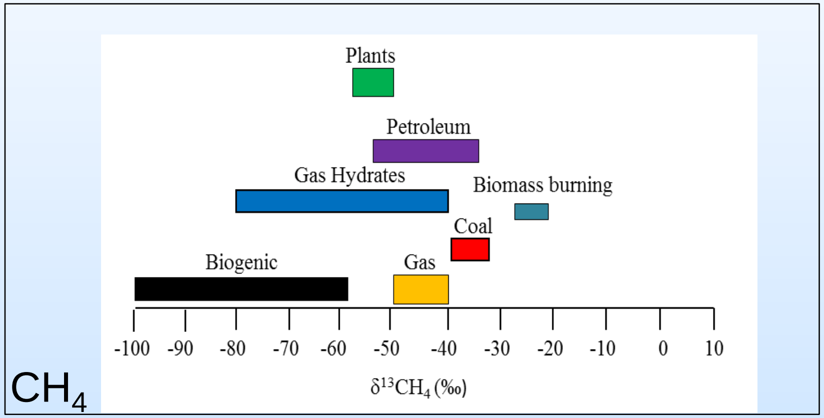
- Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
  - Advanced Seismic Reservoir Imaging
- Develop and validate technologies to ensure 99% storage permanence.
  - FMS CO_2, H_2S, and CH_4 Monitoring
  - Advanced Seismic Reservoir Imaging
- Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
  - FMS CO_2, H_2S, and CH_4 Monitoring
  - Advanced Seismic Reservoir Imaging
- Develop Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation.
  - FMS CO_2, H_2S, and CH_4 Monitoring
  - Advanced Seismic Reservoir Imaging

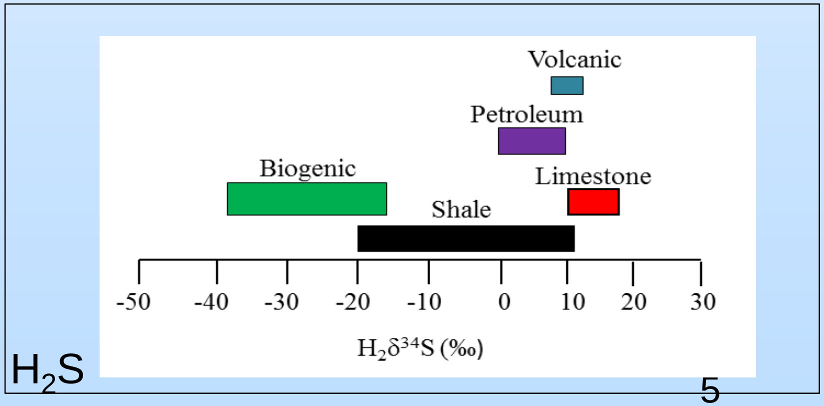
Stable Isotope Detection

- Detect Seepage of CO_2, CH_4, H_2S at sequestration sites
- Isotopic Signatures for source identification
- Frequency Modulated Spectroscopy
  - 100x to 1000x more sensitive than absorption spectroscopy
- Generally, the Atmosphere Contains
  - 98.9% $^{12}C^{16}O_2$
  - 1.1% $^{13}C^{16}O_2$
- Calibration Gases Prepared In House
  - Available vendors were too expensive and took too long

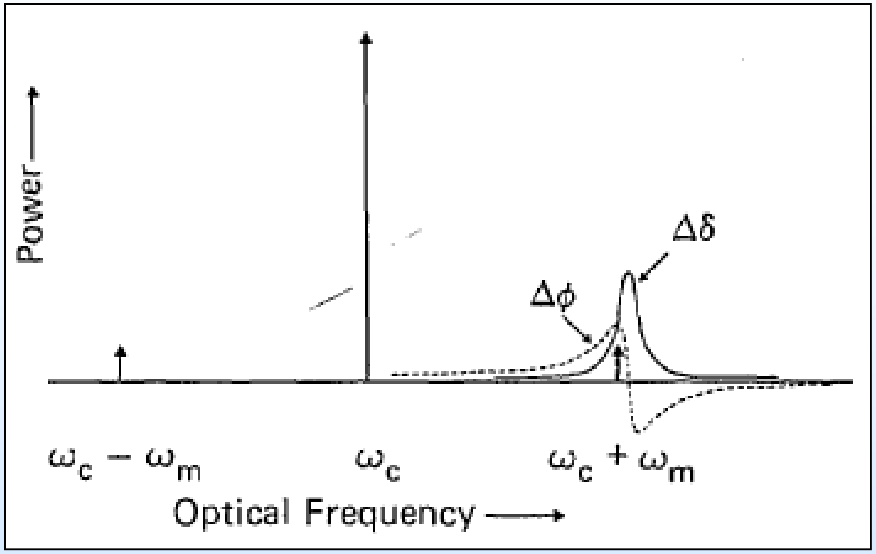
$$\delta^{13}C_{sam} = \left(\frac{^{13C_{sam}}/_{12C_{sam}}}{^{13C_{std}}/_{12C_{std}}} - 1 \right) x1000$$

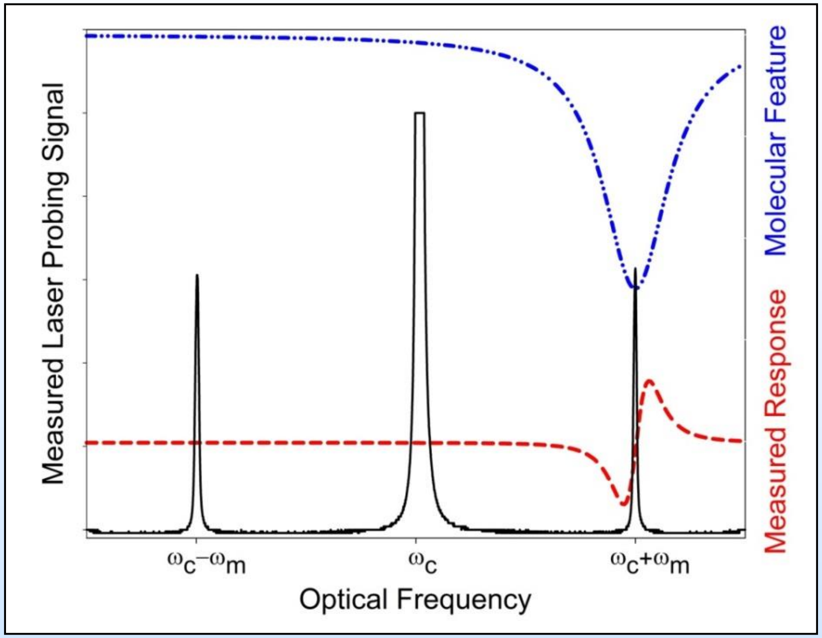






Frequency Modulated Spectroscopy



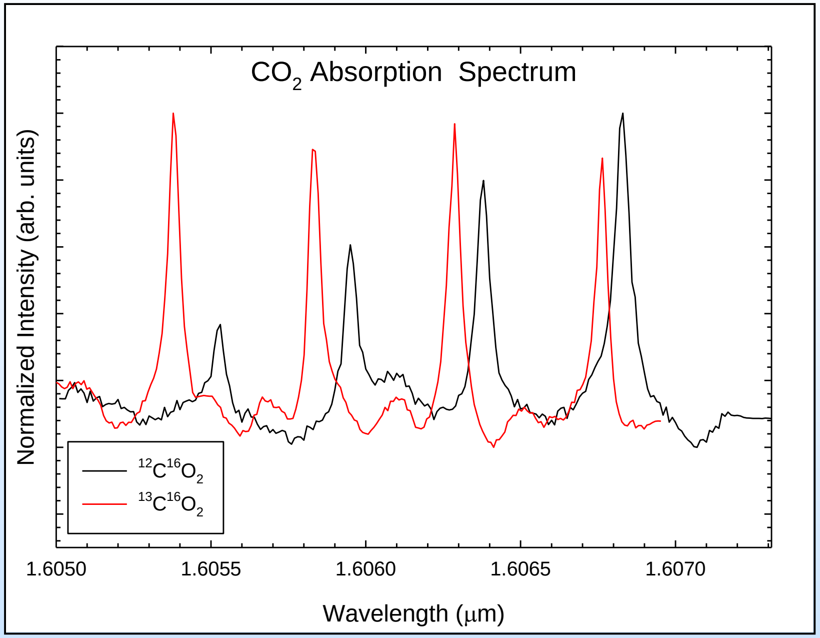


<u>Absorption Spectroscopy Maximum Line Strengths (HITRAN)</u>

$^{12}C^{16}O_2$ = 1.83x10^{-23}	$^{12}CH_4$ = 1.00 x10^{-21}	$H_2{}^{32}S$ = 1.3x10^{-22}
$^{13}C^{16}O_2$ = 2.10x10^{-25}	$^{13}CH_4$ = 1.59x10^{-23}	$H_2{}^{34}S$ = 1.8x10^{-24}

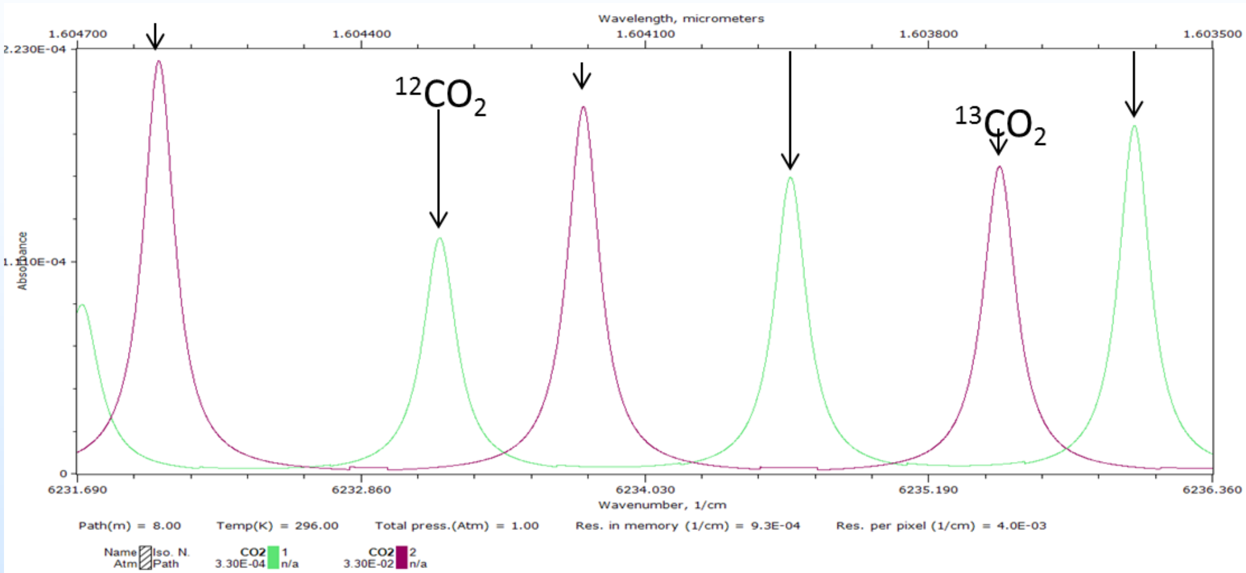
Frequency Modulated Spectroscopy

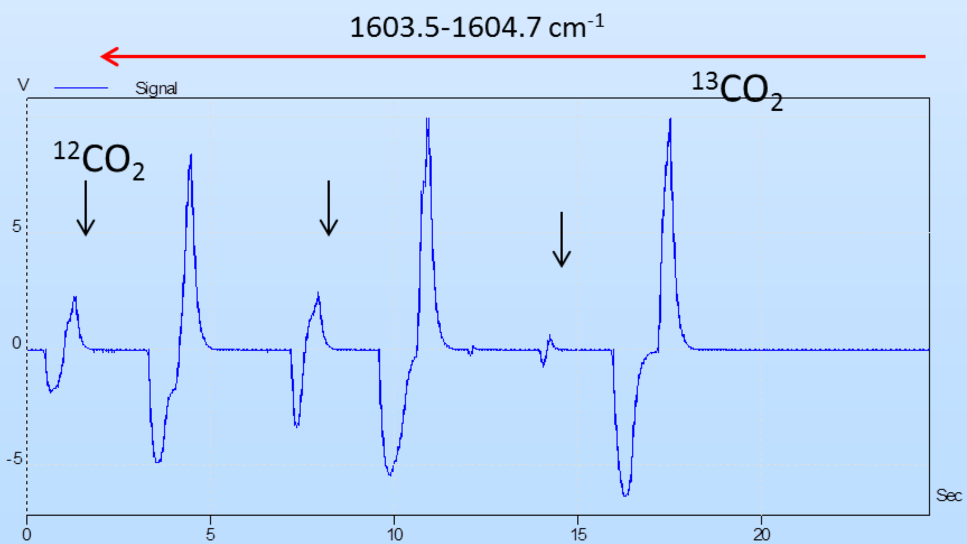
- Why 1570 – 1680nm range?
  - Telecom Electronics (1550nm)
  - Absorption Cross Section for Remote (hundreds of meters)
  - No spectral interferences.
    - H_2O or CO
- Why 1604 – 1609nm range?
  - $^{13}C^{16}O_2$ Peaks between $^{12}C^{16}O_2$ Sub-Bandheads.
  - $^{12}C^{16}O_2$ Peaks ~10x $^{13}C^{16}O_2$
  - Multiple species detection with same hardware



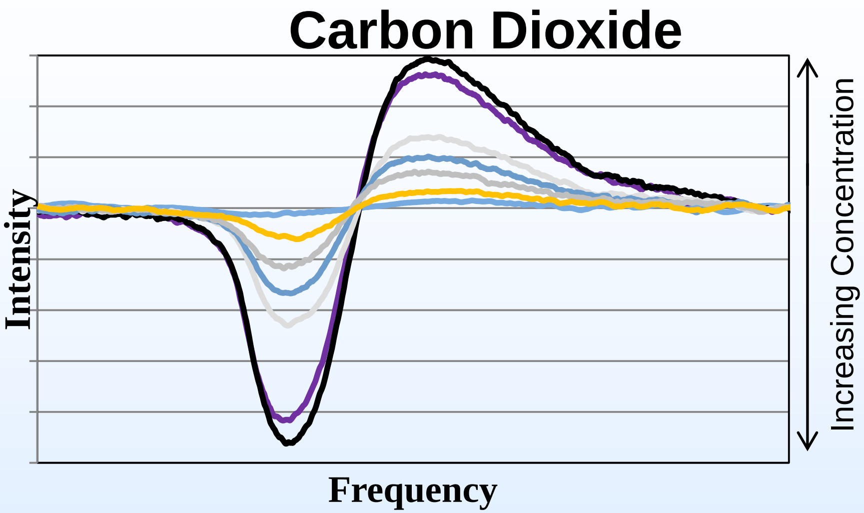
FMS Compared to HITRAN

FMS Spectra of 99% $^{13}CO_2$ with 1.0% $^{12}CO_2$

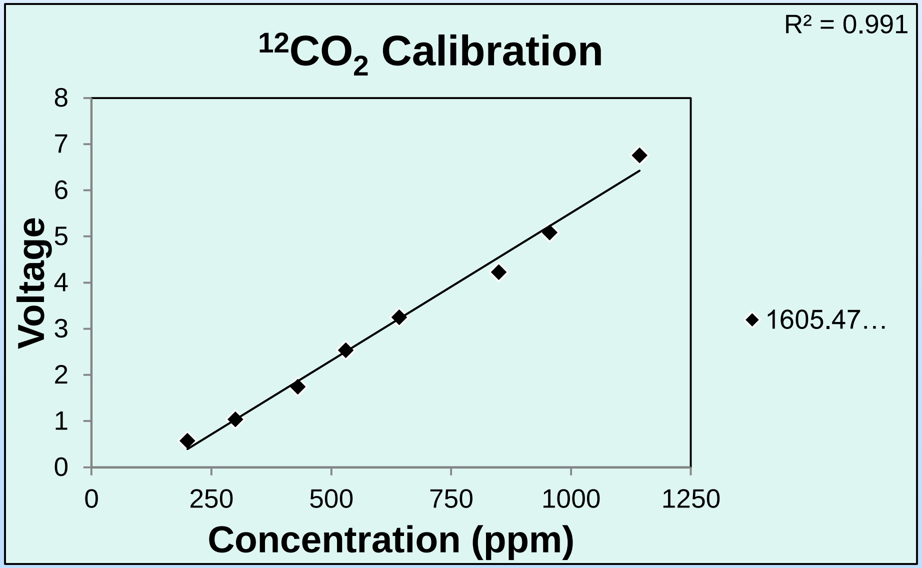


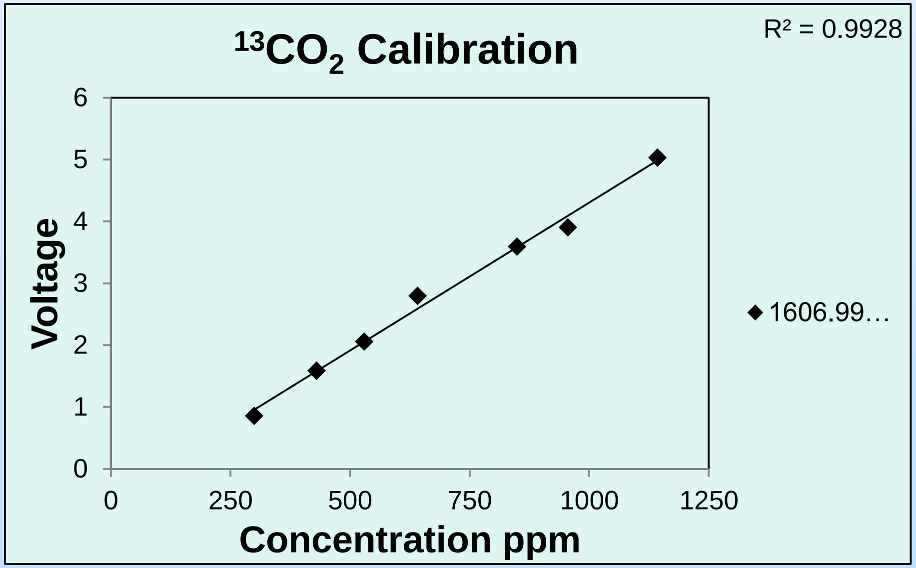


Carbon Dioxide Calibration

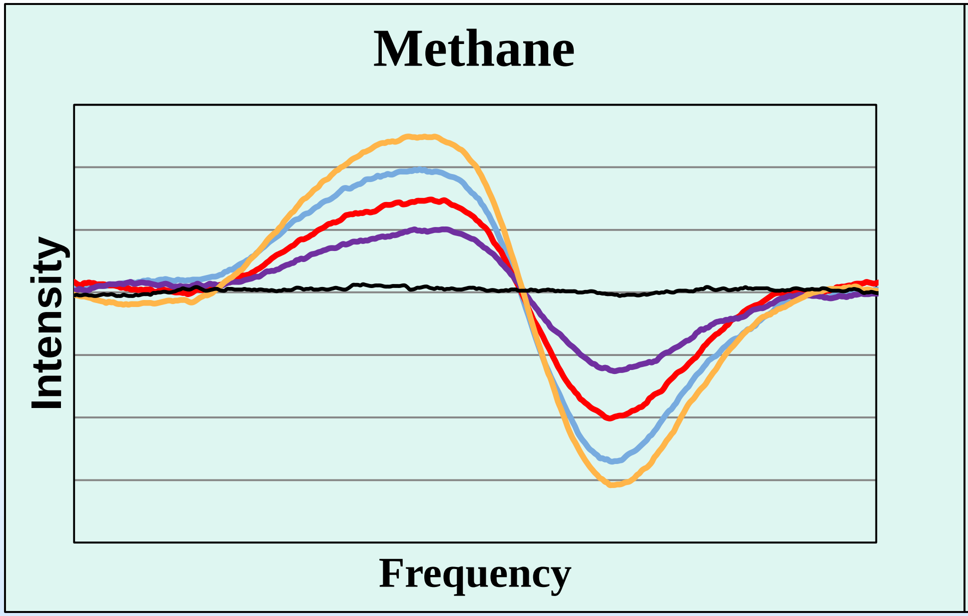


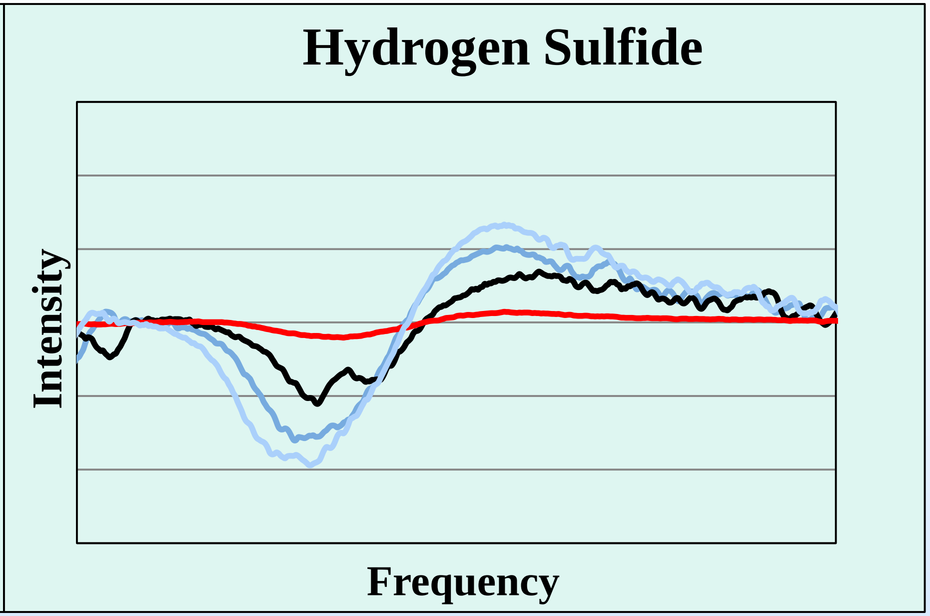
Estimated Detection Limit
$^{12}CO_2$ and $^{13}CO_2$ < 1 ppb

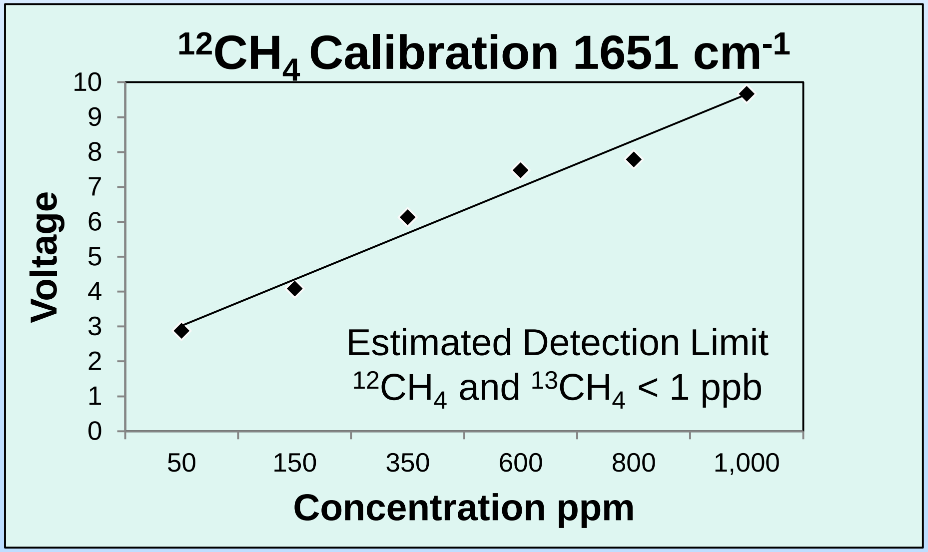


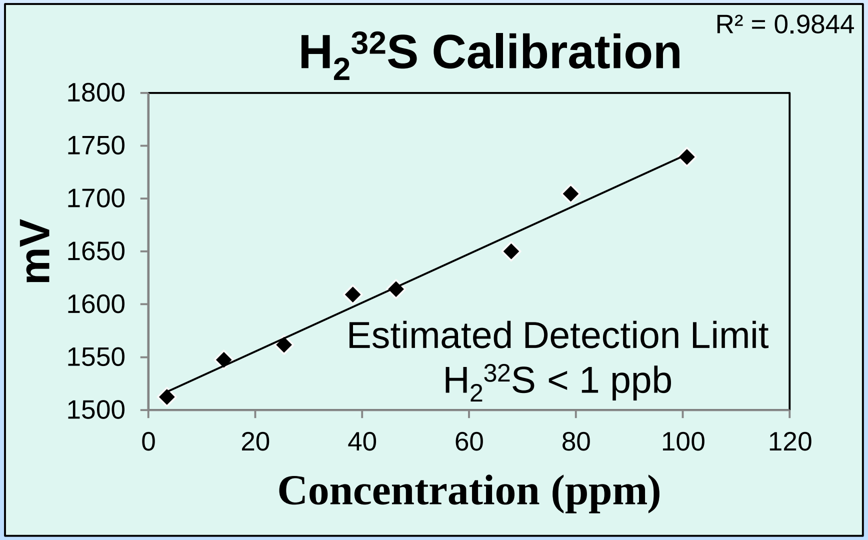


Methane and Hydrogen Sulfide Calibration





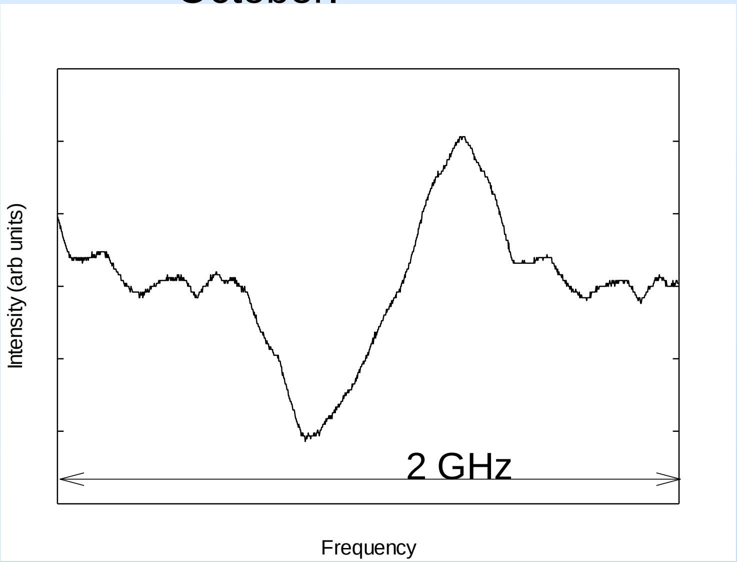




LIDAR Instrument

Added CH_4 and H_2S detection to CO_2 LIDAR instrument

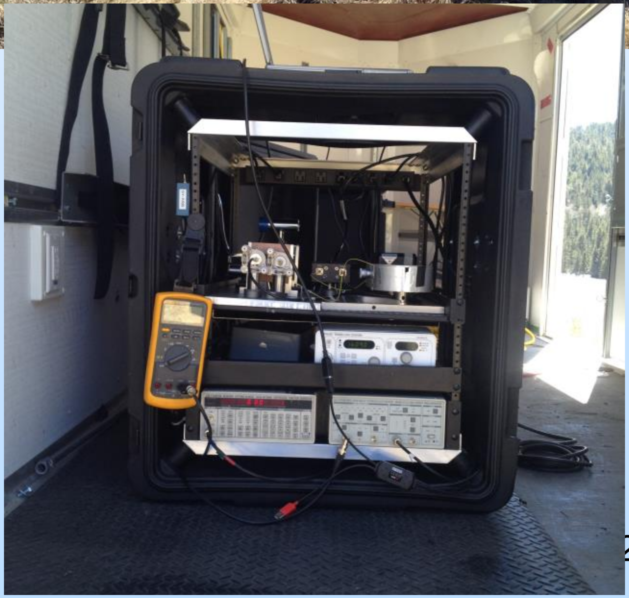
- Assembled a new external modulator
  - Custom probe of specific spectral features.
  - Improve detection limit
- Established new field site on LANL campus
  - Initiate LIDAR experiments in October.



LANL MVA Program

- Frequency Modulated Spectroscopy
  – In situ
  – Remote
  – LIDAR
  – CO_2, CH_4, H_2S (isotopes)

- Flask Collects, Mass Spectroscopy
- Water Stable Isotope Analysis



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  - **Subsurface MVA – Advanced Microseismic Imaging**
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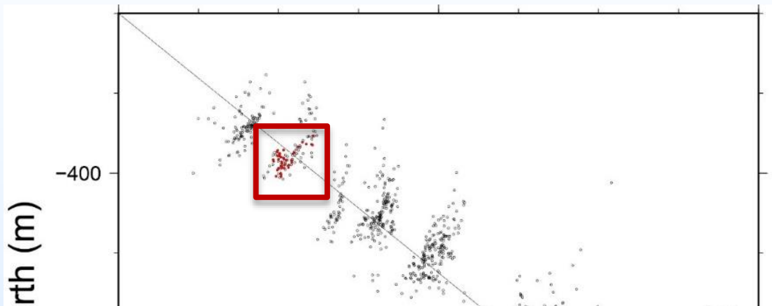
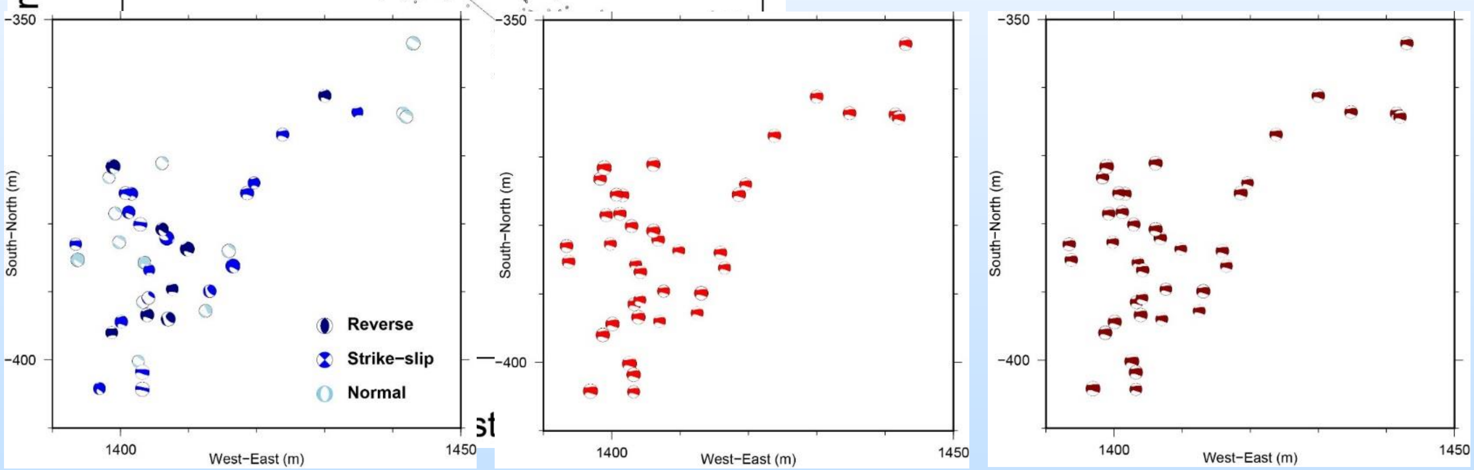
Accurate focal mechanism inversion of microseismic data acquired using multiple geophones within a single borehole

- **Motivation**
  - Using focal mechanisms of microseismic events to distinguish fluid-induced and pressure/stress-induced events.
- **Objectives**
  - Focal mechanism inversion of microseismic data acquired with a single geophone string contains significant uncertainties.
    - Develop a joint inversion method to improve focal mechanism inversion.
    - Develop a double-difference focal mechanism inversion method to further improve inversion results after joint inversion.
- **Validation**
  - Validate our new methods using real microseismic data acquired at the Aneth EOR field of an SWP Phase II project site.
- **Event Location and Focal Mechanism**
  - Event location: map pressure fronts, detect and locate fault activation, identify potential leakage.
  - Focal mechanism: elucidate the stress status, identify fracture zones, distinguish the fluid- or stress-induced events.

Adaptive joint inversion of focal mechanisms of microseismic events



Microseismic data acquired at Aneth EOR filed using 23 levels of geophones within a single borehole

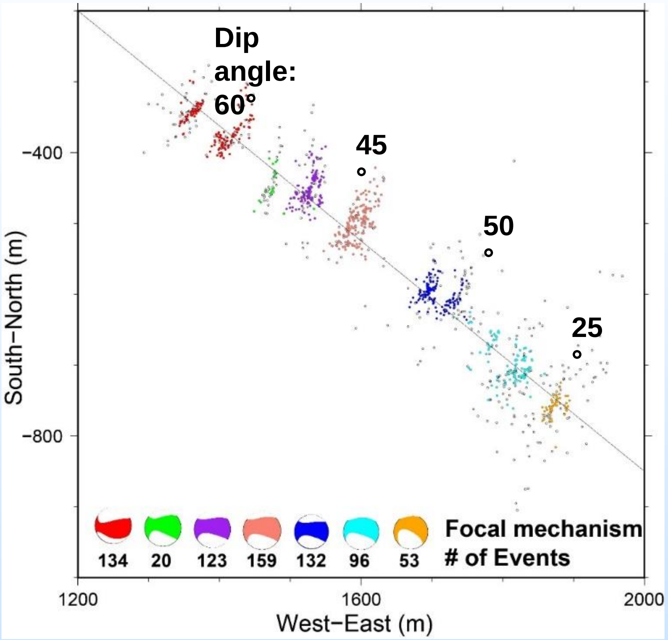


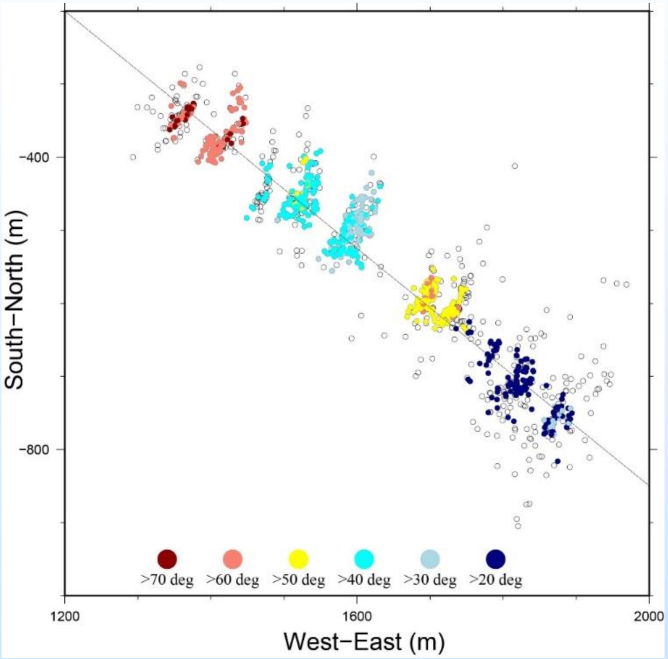
Individual inversion

Joint inversion

Double-difference inversion

Adaptive joint inversion of focal mechanisms of microseismic events





Joint inversion results

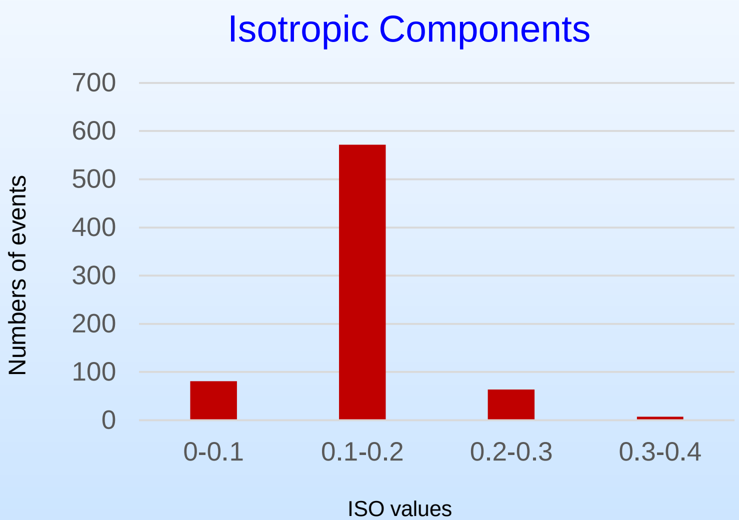
- Focal mechanisms of microseismic events are clustered in location.
- Dip angles change with location.

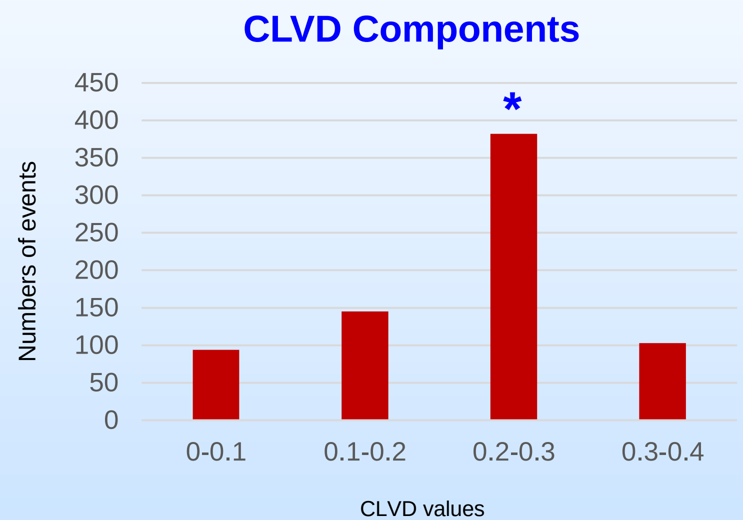
Double-difference inversion after joint inversion

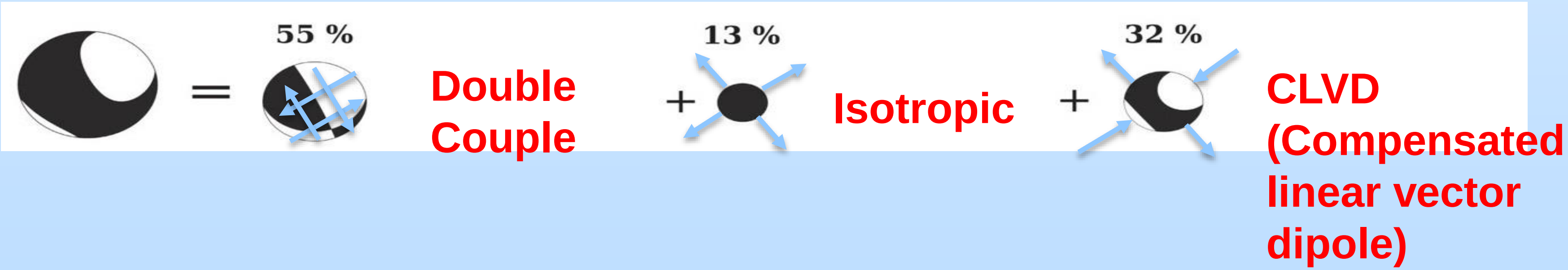
- Shows complex, varying dip angles

Adaptive joint inversion of focal mechanisms of microseismic events

*Significant CLVD components indicate the events may be fluid induced.







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Probing the Earth's Stress State in CO_2 Injection Reservoirs

Our first hypothesis (based on our lab data and many observations in Earth):

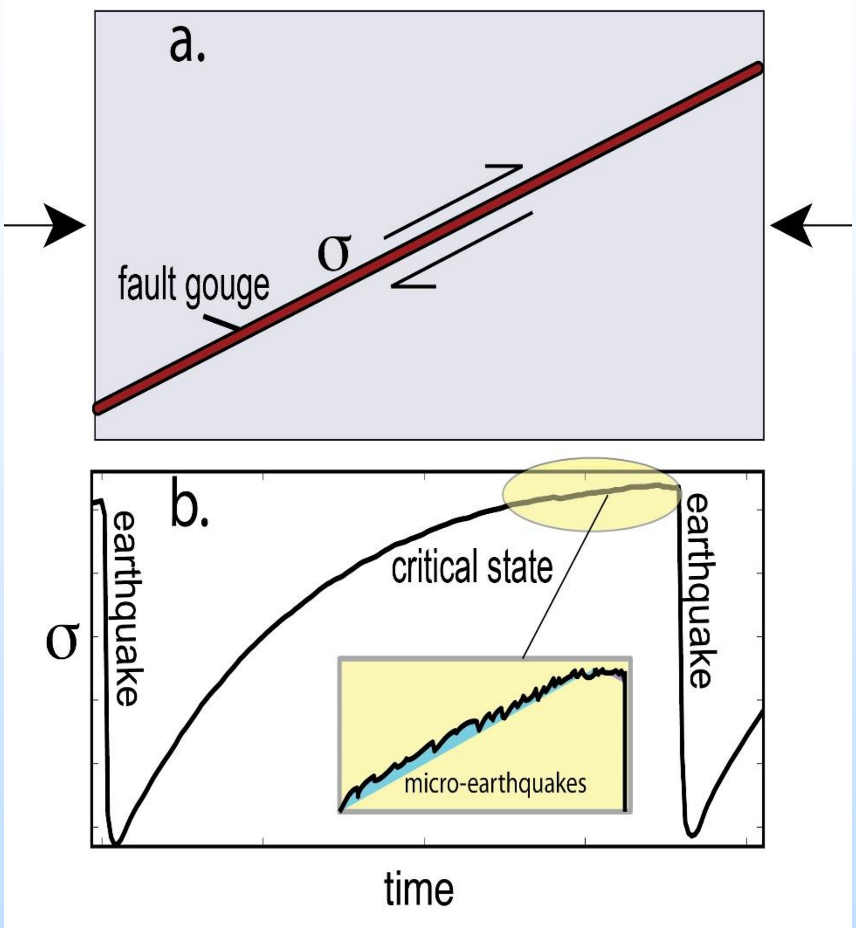
All earthquakes are preceded by precursor events—small slips.

Some, but not all, field observations confirm this hypothesis.

Hence, our second hypothesis:

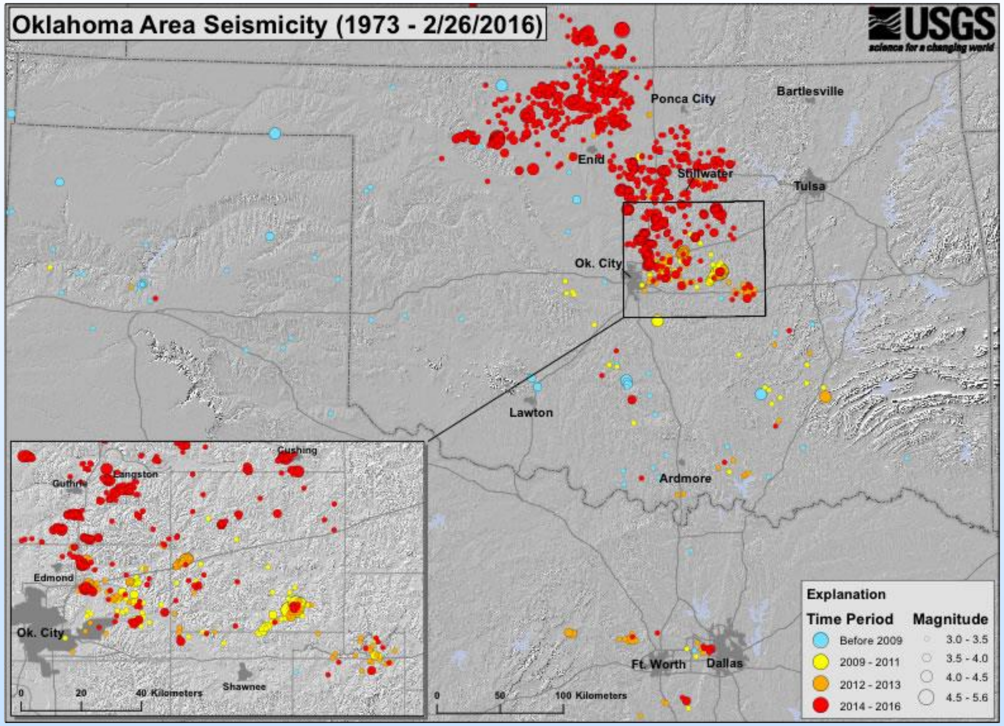
Many precursor events remain undetected due to their small size (M < –2).

Approach : (1) We push our detection threshold downwards and (2) we develop methods to detect triggered quakes that only occur in the critical state



Developed interstation waveform coherence to push the magnitude threshold downwards

17 Months prior to 2011 M5.6 Prague Earthquake



Critical state behavior increases as Prague earthquake is approached (more and more earthquakes are triggered by Earth tides). This can only happen if the system is in a critical state near failure, and if it is evolving to failure, pushed by fluid injection.

Summary

- Surface MVA – Frequency Modulated Spectroscopy
  - Real-time *remote and in situ* CO_2, H_2S and CH_4 monitoring
  - Distinguish anthropogenic from natural emissions
- Subsurface MVA – Advanced Microseismic Imaging
  - We have developed a novel joint inversion method to reduce uncertainty of focal mechanism inversion of microseismic events.
  - We have developed a new double-difference focal mechanism inversion to further improve focal mechanism inversion after joint inversion.
  - We have applied our new methods to microseismic data acquired at Aneth CO2-enhanced oil recovery field, and showed possible fluid-induced microseismic events.
- Gas/fluid injection of all kinds may induce damaging earthquakes.
  - Developed interstation waveform coherence to push the magnitude threshold downwards

Appendix

– These slides will not be discussed during the presentation, but are mandatory

Organization Chart

Melissa Fox, Program Director
Rajesh Pawar, Program Principal Investigator

Sam Clegg, MVA Task Principal Investigator

Kristy Nowak-Lovato, FMS Task Lead
Ron Martinez
Robert Currier
Rhonda McInroy
Steve Obrey

Lianjie Huang, Microseismic Task Lead
Ting Chen
Youzuo Lin
Kai Gao

Paul Johnson, Induced Seismicity Task Lead

Bibliography

- T. Chen, Y. Chen, Y. Lin, and L. Huang, 2015 AGU Fall Meeting.
- Y. Chen, T. Chen, and L. Huang, 2016 CCUS Meeting.
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- Delorey, A., N. van der Elst and P. Johnson, Tidal Triggering of Earthquakes in the Vicinity of the San Andreas Fault, *EPSL*, in review, 2016
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- Johnson, P. A., J. Carmeliet, H. M. Savage, M. Scuderi, B. M. Carpenter, R. A. Guyer, E. G. Daub, and C. Marone "Dynamically triggered slip leading to sustained fault gouge weakening under laboratory shear conditions," *Geophysical Research Letters* 43, 1559-1565 (2016). (PDF File - 1.5 MB / doi:10.1002/2015GL067056)

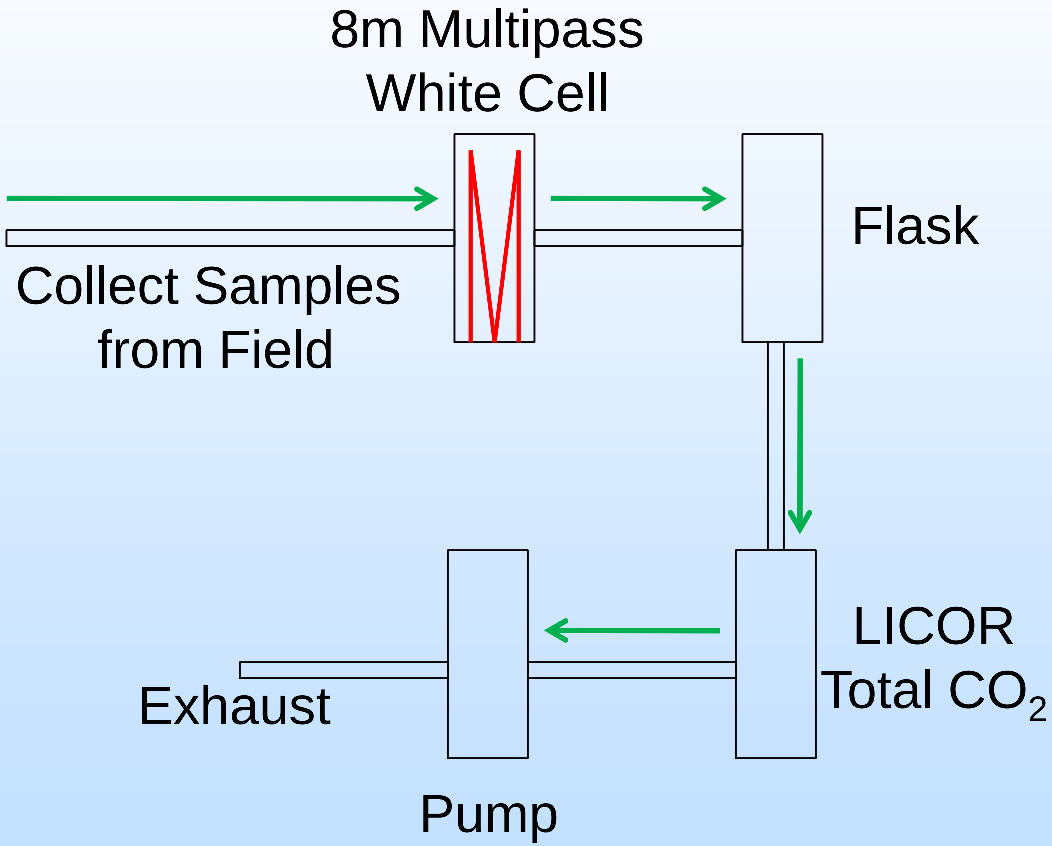
Workshop: 'State of Stress in Earth', Santa Fe New Mexico, October 19-21, 2016.

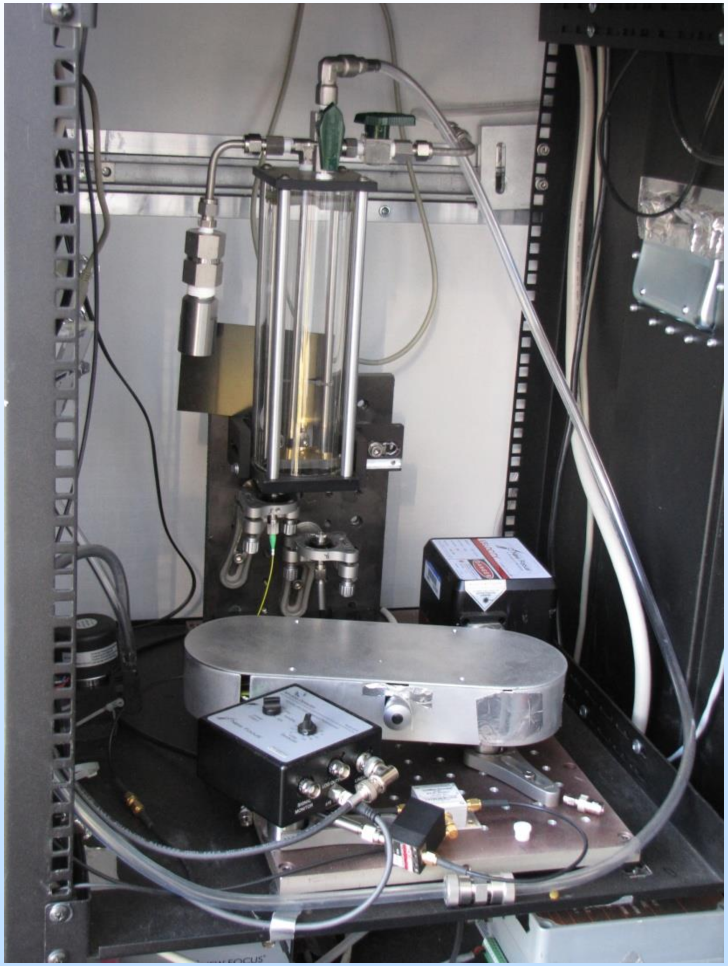
Workshop: 'applying machine learning to earthquake precursors', Center for Nonlinear Studies, Los Alamos National Laboratory, April 11-12, 2016

Special Session, American Geophysical Union Fall Meeting 2016: State of Stress

Backup

In Situ FMS Instrument





In Situ FMS Observations

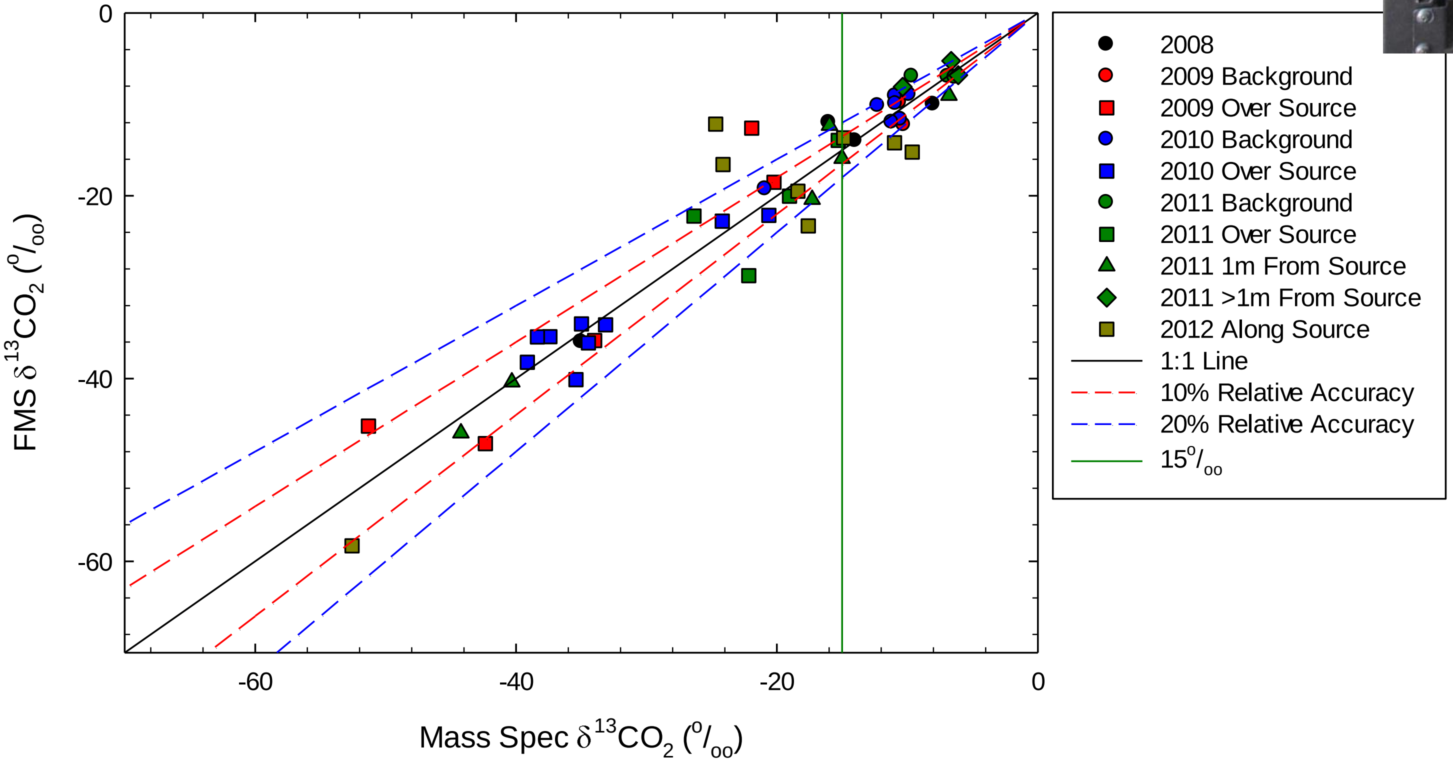
<u>Historical Trends</u>

Background > -15 $^o/_{oo}$

Most >-10 $^o/_{oo}$

3 observations <-10 $^o/_{oo}$

Seepage < -15$^o/_{oo}$



MVA Field Experiments

- 2009 - 2015 Field Experiments
  - Mammoth Springs, CA
  - Valles Caldera, NM
  - Sevilleta Long Term Ecological Research, NM
  - Farmington, NM
  - Soda Springs, UT
  - LANL Juniper-Pinion Field Site
  - ZERT, MSU, Bozeman, MT
    - Controlled CO_2 Flow & Release Rate
  - Southwest Regional Partnership, Kansas