Project Number:
DE-FC26-05NT42593

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Lawrence Berkeley National Laboratory
On behalf of Mike Gravely, WESTCARB P.I.,
California Energy Commission

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the
Infrastructure for CO_2 Storage
August 21-23, 2012

Presentation Outline

- Project Overview—Goals
- Technical Status/Accomplishments
  - Northern California characterization well
  - CCUS-NGCC engineering-economic study
  - Policy/Regulatory outreach
- Highlights of Future Plans

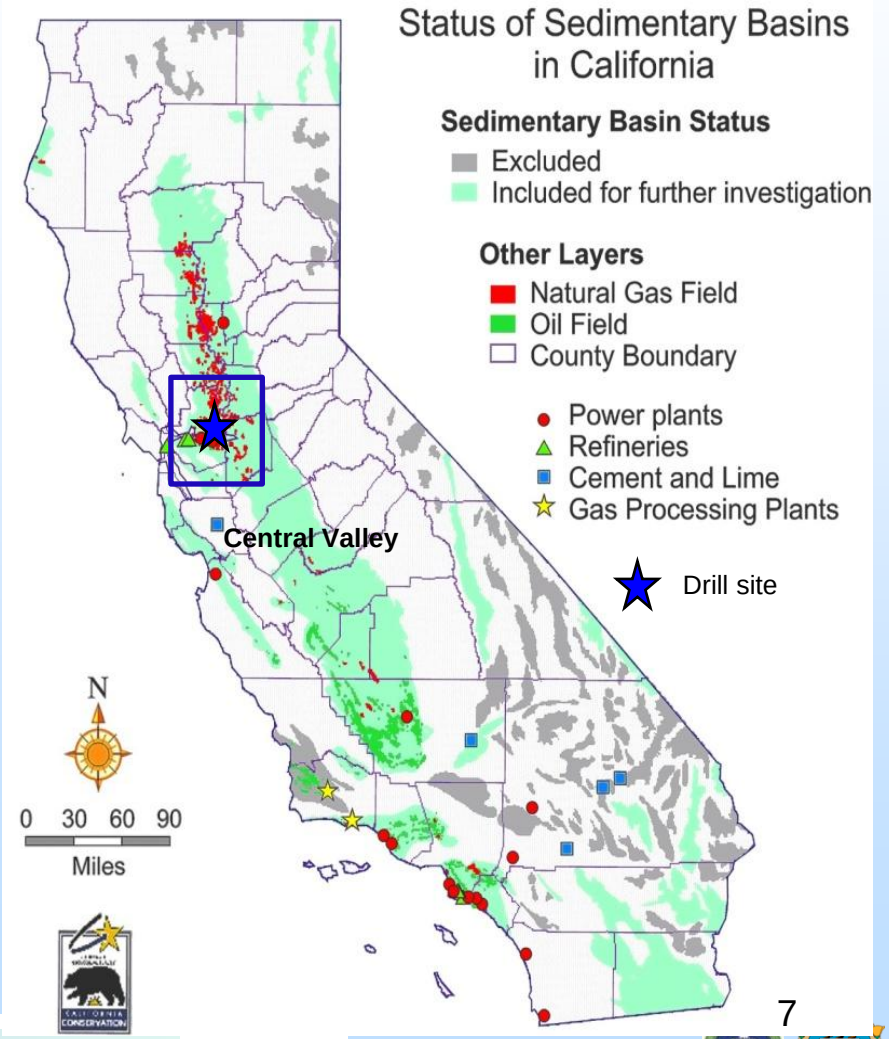
Project Overview:
WESTCARB Goals and Objectives Align with RCSP Program Goals

RCSP Goals	WESTCARB Goals and Objectives (Budget Period 3 -- through 2013)	Success Criteria
Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.	Characterize geologic sequestration potential and capacity in WESTCARB region based on geology and geographic criteria	Reports to WESTCARB website and portal Data layers for states into NATCARB
	Identify and define promising sites and facilitate the process for developing commercial-scale CCUS projects	High potential sites identified, characterization seismic or wells permitted, drilled, completed, closed; engineering/economic assessments completed
Conduct field tests through 2030 to support the development of BPMs for site selection, characterization, site operations, and closure practices.	Identify regulatory/economic impediments to project development, potential solutions to impediments, and methodologies to incorporate CCUS as accepted technology for (GHG) emissions reduction.	Workshops, testimony, reports to assist policymakers and regulators

Technical Status/Accomplishments:

Characterizing CCUS Potential of Northern California's Central Valley

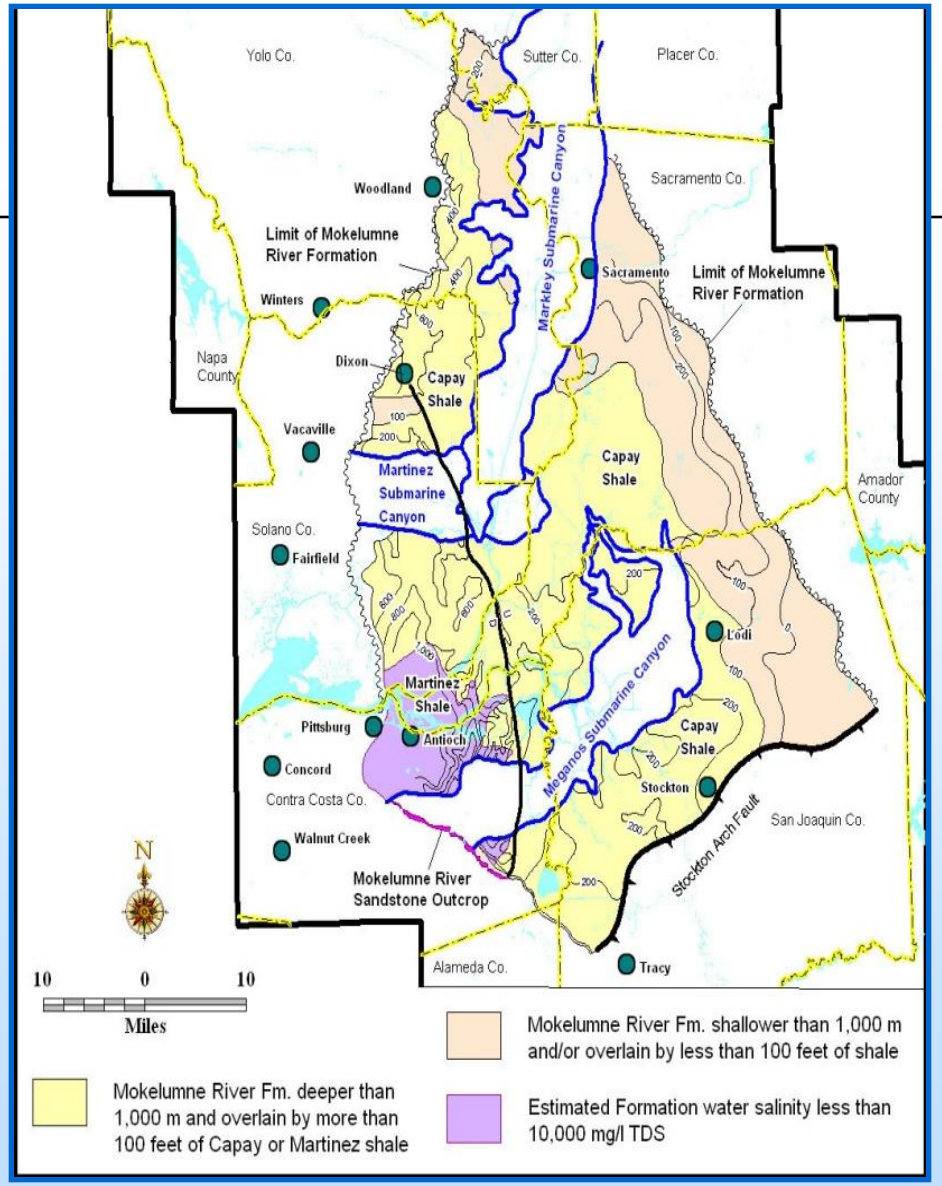
- California Geological Survey –
  - Central Valley is most promising on-shore CO_2 storage resource in WESTCARB territory with estimated resource of 75-300 Gt in saline formations and natural gas and oil-bearing formations.
- The Citizen Green #1 Well Technical Team
  - BKi
  - California Institute for Energy and Environment, University of California-Berkeley
  - Lawrence Berkeley National Laboratory
  - Lawrence Livermore National Laboratory
  - Princeton Natural Gas, LLC
  - Schlumberger Carbon Services
  - Sandia Technologies
  - Service providers (Stratigraphic, Paul Graham Drilling, Tom Fazio and many others)
  - Collaborators from two FERCs, Sandia National Lab, TBEG, UC Berkeley, CSU Bakersfield, and other universities
- < Six months from permit to well completion
- ~ $3 million dollars



Technical Status/Accomplishments:

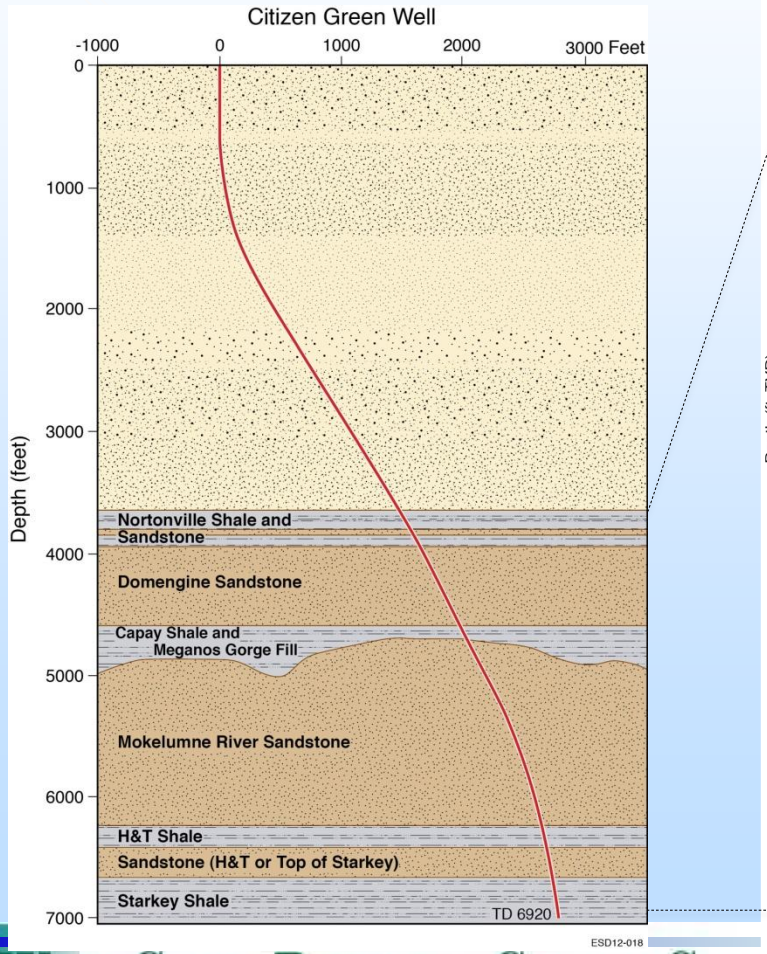
Objectives of the Citizen Green well

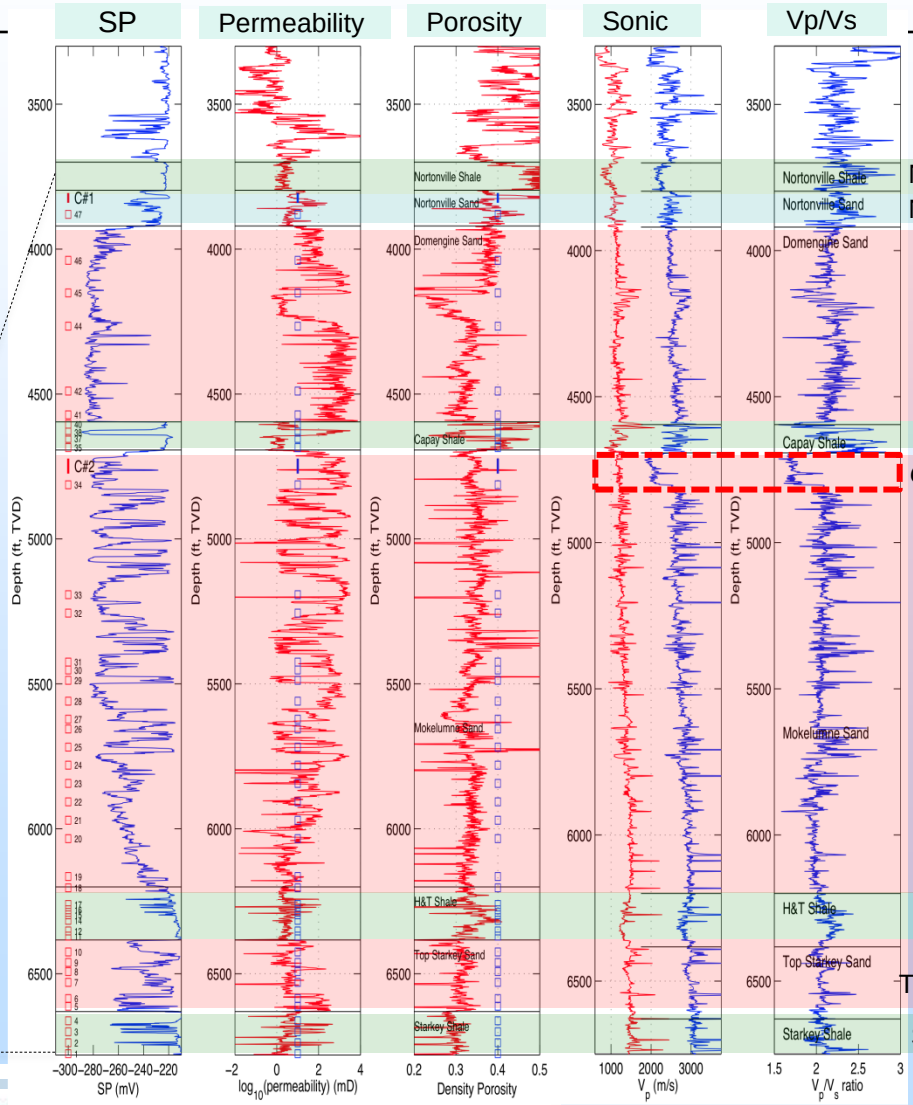
- Assess storage capacity of major regional sandstone formations
- Assess seal integrity of major regional shale units
- Integrate lab and field data to understand regional resource
  - Geochemical and petrophysical lab testing and analysis of core and fluid samples
  - Well logs and seismic
  - Outcrop and log data from nearby locations
  - Simulations of commercial-scale injection, multiphase flow and trapping mechanisms



Technical Status/Accomplishments:

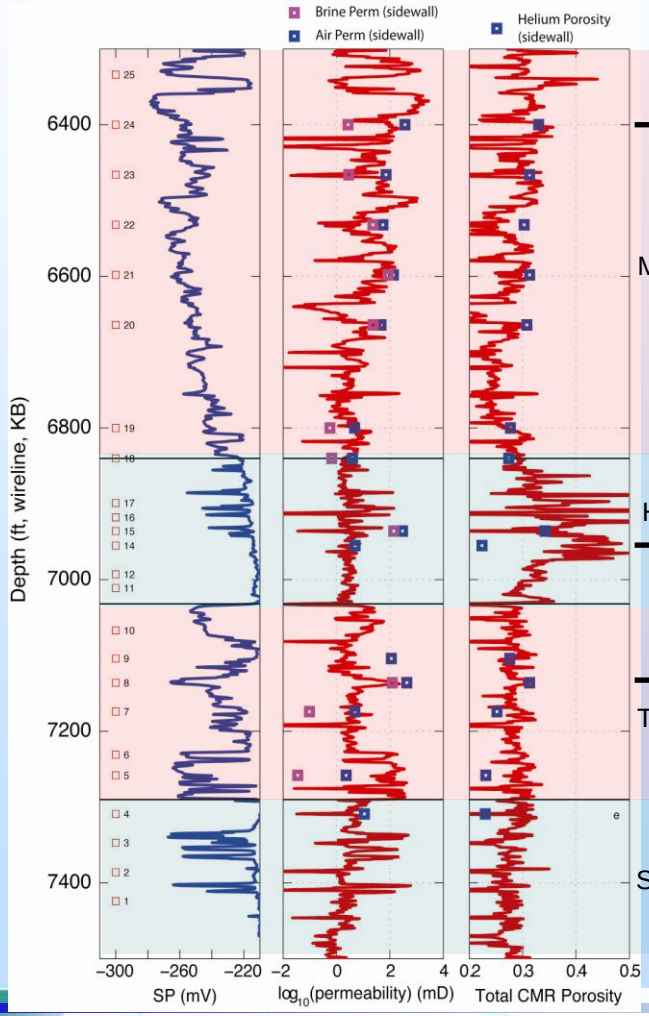
Citizen Green #1 Well drilled to 6,920 ft TVD intersected 3 target sandstones and 4 shale units





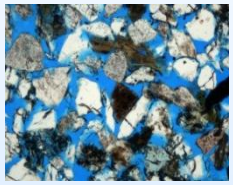
Nortonville Shale
Nortonville Sand
Domengine Fm. (sand)
Capay Shale
Gas Accumulation
Mokelumne River Fm. (sand)
H&T Shale
Top Starkey Sand
Starkey Shale

Petrophysics from Sidewall Core Analysis



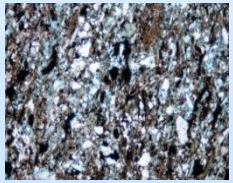
Thin Section, 10x

Surface Texture, 1x

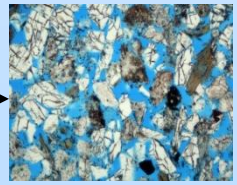


Sidewall #24
5782 ft TVD
Lower Mokelumne
Porosity 33%
Air Perm. 367 mD

Confirms Lower Mokelumne as injection target



Sidewall #14
6315 ft TVD
H&T Shale
Porosity 22%
Air Perm. < 5 mD



Sidewall #8
6496 ft TVD
Top Starkey Sand
Porosity 31%
Air Perm. 432 mD

Confirms Top Starkey as injection target

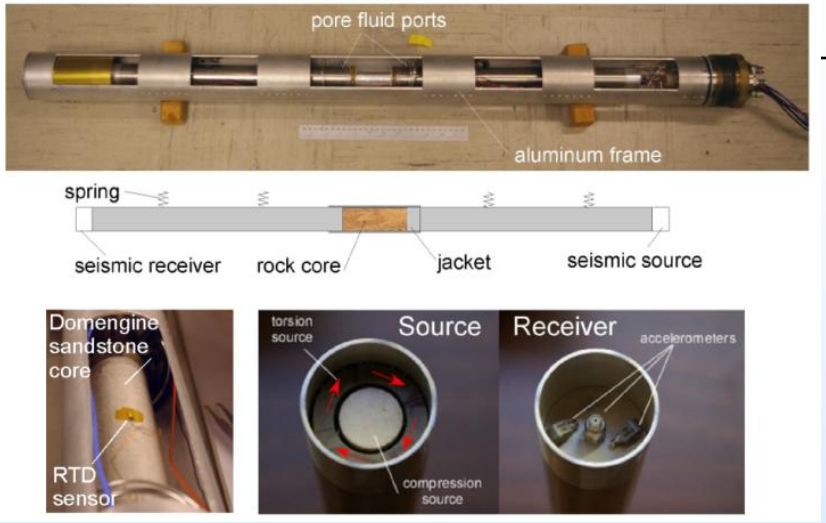
Characteristics of Storage and Sealing Formations, Citizen Green Well #1

- **Domengine –** High permeabilities (3+ Darcies) observed on Combinable Magnetic Resonance (CMR) log. Unconsolidated sandstone, over 500 ft thick. Overlying Nortonville shale questionable seal--may impair regional storage utility of Dom.
- **Mokelumne River –** High permeabilities (1+ Darcy from CMR in upper section of unconsolidated sand. Thickness 1500 ft (460 m). Tighter with depth; consolidated below 5500 ft (1676 m). Capay Shale provides good seal, supported by natural gas common in Moke regionally
- **Top Starkey Sandstone –** Moderate to low permeabilities **(**≤100 mD from CMR) Consolidated sand with shaly stringers; several sand lobes with higher permeability. H&T Shale provides good seal

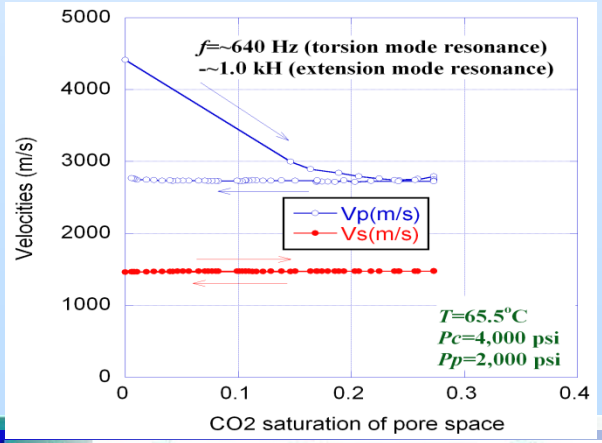
Technical Status/Accomplishments:

Petrophysical Analysis: Seismic Data from $scCO_2$ Injection in Brine-Saturated Core

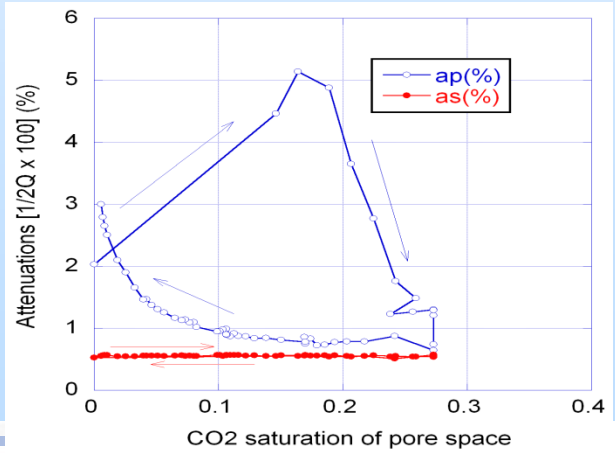
- *Sample:* Domengine sandstone core
  - 6" long, 1.5" diameter, from Black Diamond Mine
  - >2-3 Darcy permeability, ~30% porosity
- *Test conditions to mimic in-situ conditions at top of high perm section of Domengine:*
  - Confining pressure = 4,000 psi, pore pressure = 2,000 psi,
  - Temperature = 56.6°C,
  - 1% NaCl (10,000 mg/l) brine solution
- Flow $scCO_2$ into brine-saturated core until breakthrough, followed by flowing CO_2-free brine



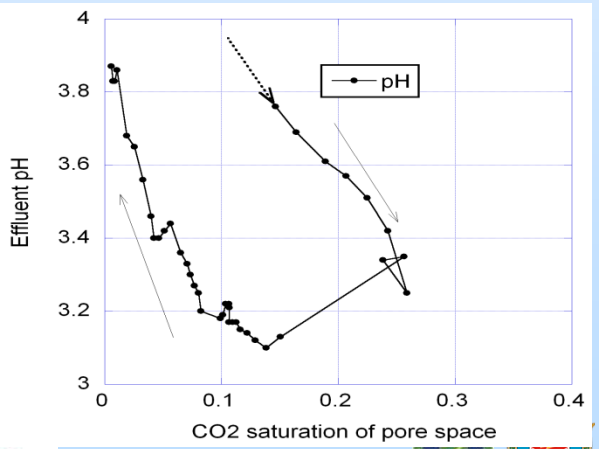
Sample in Split Hopkinson Resonance Bar apparatus for seismic experiment



Seismic velocities (Vp and Vs)



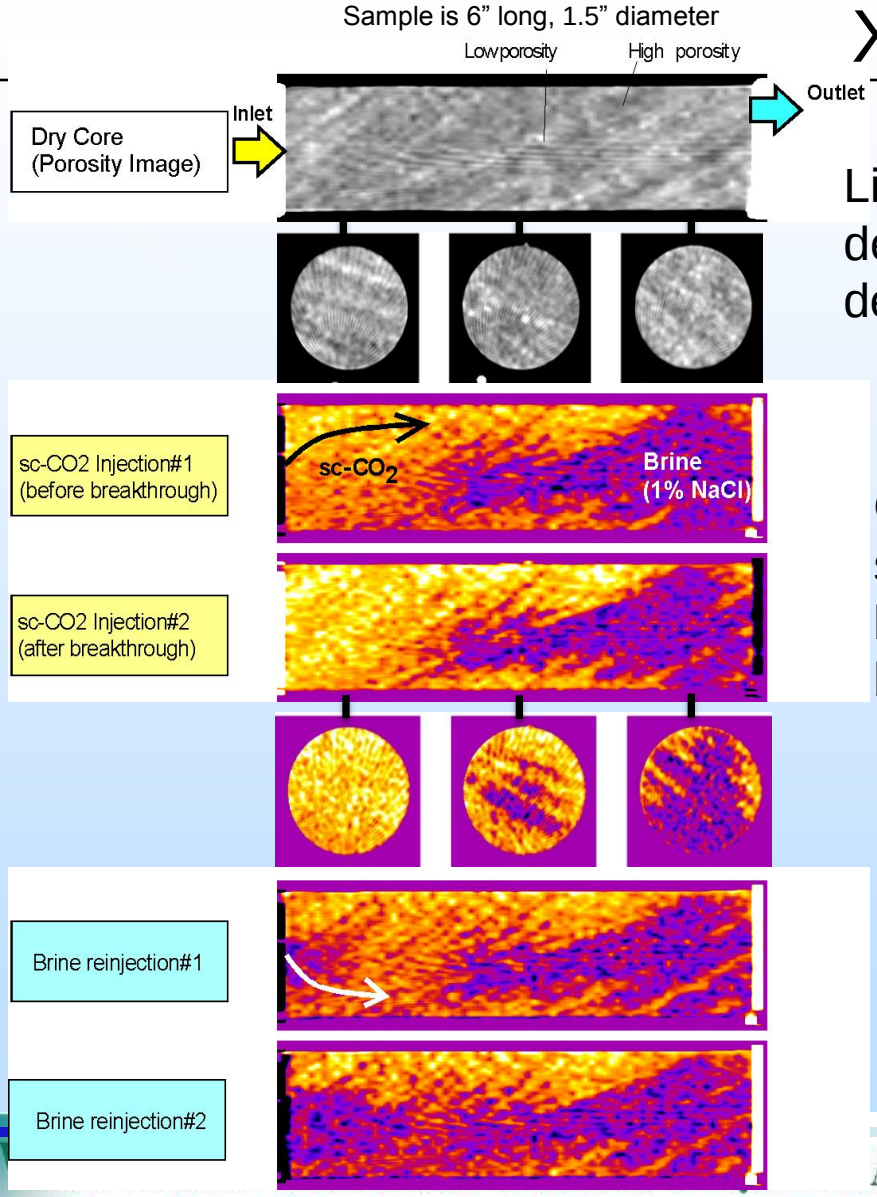
Seismic velocity attenuation



Effluent brine pH

Technical Status/Accomplishments:

$scCO_2$ Injection into Brine-Saturated Core: Concurrent X-ray CT Imaging



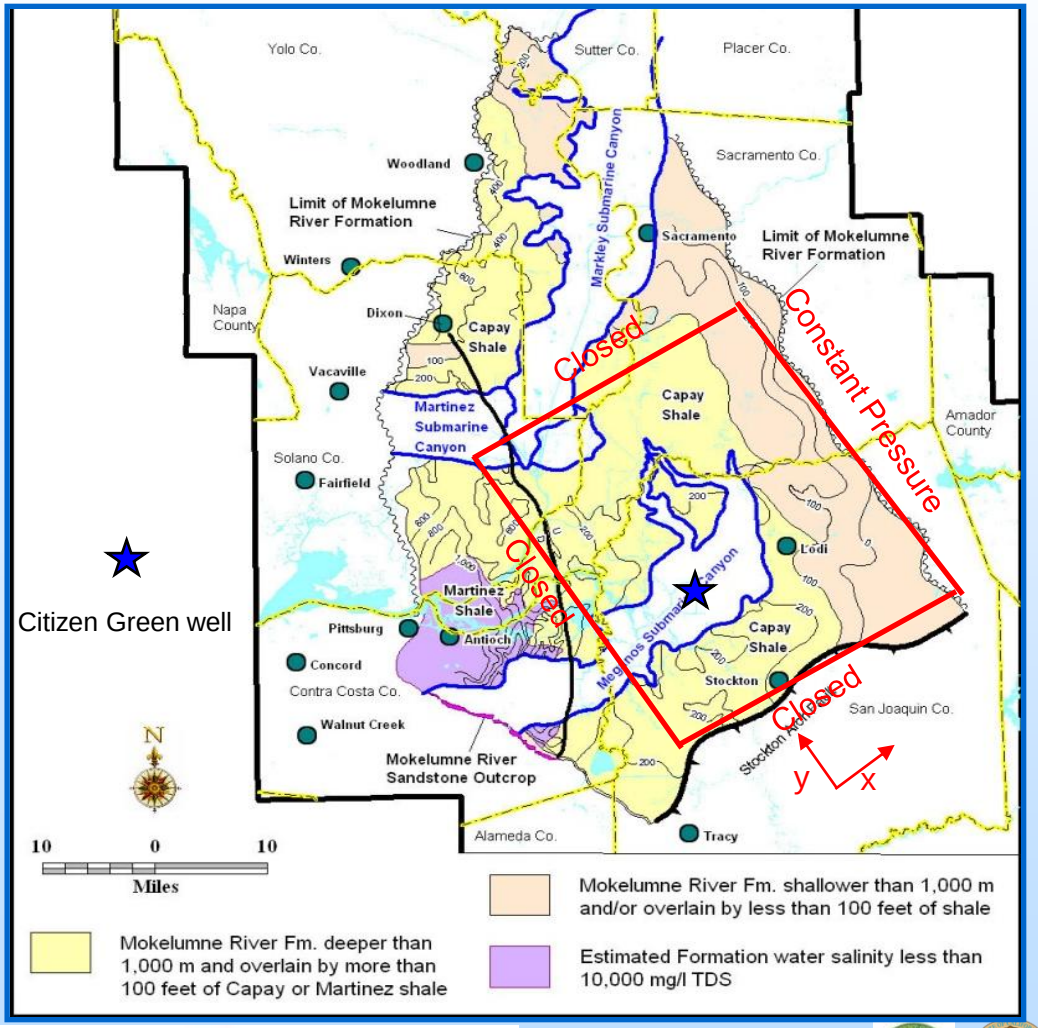
Lighter tones are lower porosity (higher density); darker tones are higher porosity (lower density). Layering is clearly visible.

CT scans showing the location in core of $scCO_2$ (yellow/orange) injected into the brine-filled (purple/blue) before and at breakthrough.

CT scans of brine re-injection following scCO2 showing as brine is re-injected, it follows a path of lower CO_2 saturation. Difference in flow behavior due to density (buoyancy) differences between fluids

CO_2 Injection Simulation Based on NMR Well Log Porosity/Permeability Data

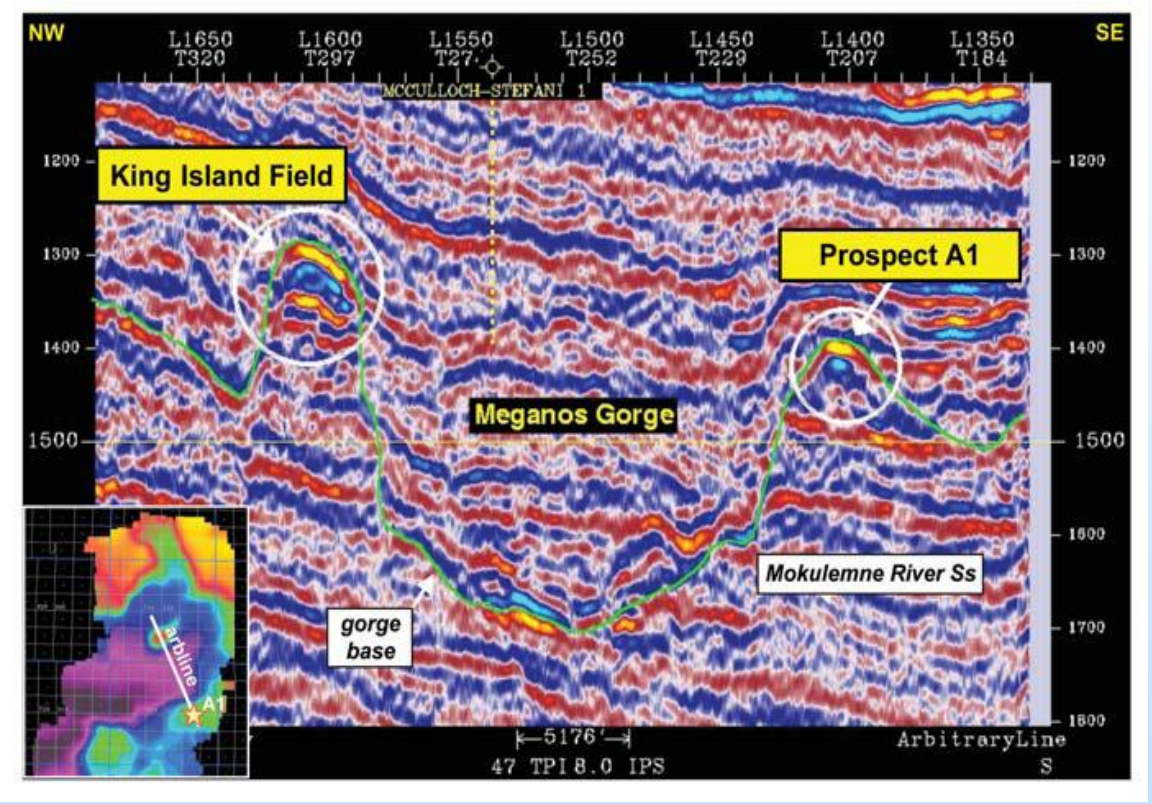
- 19 model layers based on well log permeability;
- 1.6° dip upward to ENE.
- No-flow boundary at overlying Capay Shale
- Injection into lower half of Mokelumne Fm., partitioned into 8 layers.
- Stratigraphic complexity included



Modified after Downey, C., J. Clinkenbeard, 2011, *Studies Related to Geologic Carbon Sequestration Potential in California*, California Geological Survey, CEC

Stratigraphic and structural complexity affects capacity estimates

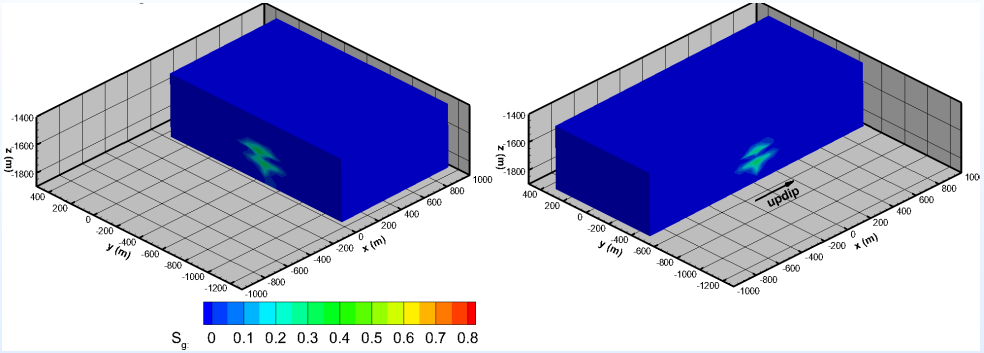
- Erosional gorge downcuts Mokelumne surrounding pinnacle at site
- Overlying and underlying formations are stratigraphically continuous
- Pervasive faulting
  - Has created gas traps
  - Spill points unknown



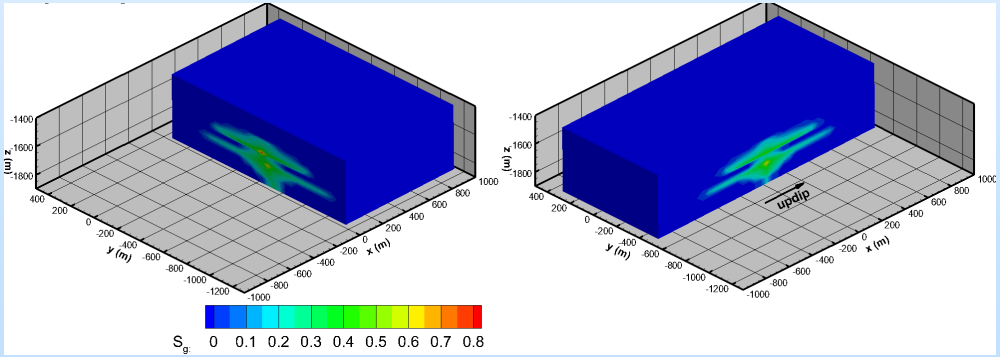
From May, J, et al, Amplitude anomalies in a sequence stratigrphic framework: Exploration successes and pitfalls in a subgorge play, Sacramento Basin, California. SEG Bulletin.

Simulated CO_2 Injection Results to Date

- Strong lateral flow within high-permeability layers; slight up-dip migration
- Strong vertical buoyancy flow within high-permeability layers
- Low permeability baffles greatly reduce effective vertical permeability
- 4 Mt CO_2 plume diameter ~3900 ft (1200 m), height 1150 ft (350 m), still 360 ft (110 m) below top of reservoir



250,000 kt CO_2 injected over 3 months

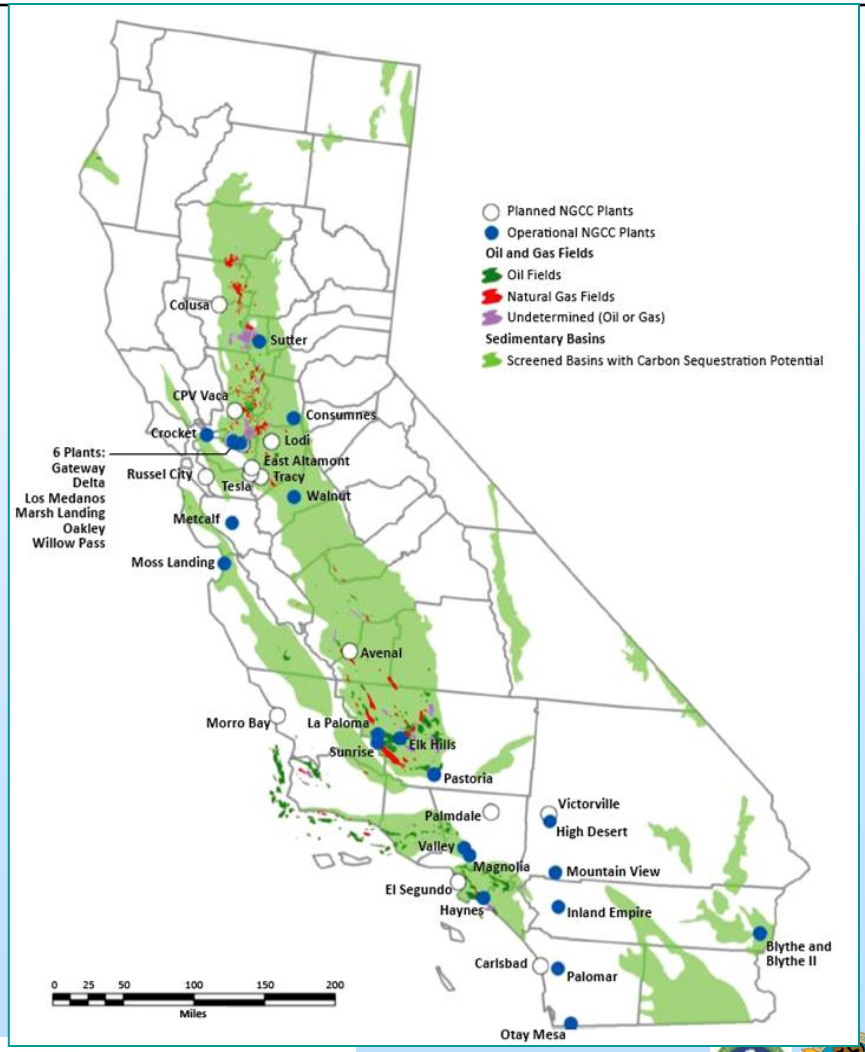


4 Mt CO_2 injected over 4 years

www.westcarb.org

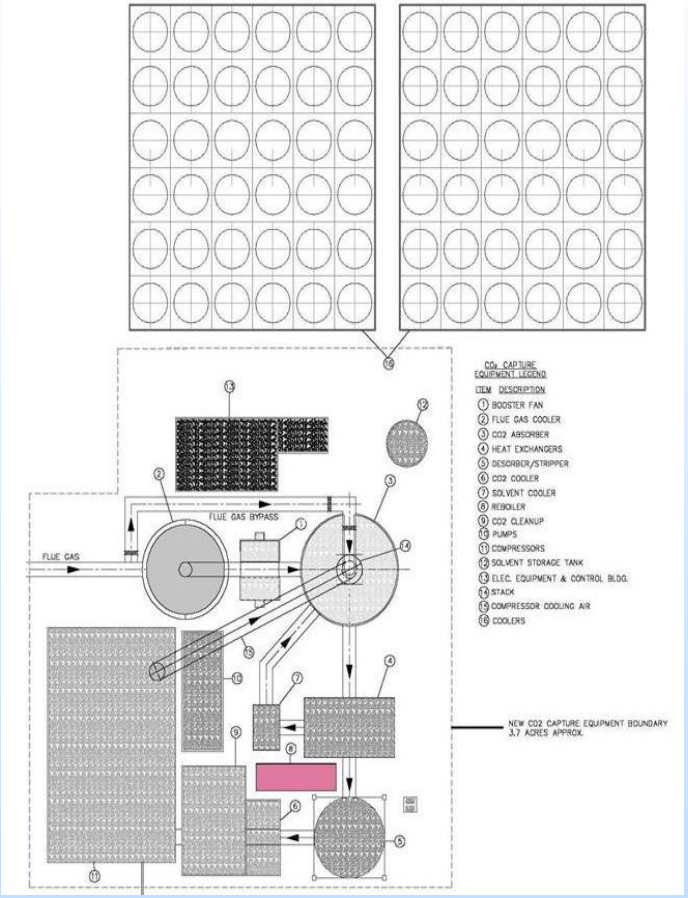
Engineering-Economic Assessment of CCUS for Natural Gas Combined Cycle Power Plants

- Technical Team
  - Bki
  - Lawrence Livermore National Lab
  - Shaw Group
  - Industry Partners (PG&E, SoCal Gas, SCE, SMUD, Clean Energy Systems)
  - Visage Energy
- ~50% of state's electricity generated with natural gas from young plants that operate at high capacity factors.
- Many plants located above or near potential CO_2 resource, including oil fields suitable for CO_2-EOR.



Interim Findings: Capture & Compression

- For retrofit NGCC plants with dry cooling, conventional post-combustion capture leads to cost and energy penalties for solvent and compressor cooling.
  - Potential design solution saves >60MW: Relax solvent CO_2 absorber inlet temperature design point; Accept more hot days on which solvent cannot be cooled to design temperature
  - Potential technical solution: Find solvents effective at higher operating temperatures (without undue regeneration heating requirements)
- CCS more cost effective by about 30% ($16/MWh) for “new build” than retrofit because:
  - CCS integrated into plant design optimizes thermal integration of capture plant and base plant processes
  - Equipment design selected to better accommodate capture operation, and optimize plant layout



Interim Findings: Economics

- Sensitivity studies identified 4 main factors on CCS economics:
  - capacity factor
  - capital cost
  - price on CO_2
  - discount rate.
- Plugging the higher variable O&M cost of an NGCC-CCS plant into a conventional grid dispatch model will lead to unacceptably low dispatch (capacity factor)
  - Potential solution: Regulatory or ISO support for early commercial projects, such as a “must run” designation or a “loading order” priority.

Interim Findings: Storage and Transportation Costs

- There are trade-offs between well field site selection and pipeline costs.
  - Pipeline costs increase with urbanization (siting sensitivities, number of crossings of other infrastrucuture)
  - Pipeline costs depend on distance and capacity
  - Well field costs (well length, number of wells) vary with site characteristics (depth of storage fm, capacity and injectivity per well, drilling difficulty).
  - Well field costs tend to increase faster than pipeline costs as project size grows.

Policy/Regulatory Outreach

- California CCS Review Panel
- Seismic Hazards in West Coast Region
- California Senate Bill 1139
- USEA Workshop for Policymakers

Highlights of Future Plans

1. Characterization of high potential sites in Arizona
2. “Virtual Petrophysics” and other ways to reduce characterization costs/risks
3. Cross-cutting issues for site selection : tools for demographic issues, seismic, competing subsurface activities
4. Integration and issues for CCUS in future energy planning scenarios
5. Exploring pilot or demonstration project options with industry partners

WESTCARB ANNUAL MEETING
week of October 15, 2012
in beautiful Bakersfield, CA

Acknowledgments, Disclaimers

- Acknowledgments:
  - This material is based upon work supported by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) under Grant Number DE-FC26-05NT42593. This project is managed and administered by the California Energy Commission and funded by DOE/NETL and cost-sharing partners.

- Disclaimers:
  - "This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."
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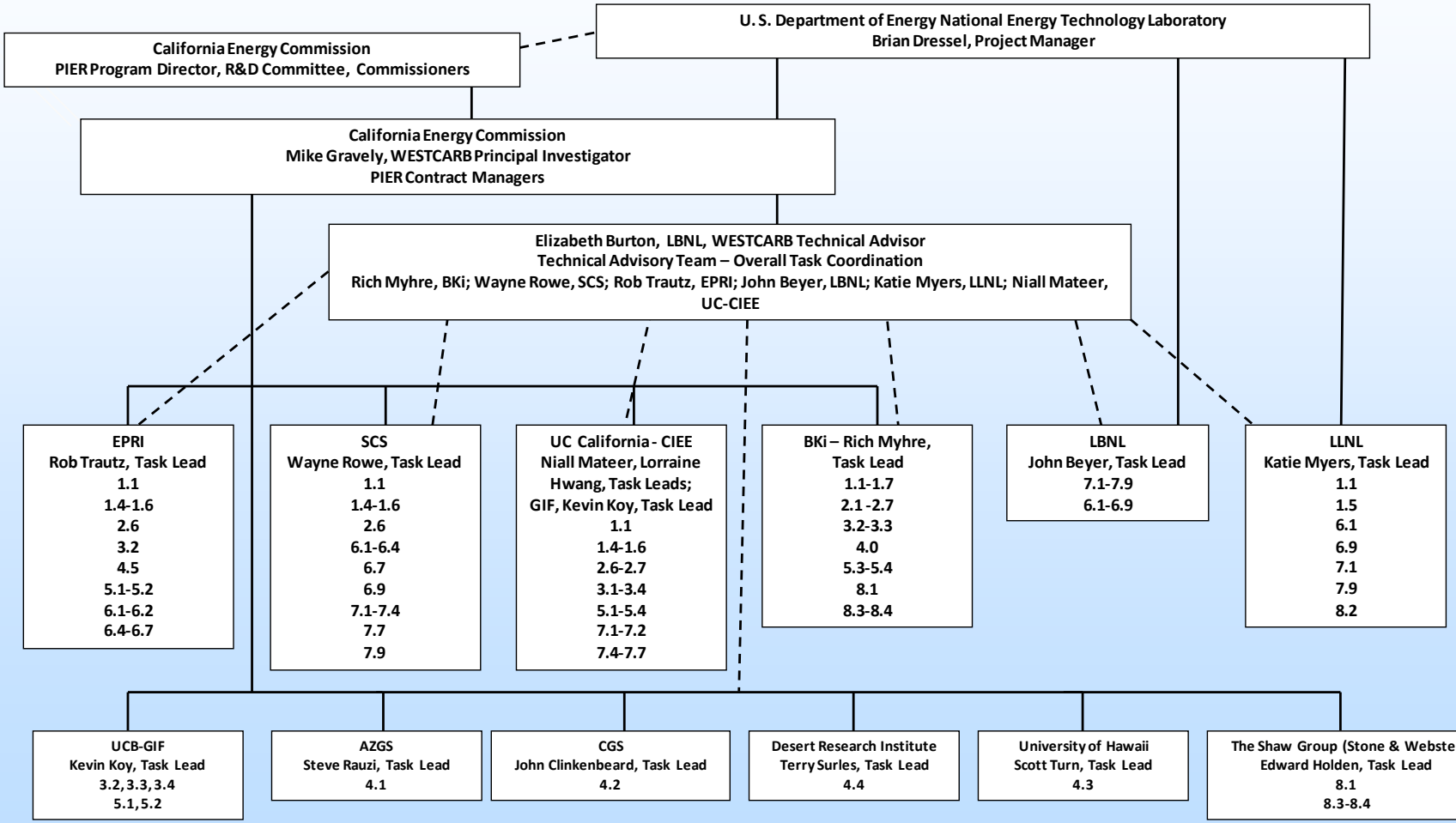
Appendix

- Organization Chart
- Gantt Chart
- Bibliography

Organization Chart



Gantt Chart

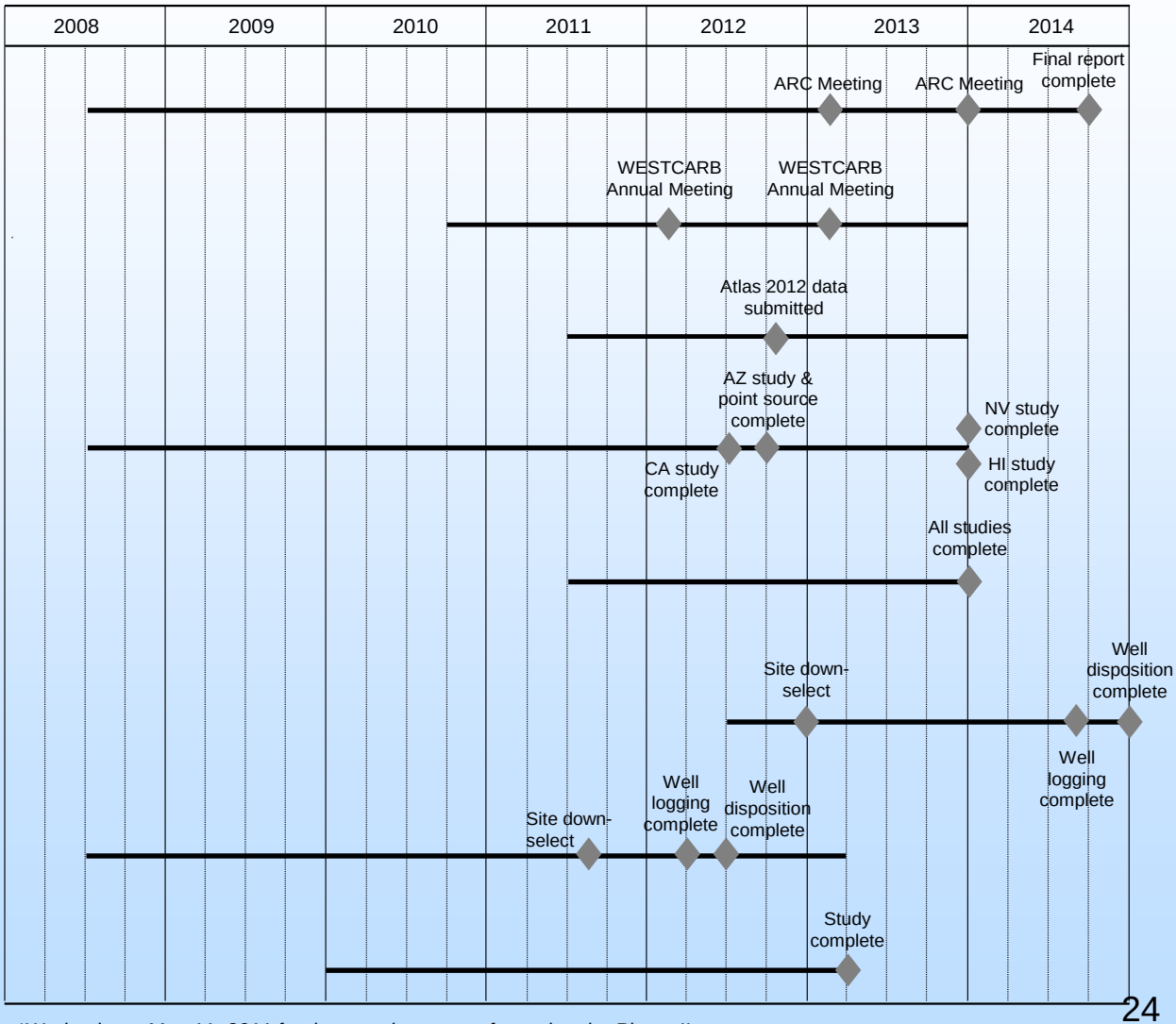
Budget Period 3

Years are federal fiscal years, October through September

Key: Major Task Milestone

Task

1. Project Management & Assessment
2. Outreach & Education
3. Technical Support for DOE/NETL Programs, Databases, & Publications*
4. Regional Characterization of States and Province
5. Regional Characterization: Integrated Studies & Cross-Cutting Issues*
6. Field Characterization of High CCS Potential Sites in Arizona
7. Field Characterization of High CCS Potential Sites in California
8. CCS for NGCC Assessment



*Work prior to May 11, 2011 for these tasks was performed under Phase II
Work prior to July 28, 2010 for Subtasks 8.2-8.7 was performed under Phase II

Revised January 2012

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(under Phase III, 2012)

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