SECARB Anthropogenic Test Lessons Learned

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Presentation Outline

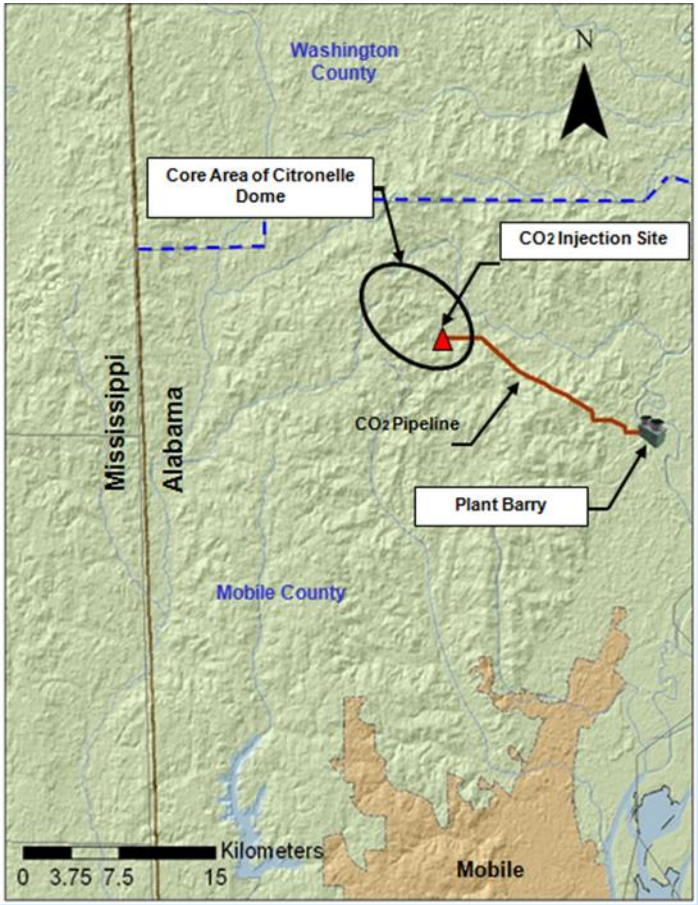
- Project Introduction and Status
- Permitting, Planning and Operations Lessons Learned
- Monitoring Lessons Learned

Project Objectives

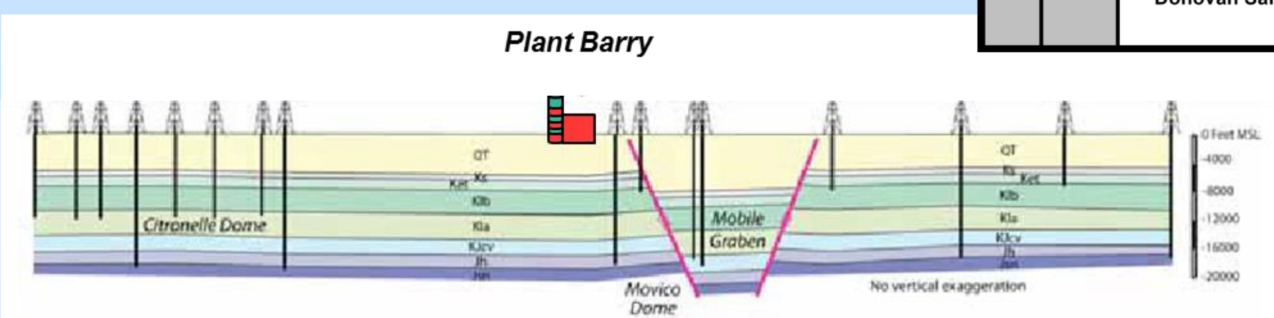
Baseline 1 year	Injection 2 years	Post 3 years
APR 2011 to AUG 2012	SEPT 2012 to SEP 2014	SEP 2014 to SEPT 2017

1. Support the United States' largest prototype CO_2 capture and transportation demonstration with injection, monitoring and storage activities;
2. Test the CO_2 flow, trapping and storage mechanisms of the Paluxy;
3. Demonstrate how a saline reservoir's architecture can be used to maximize CO_2 storage and minimize the areal extent of the CO_2 plume;
4. Test the adaptation of commercially available oil field tools and techniques for monitoring CO_2 storage
5. Test experimental CO_2 monitoring activities, where such technologies hold promise for future commercialization;
6. Begin to understand the coordination required to successfully integrate all four components (capture, transport, injection and monitoring) of the project; and
7. Document the permitting process for all aspects of a CCS project.

Storage Site: The Citronelle Oilfield



System	Series	Stratigraphic Unit	Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene		Citronelle Formation	Freshwater Aquifer
	Miocene	Undifferentiated		Freshwater Aquifer
	Oligocene		Chickasawhay Fm.	Base of USDW
		Vicksburg Group	Bucatunna Clay	Local Confining Unit
	Eocene	Jackson Group		Minor Saline Reservoir
		Claiborne Group	Talahatta Fm.	Saline Reservoir
		Wilcox Group	Hatchetigbee Sand	Saline Reservoir
	Paleocene		Bashi Marl	
			Salt Mountain LS	
		Midway Group	Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group		Confining Unit
		Eutaw Formation		Minor Saline Reservoir
		Tuscaloosa Group	Upper Tusc.	Minor Saline Reservoir
			Mid. Tusc. — Marine Shale	Confining Unit
			Lower Tusc. — Pilot Sand, Massive sand	Saline Reservoir
	Lower	Washita-Fredericksburg	Dantzler sand	Saline Reservoir
			Basal Shale	Primary Confining Unit
		Paluxy Formation	'Upper' 'Middle' 'Lower'	Injection Zone
		Mooringsport Formation		Confining Unit
		Ferry Lake Anhydrite		Confining Unit
		Donovan Sand	Rodessa Fm. Upper'	Oil Reservoir
			'Middle'	Minor Saline Reservoir
			'Lower'	Oil Reservoir



Structure map by GSA

Storage Project Status

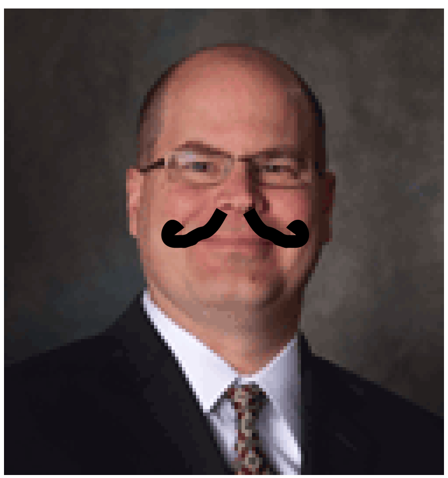
- Three deep wells drilled in 2011/2012
- Experimental Modular Borehole Monitoring System tool string run in early 2012
- Injection commenced on August 20, 2012
- Injection ended September 1, 2014
- 114,104 metric tons of CO_2 injection
- Entered the three year Post-Injection Site Care Period in September, 2014
- CO_2 breakthrough at the D-9-8#2 observation well in late 2015
- Testing and monitoring activities indicate containment

Permitting, Planning and Operations Lessons Learned

Or what we like to call …

The Good

The Bad



…And The Ugly

What went well?

- Integration of capture unit, pipeline and injection operations
  - ➢ Required transfer of CO_2 custody at plant gate from Alabama Power to Denbury
  - ➢ No outages due to “lack of communication”
  - ➢ All monitoring requirements met
- Receptiveness of UIC regulators, the Alabama Department of Environmental Management
  - ➢ First of its kind permitted as a Class V experimental well(s) by Alabama with elements that reflect Class VI well requirements

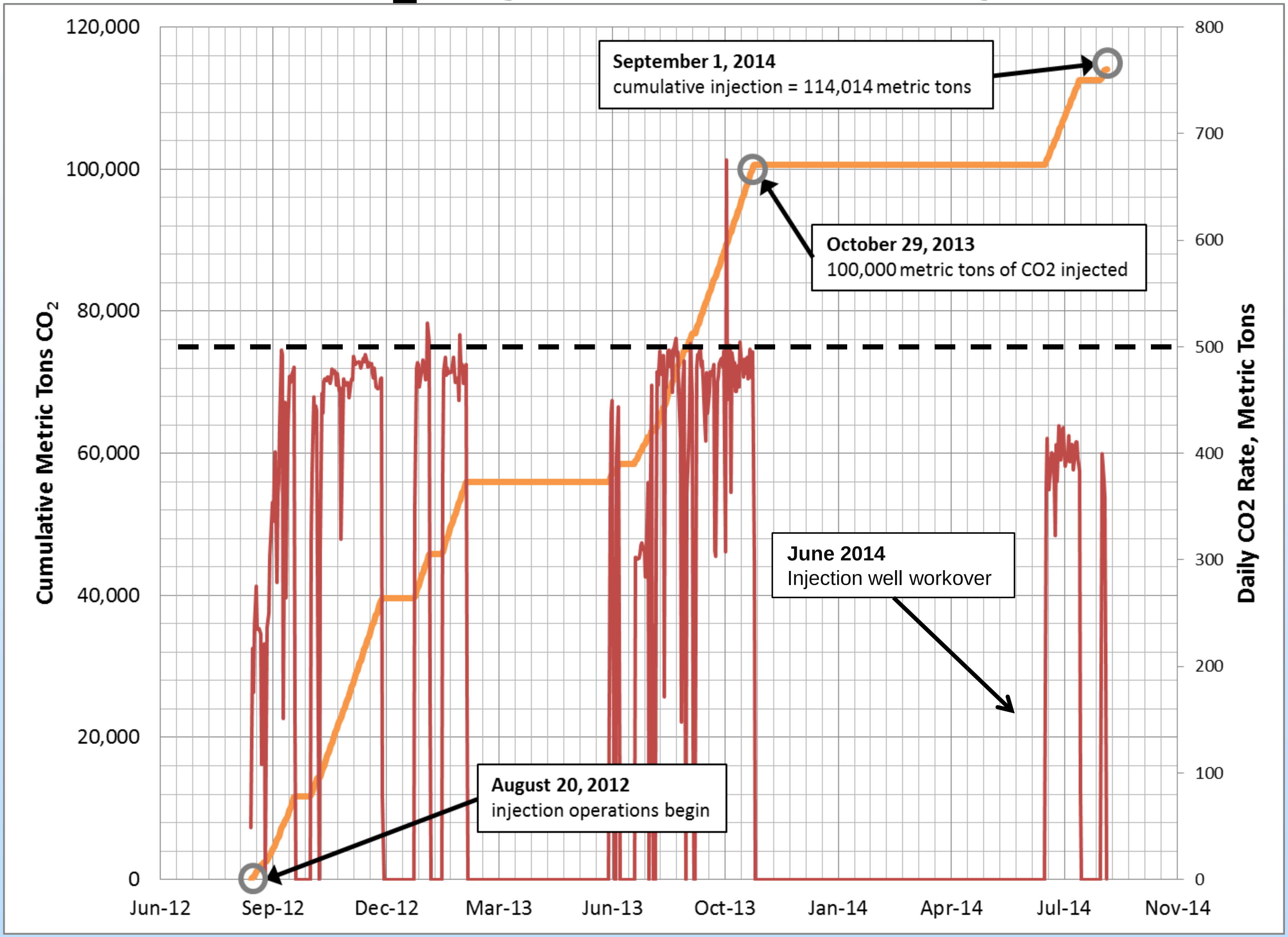
What Could Have Gone Better

- Amount of capture unit downtime was disappointing
  - Mostly a function of low dispatch of a coal-fired unit where the capture unit was drawing from a slip stream
  - Planned 300-400 kilotonnes of injection, realized 114 kilotonnes
- Pressure drop in pipeline during 2013-2014 capture unit outage
  - Iron (magnetite?) precipitate collected in pipeline, clogged pump filter on startup
  - Resulted in about 35 kilotonnes of non-injection in mid-2014

What Could Have Gone Better (2)

- Well workovers have been challenging!
  - In 2014 the injection well (D-9-7#2) was killed with a heavy mud so the tubing and packer could be pulled for a crosswell seismic survey resulting in injectivity damage
  - In July 2016 an attempt was made to pull the tubing-deployed monitoring tool string from the D-9-8#2 well. Despite multiple tubing cuts the tool string could not be completely removed and the well was ultimately plugged and abandoned.

CO_2 Injection History

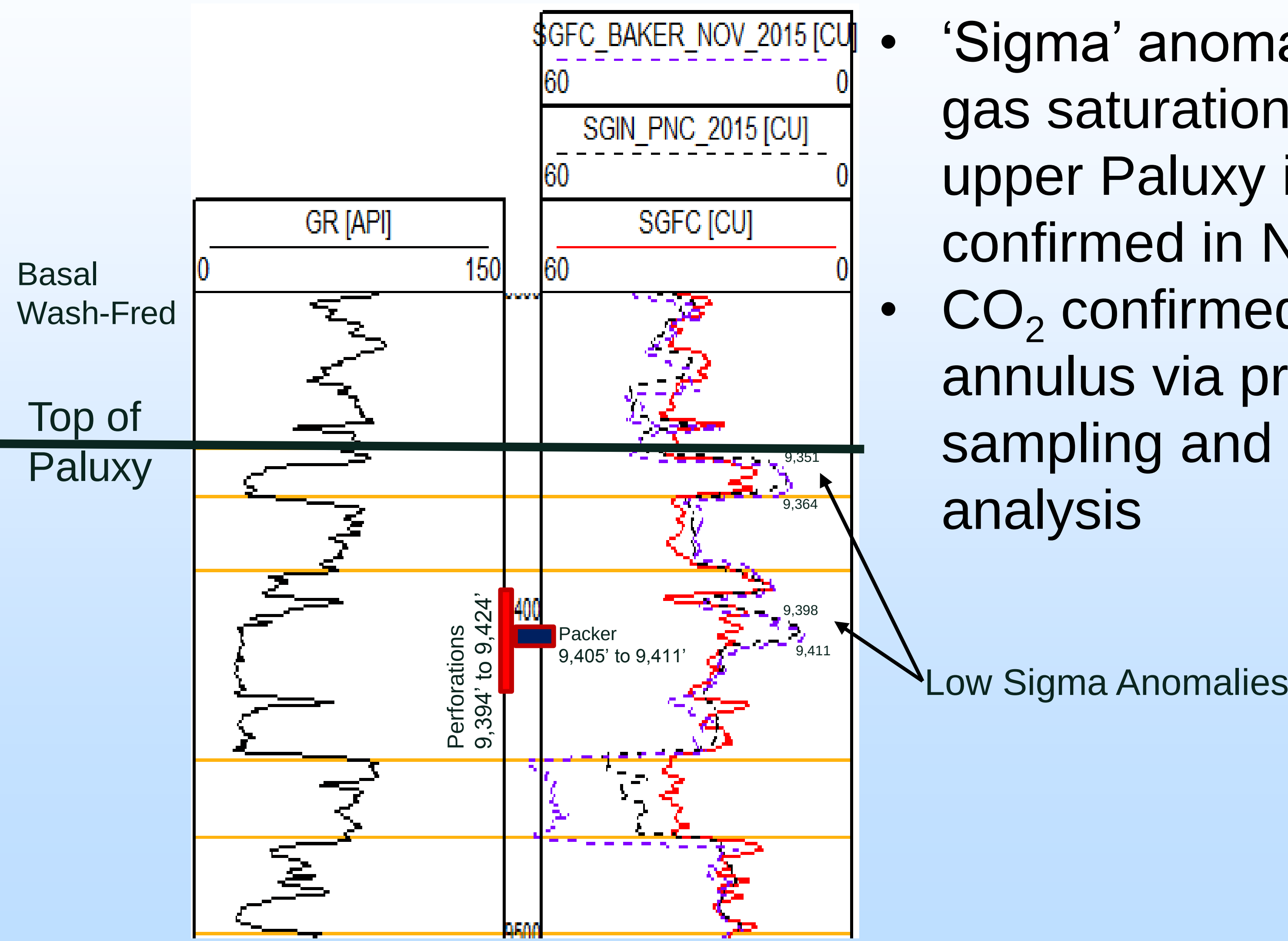


Monitoring Lessons Learned

What went well?

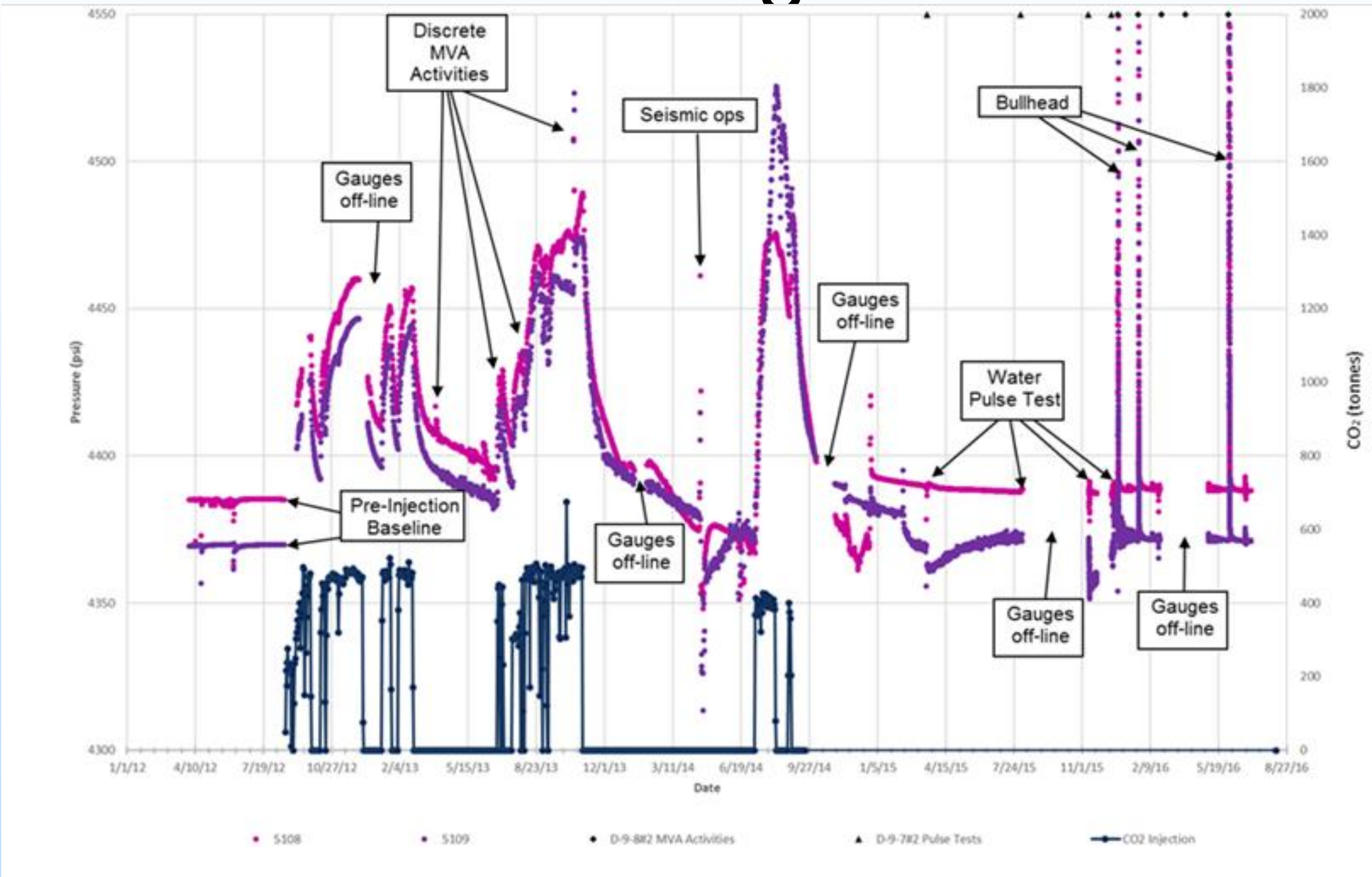
- Successful identification of CO_2 breakthrough with cased hole pulsed neutron log
- Pressure gauge data and frequent injection pauses/startups provide and opportunity for “cheap” pressure transient analysis
- Fiber optic arrays (DTS and DAS) worked better than expected
  - Temperature data utilized to diagnose a bad completion
  - high density acoustic dataset
  - time-lapse acoustic imaging appears promising

Cased Hole Pulsed Neutron Log Used to Identify CO_2 Breakthrough

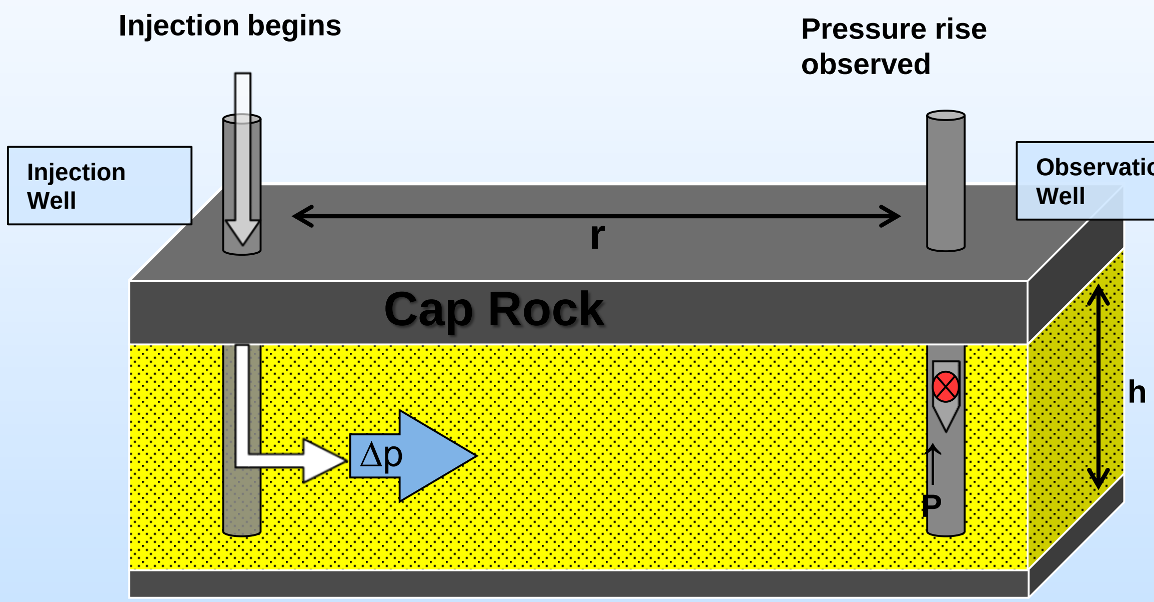


- 'Sigma' anomaly indicated gas saturation buildup in the upper Paluxy in Aug. 2015, confirmed in Nov. 2015
- CO_2 confirmed in casing annulus via pressure, tracer sampling and compositional analysis

Pressure Response at D-9-8#2 Monitoring Well

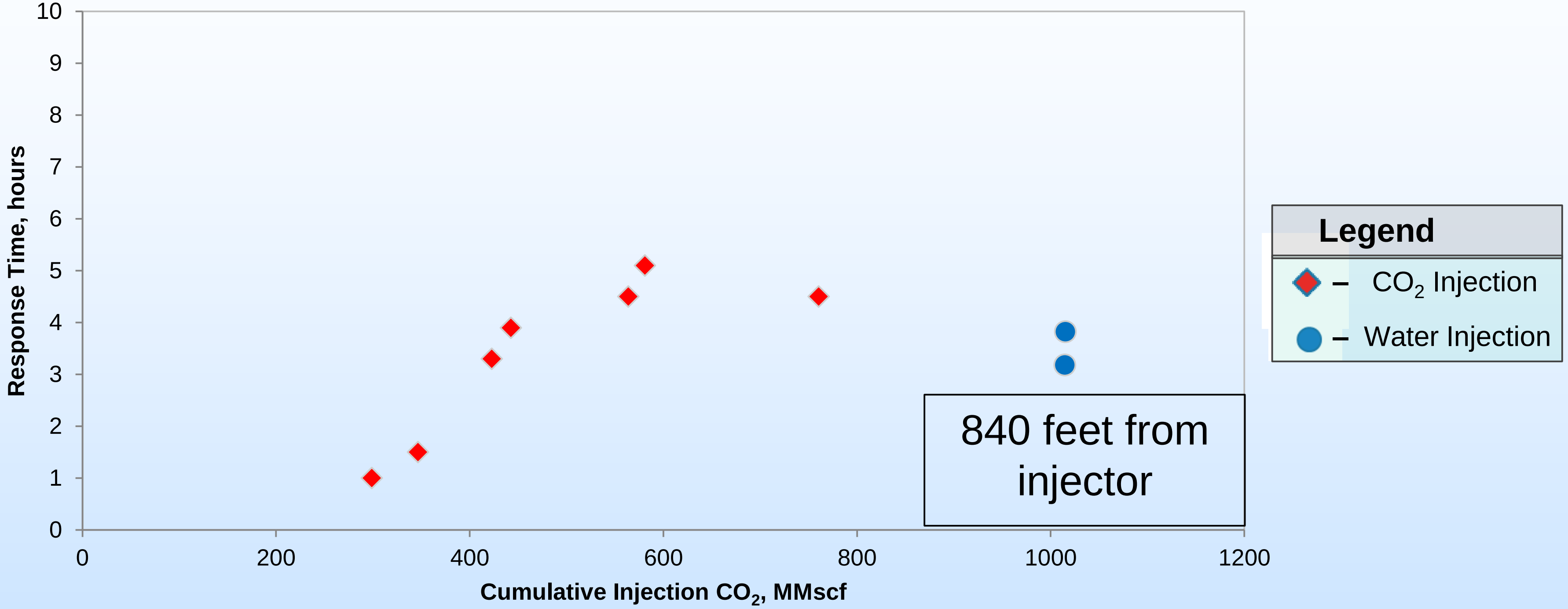


Injection Interruptions provided an opportunity for cheap pressure transient analysis



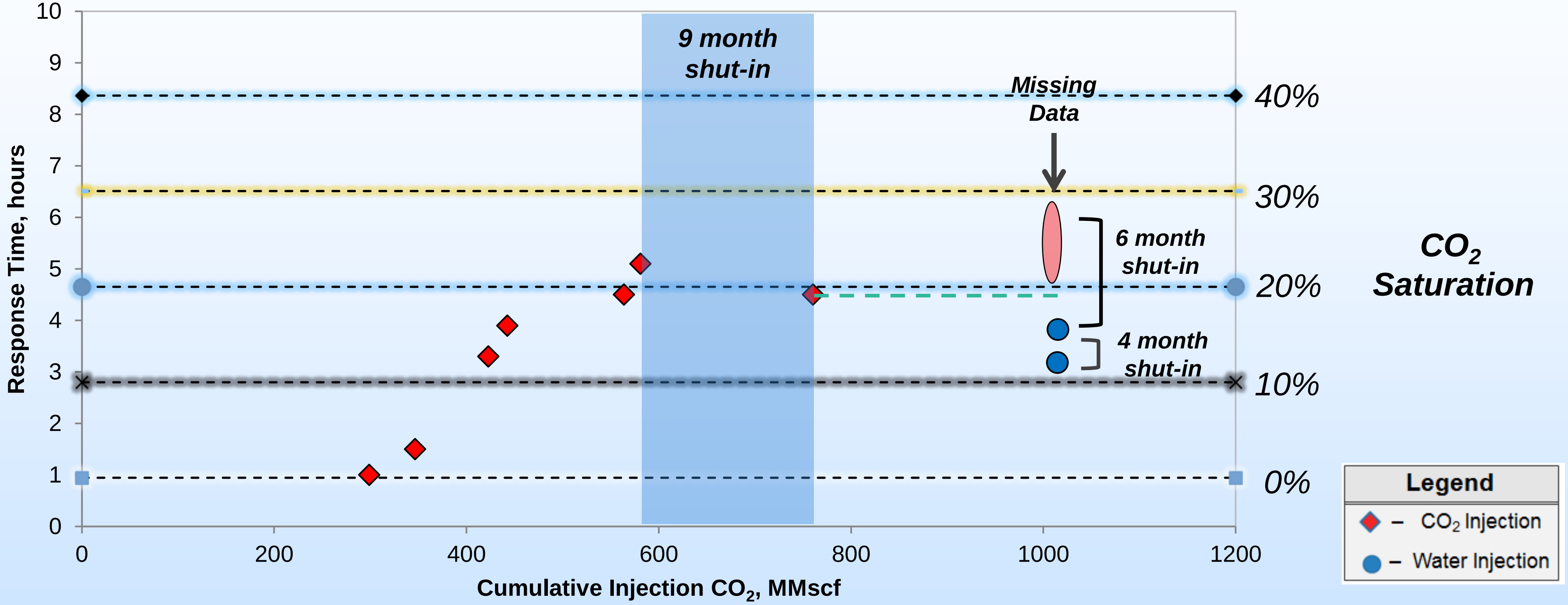
Time the pulse takes to reach the observation well is a function of reservoir characteristics

D-9-8#2 Pressure Response Times



- Red diamonds represent CO_2 injection starts
- Blue circles represents post-injection water pulse tests

D-9-8#2 Saturation Changes



Theoretical response times for a pressure transient to travel from the injector to the observation well were calculated as a function of CO_2 saturation in the reservoir. Assume:

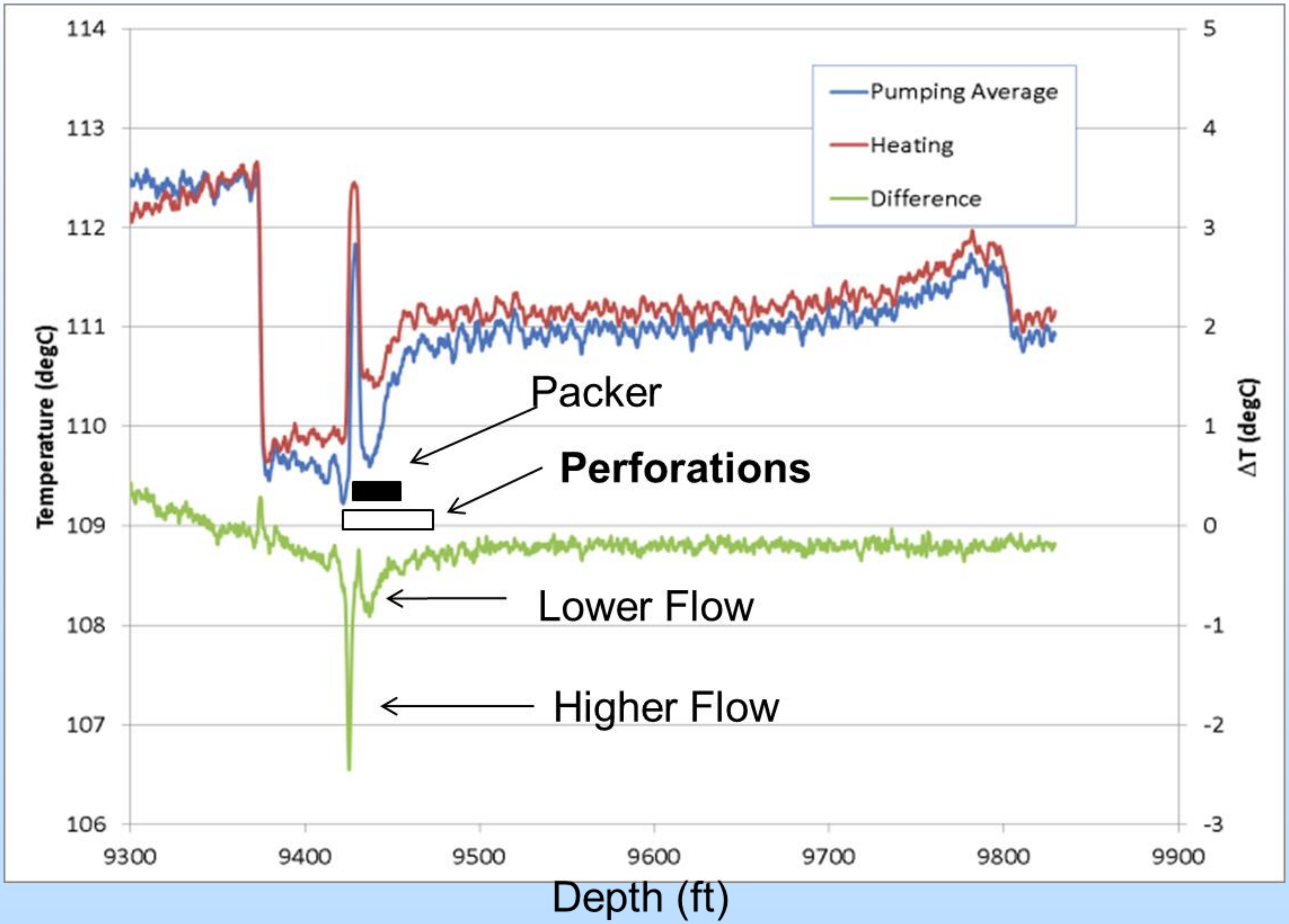
- Homogenous distribution of CO_2 in reservoir
- Fixed reservoir properties

Distributed Fiber Optic Arrays Provide a Lot of Bang for the Buck

- Distributed temperature FO proved its utility in identifying a bad completion in the D-9-8#2 (packer set in perforations)
- Distributed acoustic FO provided a high-density single mode array
  - Wave-form acquired using stacked VSP-DAS provides a good match with conventional geophone results
- ***For further information on distributed FO, please attend Rob's presentation at 2:15 this afternoon in the Geophysics 2 session.***

Heat Pulse with Annular Pump Test

Identify location of 30 ft perf. interval with respect to packer



Temperature Data:

Heating

Heating during Pumping (~1 hour average)

Difference

What would we do differently?

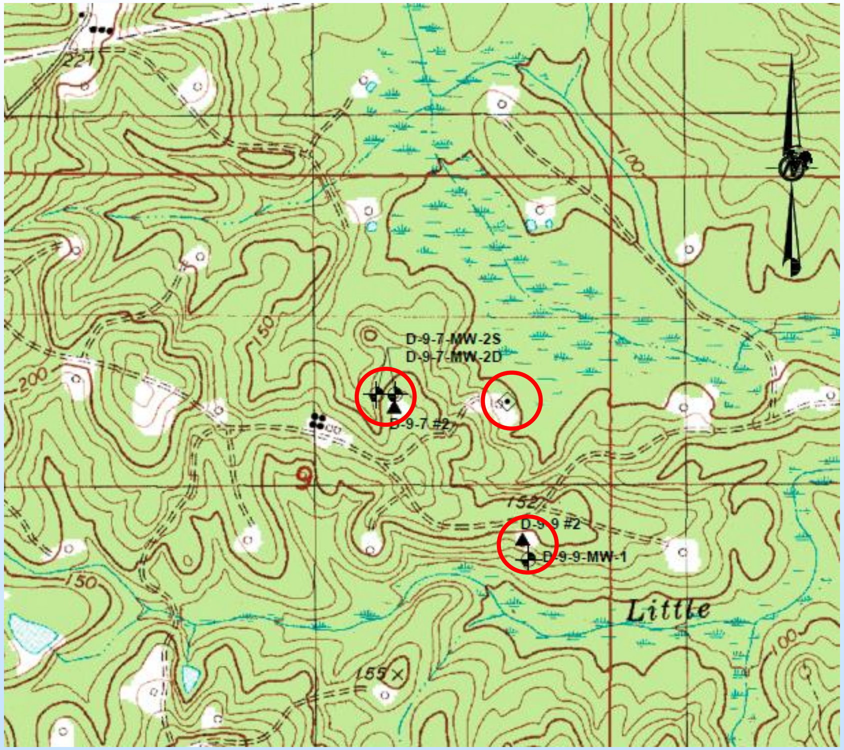
- Install USDW monitoring wells earlier, develop and sample for a longer period prior to injection
  - ➢ Large background data sets are required to avoid false positive/negatives in statistical results.
  - ➢ Monitoring well geochemistry can vary as wells are developed.

Citronelle Groundwater Sampling Program

- Three dedicated groundwater sampling wells and one water supply well

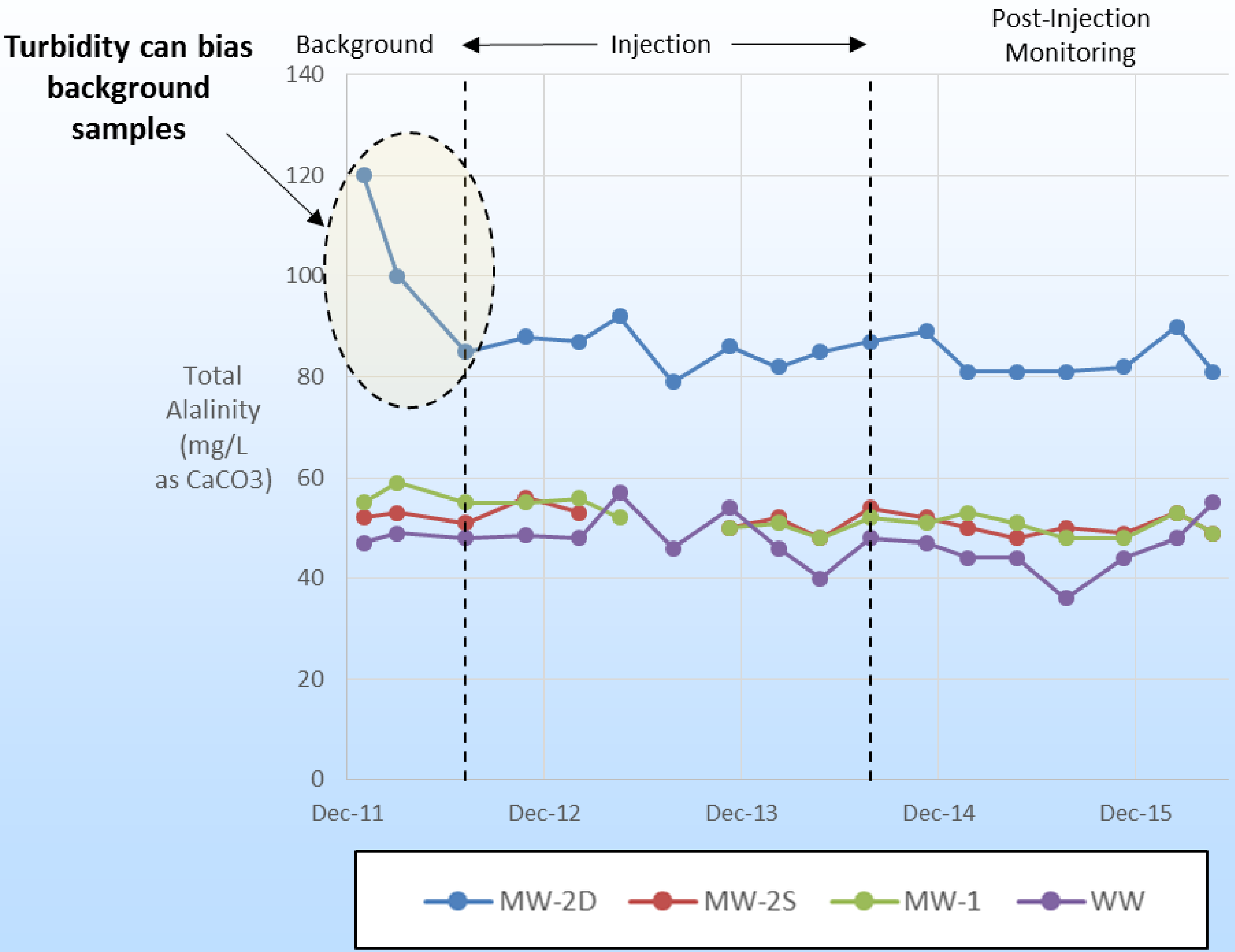
Well	Depth (ft)	Elev. (ft)
D9-9 MW-1	169.6	-20.23
D9-7 MW-2S	170.8	-5.24
D9-7 MW-2D	501.0	-335.6
D9-8 WW	143	--

- Three background sampling events prior to CO_2 injection
- Fifteen quarterly sampling events since injection started
- 17 metals, alkalinity, TDS, TIC, pH…etc.

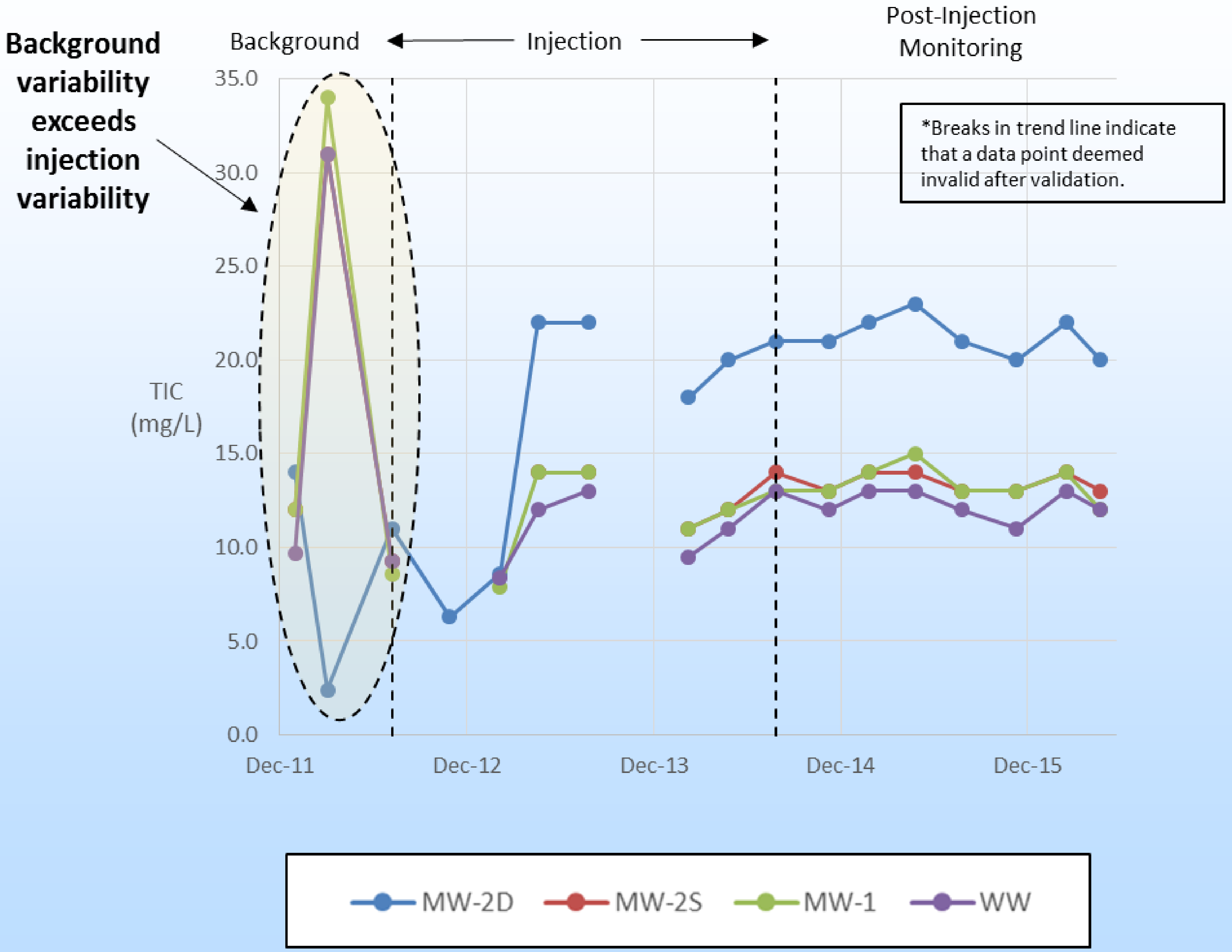


Groundwater sampling locations (circled)

Total Alkalinity



Total Inorganic Carbon (TIC)



Project Closure

- Complete post-injection monitoring
  - Partial repeat of baseline VSP
  - Continue quarterly groundwater sampling
- Demonstration of CO_2 containment within the injection zone and non-endangerment of USDWs using modeling and monitoring results
  - Close out UIC permit
- Temporary abandonment of remaining project wells and transfer of test site to Denbury

Thank You From The SECARB Team