Geologic Characterization Based on Deep Core and Fluid Samples from the Sacramento Basin of California – an Update

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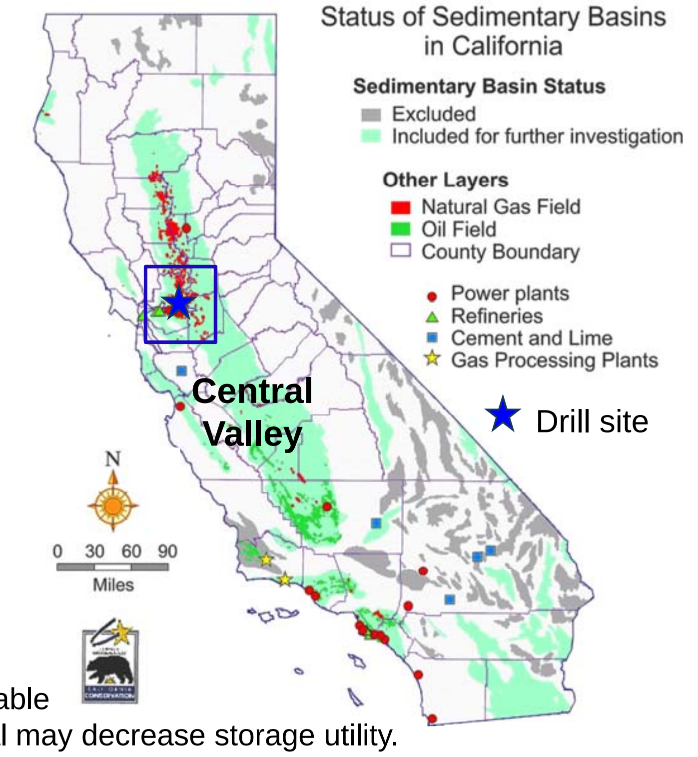
May 2013

West Coast Regional Carbon Sequestration Partnership westcarb.org

CO_2 Storage Opportunities in California's Sacramento Basin

- The Central Valley of California is the most promising on-shore CO_2 storage resource in WESTCARB territory, with an estimated capacity of 75-300 Gt. The Valley is divided into the Sacramento Basin in the north and the San Joaquin Basin in the south.
- In December 2011, WESTCARB drilled a stratigraphic well to assess the CO_2 storage potential of regionally extensive saline and gas-bearing formations in the southwestern Sacramento Basin.
- The Citizen Green well was drilled directionally to a vertical depth of 6,920 feet (2,109 meters) on King Island, an agricultural area near Stockton. Core samples and logging data are being analyzed at LBNL and shared with researchers at two of DOE's Frontier Energy Research Centers.
- CO_2 storage capacity of the sandstone formations and integrity of the overlying shale units are being evaluated. Simulations of CO_2 injection, multi-phase flow, and trapping mechanisms are being performed. The formations are laterally extensive, so the data will have regional application.

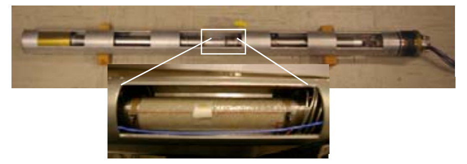


Potential Storage Formations Penetrated by Citizen Green Well

- **Domengine Formation** – High permeabilities (3+ Darcies) observed on Combinable Magnetic Resonance (CMR) log. Unconsolidated. Questionable stratigraphic seal may decrease storage utility.
- **Mokelumne River Formation** (primary target) – 1+ Darcy CMR permeabilities in the upper section where cores were unconsolidated sand. Thickness 1507 ft (460 m). Becomes tighter with depth; consolidated below 5500 ft (1676 m). Natural gas accumulation at Capay/Mokelumne River boundary suggests seal integrity.
- **Top Starkey Formation Sandstone** – Considerably lower mean permeability, but several lobes show more promise with CMR permeability ~100 mD.

Seismic Measurements During CO_2 Flood of Sandstone Core

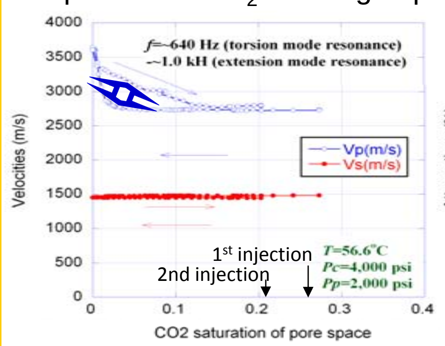
LBNL's new petrophysical CT scanner



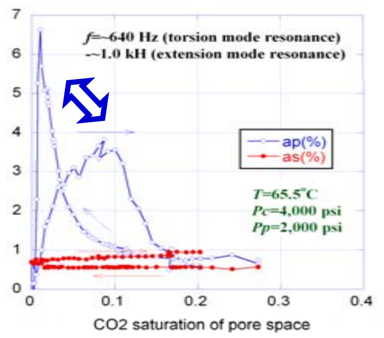
Seismic Split Hopkinson Resonant Bar (Short-core resonant bar, Nakagawa, 2011, Rev. Sci. Instr.)

Seismic measurements

LBNL's Split Hopkinson Resonant Bar (Short-core Resonant Bar) test setup was used to measure kilohertz-range seismic velocities and attenuations of a core sample during supercritical CO_2 flooding experiments.



Seismic velocities (Vp and Vs)

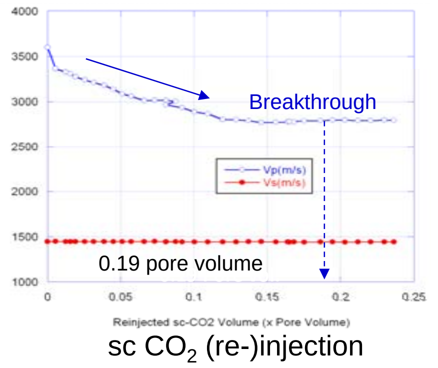


Seismic attenuation

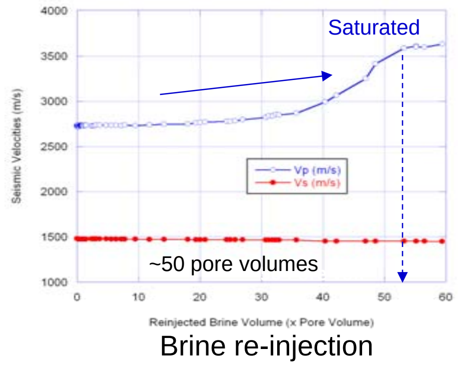
- Sample: Domengine Fm sandstone core (6" long, 1.5" diameter, >2-3 Darcy permeability, ~30% porosity) from the Black Diamond Mine, located 39 km (24 mi) WSW of the Citizen Green well
- Repeat test conditions: Confining pressure = 4,000 psi, pore pressure = 2,000 psi, temp = 56.6°C, the estimated in-situ conditions at the top of the high-permeability section of the sedimentary unit. Brine is a 1% NaCl (10,000 mg/l) solution

Residual trapping of CO_2 and its removal

P-wave velocity is a good indicator of CO_2 saturation in the pore space (for relatively low saturation, S<40%). During injection, CO_2 breakthrough through the core occurred at only ~19% of the pore CO_2 saturation. In contrast, to remove all CO_2 in the pore space, more than 50 pore volumes of brine needed to be injected.



sc CO_2 (re-)injection



Brine re-injection

(Note: The sc CO_2 injection test was conducted immediately after the brine re-injection test of a preceding separate experiment.)

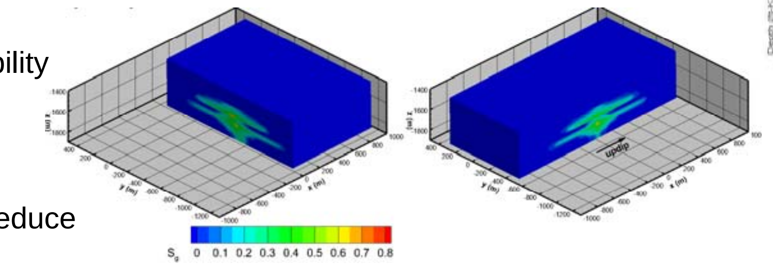
CO_2 Injection Simulation Based on Well Log Data

Use of Well Log and Sidewall Core Data for Simulated CO_2 Injection into Mokelumne River Fm Sandstone

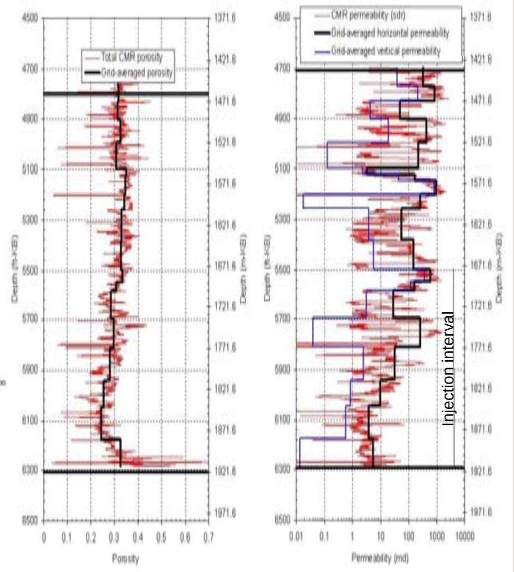
- Nuclear Magnetic Resonance (NMR) Total Porosity is a good match with sidewall core helium porosimetry data. NMR permeability estimates are good for formations penetrated by the well
- Injection (well perforation) over the lower half of Mokelumne River Formation
- Model captures high permeability in upper half, downward flow in lower half

Simulated injection of 4 Mt of CO_2 at a rate of 1 Mt/year

- ~25% of injected $scCO_2$ dissolves in the formation brine
- Strong lateral CO_2 flow in high-permeability layers. Slight up-dip migration.
- Strong vertical buoyancy flow in high-permeability layers
- Low permeability shale greatly reduce effective vertical permeability
- ~3 Mt $scCO_2$ plume diameter 3900 ft (1200 m); height 1150 ft (350 m), still 360 ft (110 m) below top of reservoir.



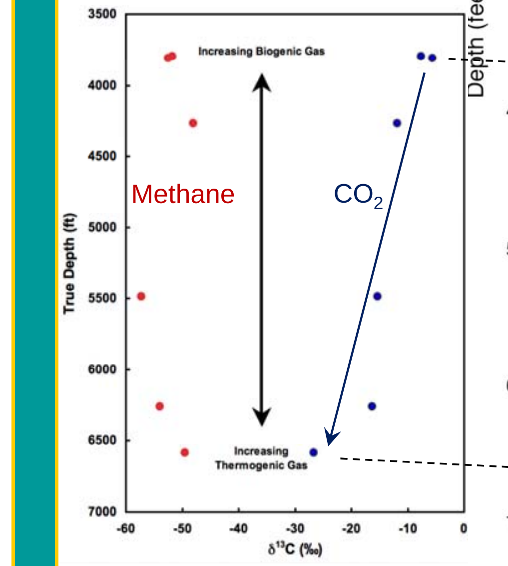
Distribution of ~3 MT of $scCO_2$ at the end of 4 years of injection

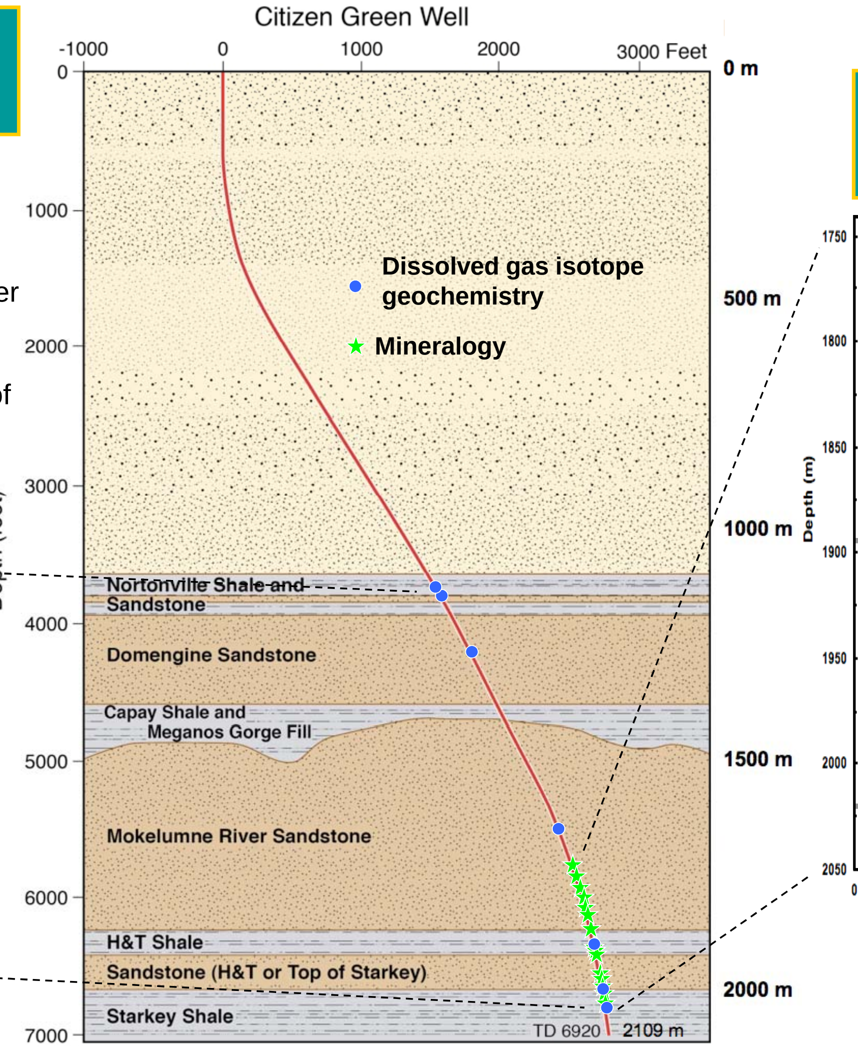


Nuclear Magnetic Resonance (NMR) log data and selected porosity/permeability layers

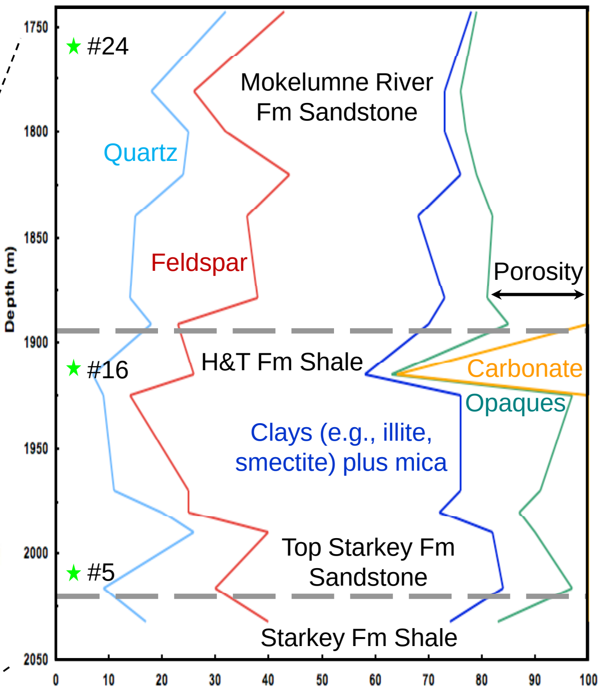
Isotope Geochemistry

A significant decrease in $\delta^{13}C$ of dissolved CO_2 with depth likely represents a change from biogenic CO_2 derived from methanogenic activity in the upper section, to CO_2 produced during abiotic thermal gas production deeper in the section. The $\delta^{13}C$ of methane is consistent with a mixture of thermogenic and biogenic gas.

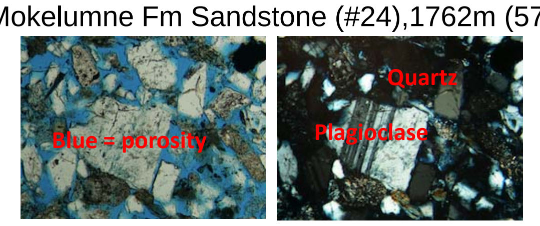




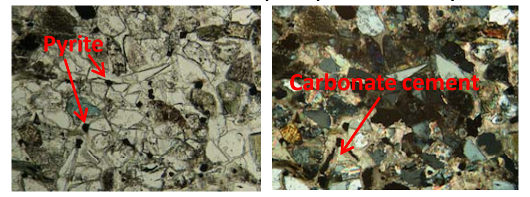
Mineralogy from Core Samples



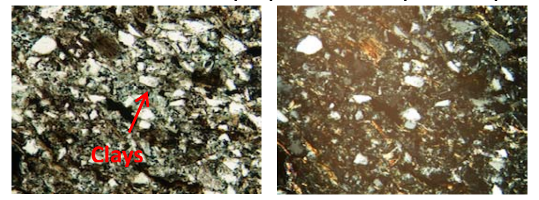
Mineralogy from thin-section point count of sidewall cores



Mokelumne Fm Sandstone (#24),1762m (5782ft)

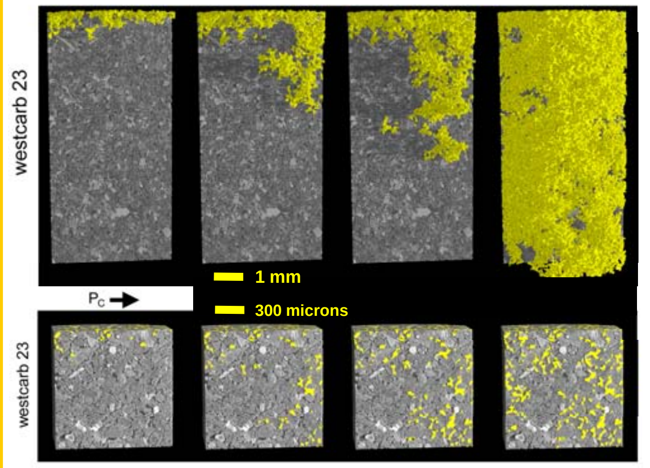


H&T Fm Sandstone (#16), 1915 m (6283 ft)



H&T Fm Shale (#5), 2016 m (6614 ft)

Characterization of Rock Microstructure & Mineralogy

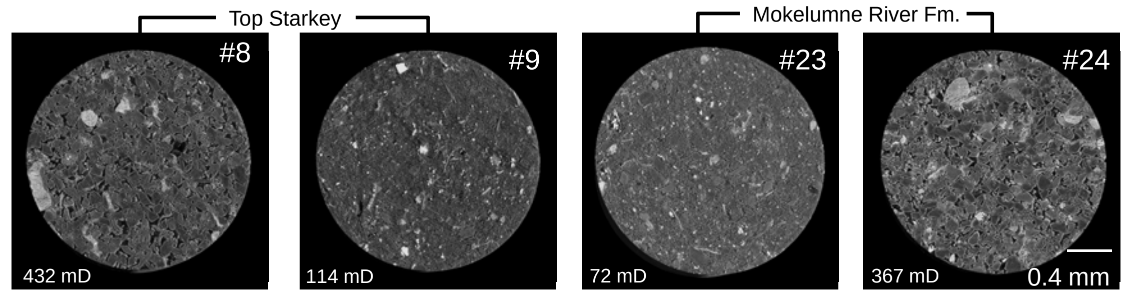


Virtual Petrophysics

For CO_2 storage characterization, the evaluation of petrophysical properties, particularly relative permeability for predictive modeling studies, has the high costs of acquiring continuous core and conducting core flood experiments. Alternatively, petrophysical data for multiphase flow models can be acquired by scanning small samples at high resolution using 3D micro-CT imaging and conducting pore scale modeling. To test this approach, we scanned 6 sidewall cores from the Citizen Green well at LBNL's Advanced Light Source for 3D microstructure and modeled permeability, $P_c(S)$, and effective diffusivity. Results are being compared with single phase permeability and $P_c(S)$ results.

Left: A Citizen Green well core sample (#23) from the Mokelumne River Formation with modeled $scCO_2$ distribution during a $P_c(S)$ calculation run.

Synchrotron micro-CT data also complement optical microscopy and Scanning Electron Microscopy (SEM) data for pore space characterization. The images at right were acquired for modeling studies but also provide 3D quantification of grain size and porosity. Note: #8 and #24 (highest permeability samples) exhibit the most open pore structures.



Mineralogical Characterization for Reactive Transport Modeling

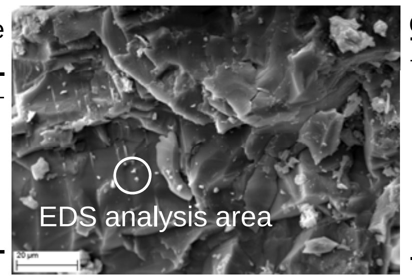
Predicting the long term fate of injected $scCO_2$ requires models incorporating both multiphase flow and reactive chemistry. On-going development of the reactive transport model (RTM) for the Citizen Green site necessitated a detailed study of the solid phase chemistry of the lower horizons considered for injection (Starkey and Mokelumne River Fm). Quantitative x-ray powder diffraction (QXRPD) was carried out to evaluate the primary mineral fractions. Trace phases and feldspar composition were evaluated using Electron Dispersive Spectroscopy (EDS).

				Flow Properties		Quantitative XRPD (Rietveld) [weight %] (s.d. relative to the last significant digit)								
Sample ID	Wireline depth [ft]	TVD [ft]	Formation	Porosity (He) [%]	Permeability (gas) [mD]	Quartz	K-feldspar	Plagioclase (more sodic: Andesine)	Plagioclase (more calcic: Labradorite)	Kaolinite	Chlorite	Pyrite	Amphybole	Detrital mica
#8	7136	6492.3	Top Starkey Sand	31.4	432.6	42.8(11)	8.7(9)	39.6(15)	n.d.	1.4(4)	4.7(5)	<1	<1	2.4(6)
#9	7104	6460.9	Top Starkey Sand	27.6	114.3	39.9(4)	6.5(2)	27.3(6)	n.d.	5.7(4)	8.5(5)	1.2(1)	n.d.	9.5(6)
#15	6936	6296.8	H&T Shale (sand stringer)	34.2	299.9	44.1(4)	16.6(3)	30.4(4)	n.d.	4.2(3)	4.5(4)	n.d.	n.d.	<1
#21	6598	5970.1	Mokelumne River Fm.	31.3	135.5	33.9(11)	22.0(11)	34.5(15)	n.d.	3.6(4)	5.4(6)	<1	<1	<1
#23	6466	5843.1	Mokelumne River Fm.	31.3	71.9	36.3(18)	12.6(3)	<1	36.6(6)	2.7(3)	5.4(4)	<1	<1	5.0(7)
#24	6400	5780.1	Mokelumne River Fm.	33	367.1	40.3(5)	17.1(6)	3.6(8)	29.2(6)	5.2(5)	4.0(6)	n.d.	<1	<1
Shale baffle	5249	4725.2	Mokelumne River Fm.	NA	NA	17.0(3)	32.7(6)	6.5(2)	n.d.	34.9(6)	n.d.	n.d.	n.d.	8.4(3)
Top reservoir	5247	4723.5	Mokelumne River Fm.	NA	NA	27.8(5)	16.2(4)	34.0(10)	n.d.	3.6(4)	17.0(5)	n.d.	n.d.	<1

The upper Mokelumne River Fm appeared to be relatively non-reactive (quartz, K-spar, & albite). But QXRPD detected a significant portion of potentially reactive phases, especially Ca-plagioclases, in the lower Mokelumne and Starkey. The composition of these plagioclases is variable, but they are generally rich in Ca, with terms from Andesine to Labradorite providing the best fit. This was confirmed by SEM-EDS analysis (right). This combination of high injectivity and reactivity make the top Starkey and lower Mokelumne attractive injection targets.

Plagioclase EDS

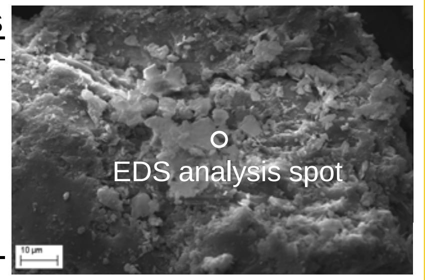
	Wt [%]
O	42.2
Si	32.7
Al	13.7
Na	6.2
Ca	4.5
Fe	0.3
K	0.3



SEM image of a plagioclase surface. EDS analysis confirms a significantly calcic plagioclase. Data from sample #8 (top Starkey Fm sandstone).

Chlorite EDS

	Wt [%]
O	46.7
Si	22.6
Fe	11.2
Al	9.4
Mg	3.8
K	3.1
Na	1.1
Ti	0.9
Ca	0.7
Cl	0.5



SEM image of a quartz grain covered with chlorite and kaolinite particles. Data from sample #9 (top Starkey Fm sandstone).

Accessory phases, SEM Secondary Electron (SE) images:
a) Framboidal pyrite
b) Amphybole, Fe-rich
c) Detrital mica, biotite fragment
d) Smectite (total amount in the sample below XRPD detection limit) covering a quartz grain.