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Update on Subsurface Characterization at the Citizen Green Deep Research Well

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Site Characterization Effort

Goal : **Acquire multi-scale dataset (from micron to km) to provide constraints for multiphase flow, reactive transport, & seismic MVA modeling for prospective CO_2 injection in the region**

This Talk *: Update* on progress towards site characterization

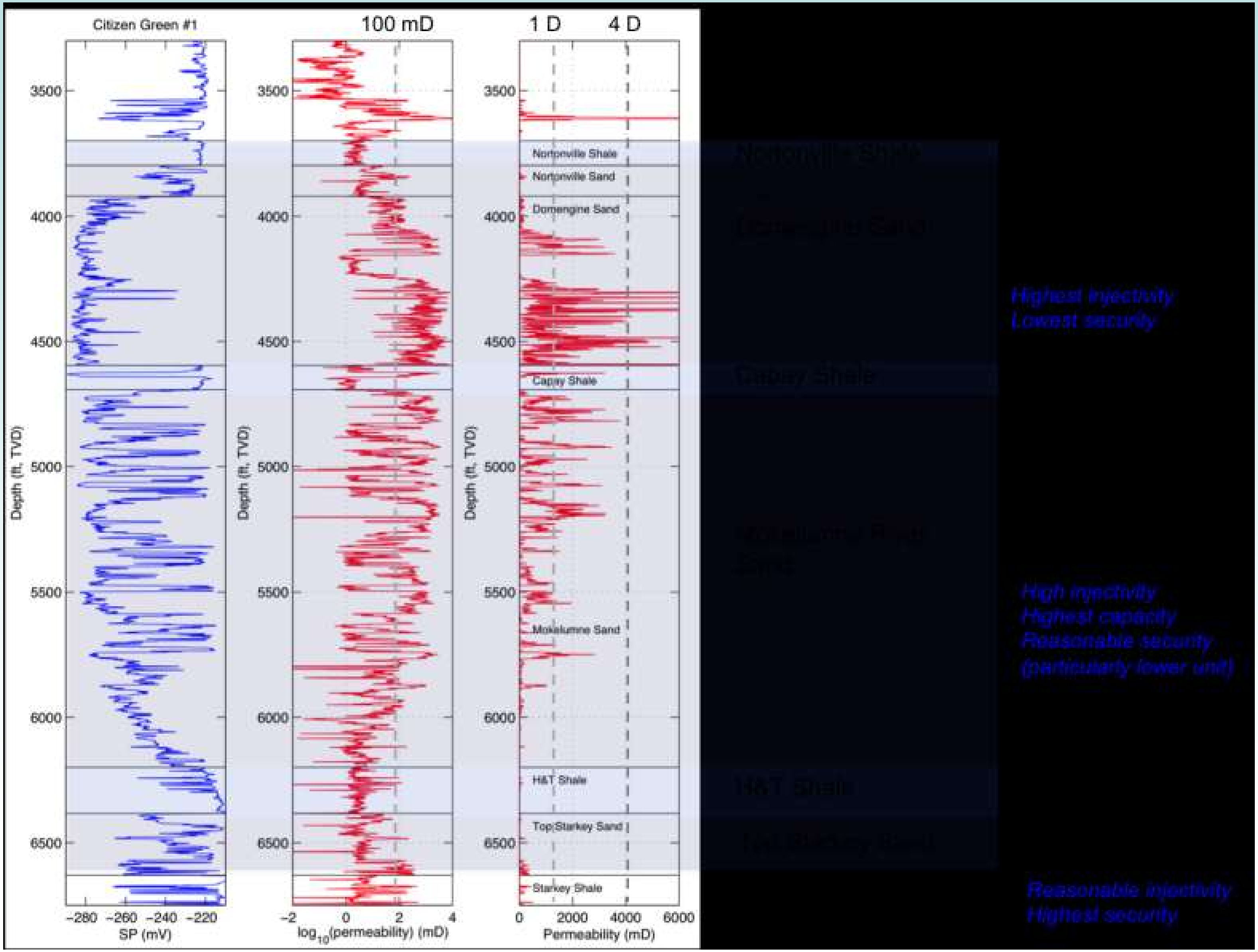
Task 1 : Log analysis for flow model construction

Task 2 : Core analysis for flow properties & solid phase chemistry

Task 3 : Micro-CT imaging for virtual petrophysics (single & multiphase permeability, effective diffusivity, and capillary pressure curve P_c[sat])

Task 4 : Incorporation of petrophysics & regional well data for model construction

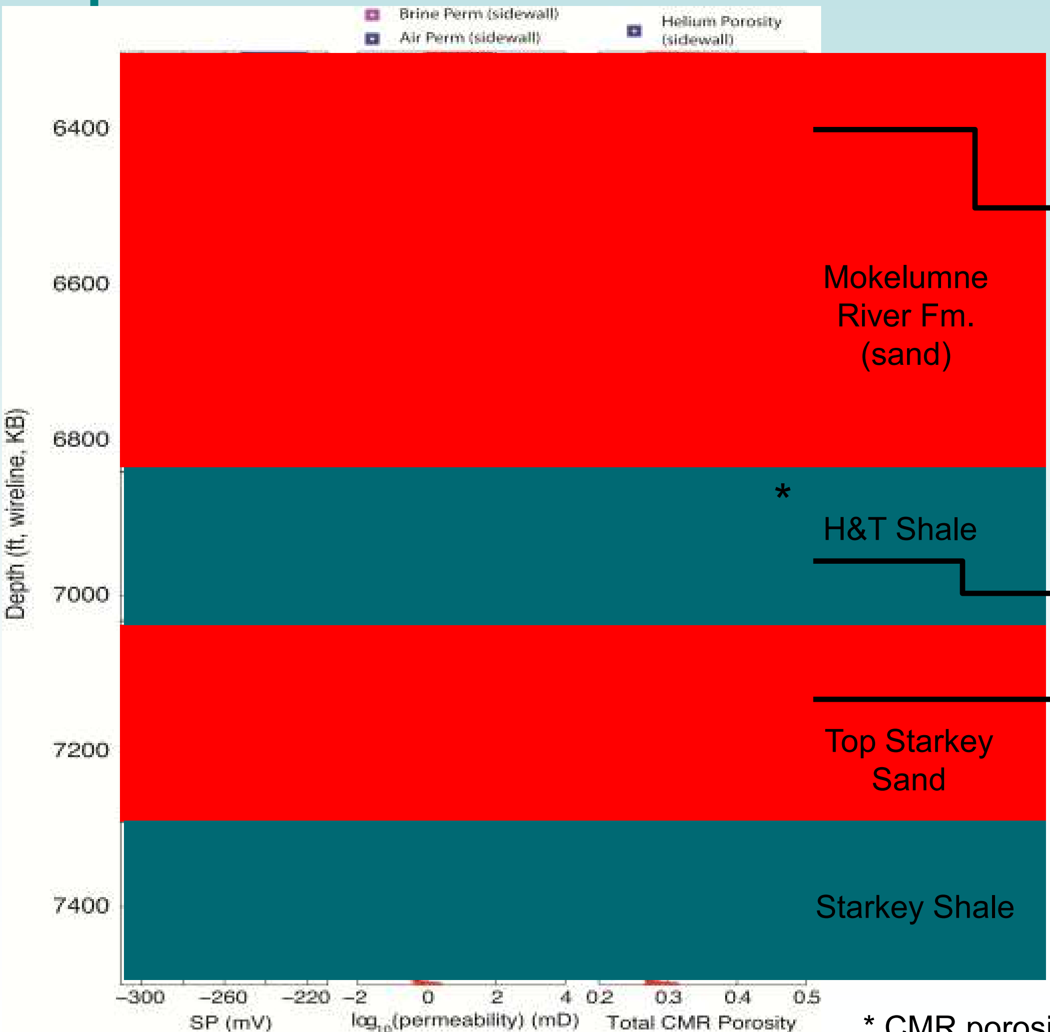
Permeability and Reservoir ID from CMR



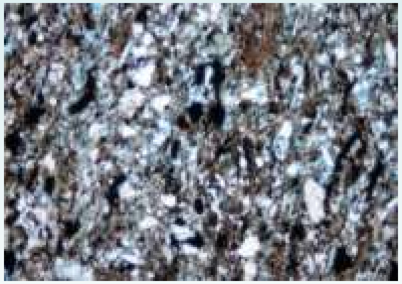
Sidewall Comparison with CMR & Thin-Section

Gas permeability & He porosity similar to CMR estimates

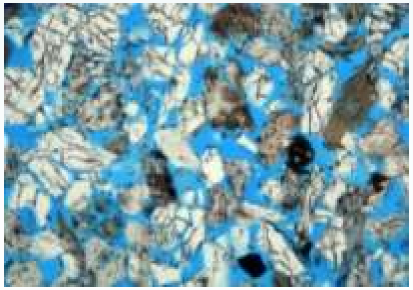
Permeable sands are angular & feldspar-rich in thin section with minimal cementation



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



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

* CMR porosity includes bound & capillary trapped water in addition to the more conventional free water porosity

Preliminary Solid Phase Mineralogy

1. Initiated quantitative XRD analysis of samples from a variety of depths
2. Data will be used to parameterize ToughREACT model of site
3. Mokelumne River Sand has low Quartz/Feldspar ratio of 0.42, should be relatively reactive in comparison to quartz dominated sands (mineral trapping possibility?)
4. Currently processing splits from sidewall samples

	Quartz	K-feldspar (microcline)	Plagioclase (low albite)	Plagioclase (andesine)	Detrital mica (illite2M1)	Chlorite	Kaolinite	Pyrite	Montmorillonite‡	Accessories
Non-Marine Overburden Cuttings, 930 ft	31.2	5.4	43.6	5.1	5.9	n.d.	n.d.	n.d.	7	1.8
Domengine sandstone (BDM)	73.8	22.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3.5	n.d.
[redacted]										
Mokelumne River Fm. Whole Core, 5249 ft [shale baffle]	17.0	16.2	6.5	n.d.	8.4	17.0	34.9	<1	<1	n.d.
Starkey Fm. Cuttings 7146 ft	37.5	11.1	34.2	n.d.	7.7	1.3	1.8	1.1	<1	5.3*

‡Turbostratic disorder model
*Possible apatite and clinopyroxene

Micro-CT Characterization of Core Samples

Problem :

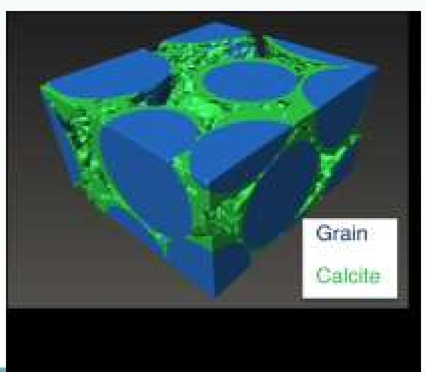
While single phase flow properties are well-constrained by logs & core samples, multiphase properties including $P_c(S)$ relationships & relatively permeability are not. These relationships are key for effective reservoir modeling.

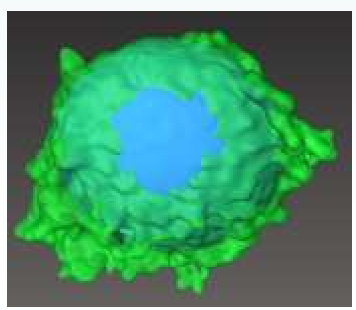
Solution :

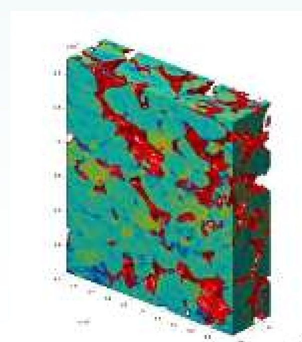
Use high-resolution 3D imagery of small samples from the Citizen Green well (acquired using synchrotron micro tomography) combined with pore-scale modeling to predict 2-phase flow properties from structure.

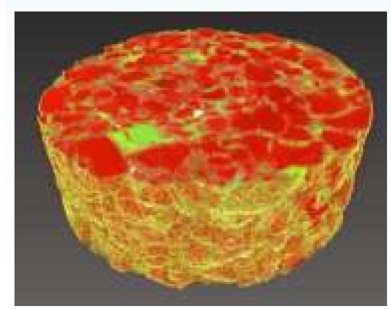
Method :

Synchrotron micro-CT is similar to medical CT but spatial resolution is considerably smaller (down to 440 nm). Fully 3D (required for models).





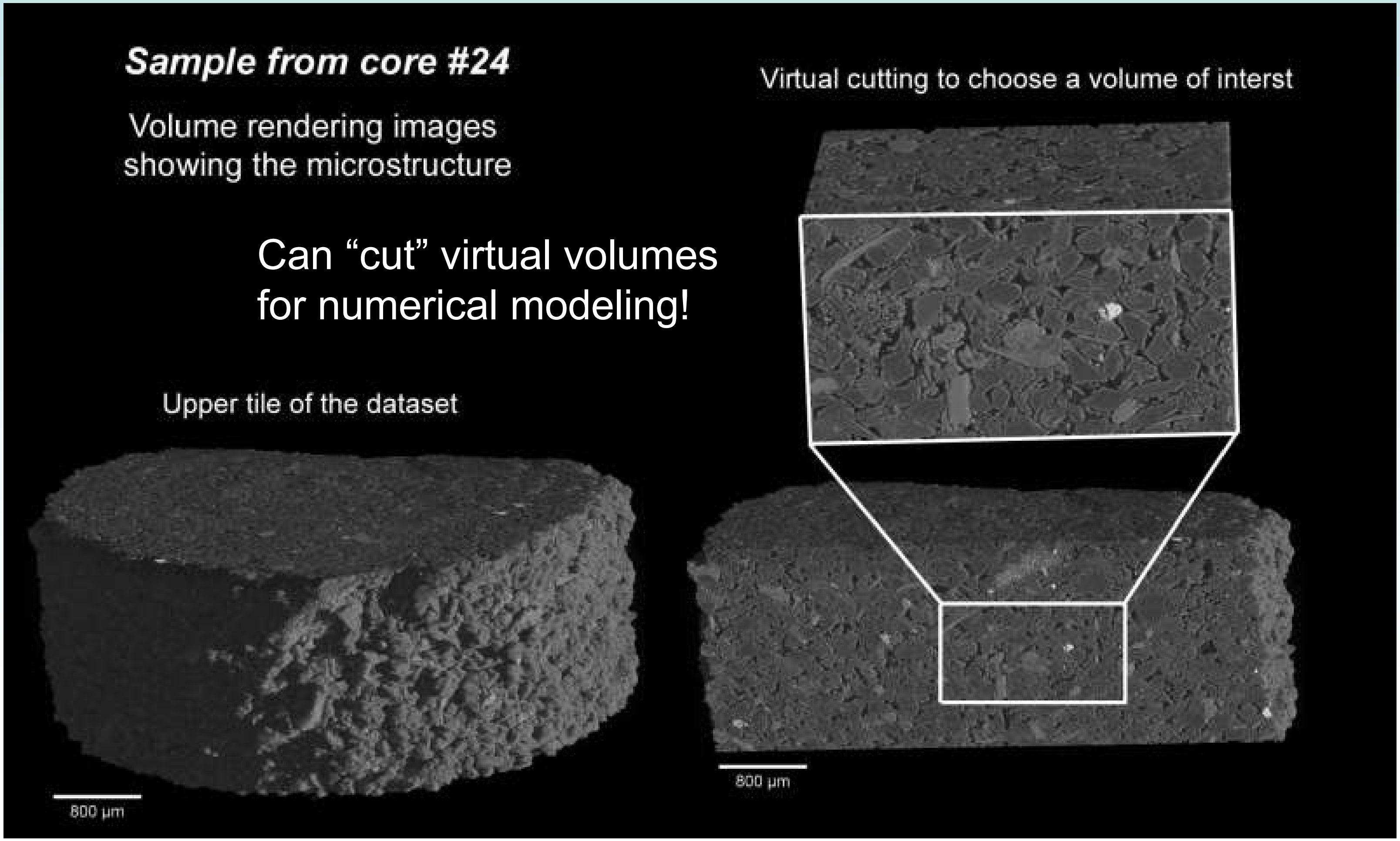




Low-Resolution Scan : Mokelumne River #24

Lower resolution scans (4.4 micron voxels) more appropriate for flow modeling, captures multiple REVs* (~5mm).

* Representative Elementary Volume - basically the amount needed for continuum assumptions about flow to be valid



Stratigraphy : Adding Lateral Variability

Current TOUGH2 flow model largely 1D (+ dip). However, more complicated boundary conditions + 3D structure eventually required.

Initial analysis targeting reservoir and seal continuity across 3 mile range

Currently examining 6 well E/W fence

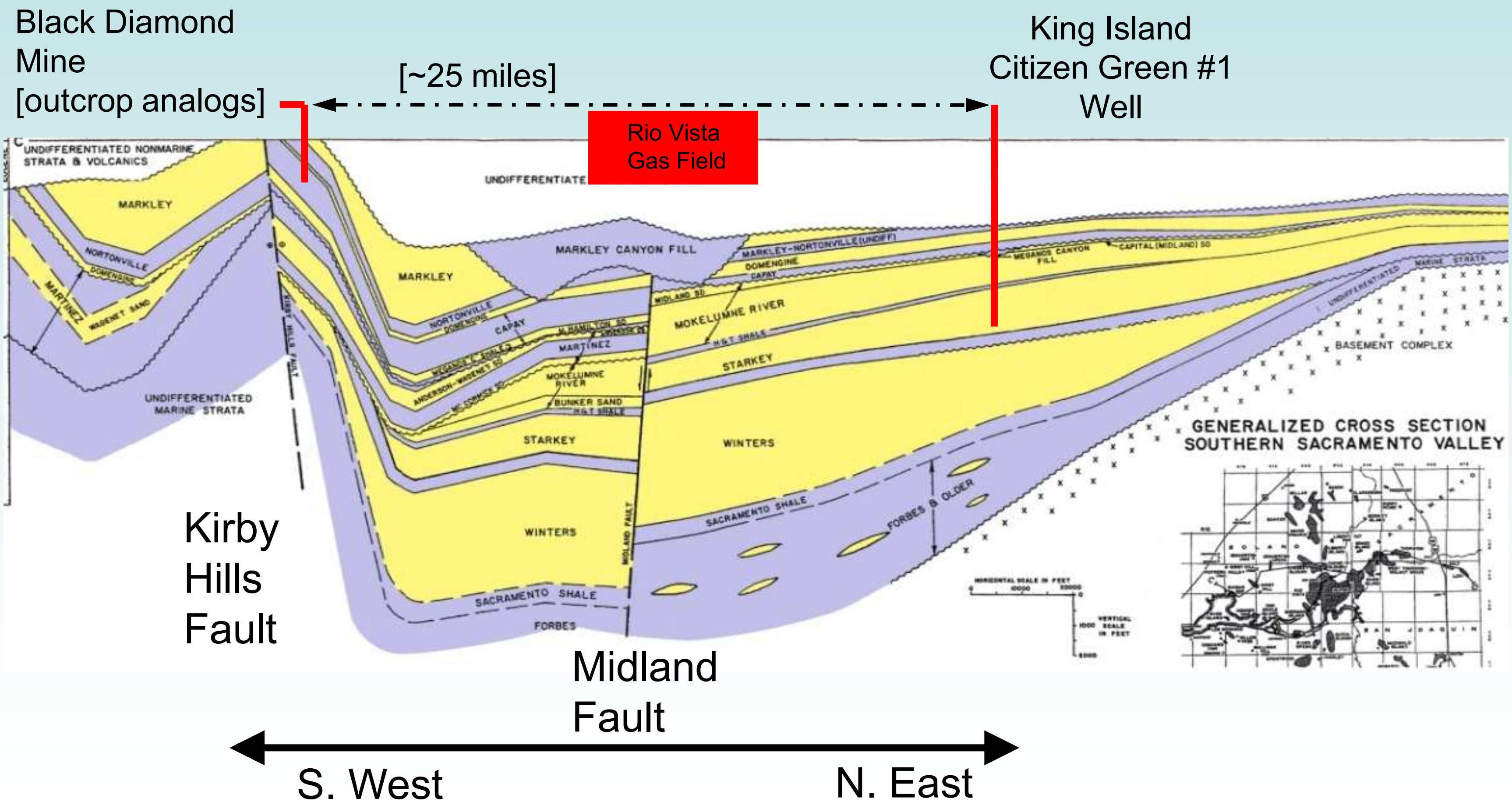
Working on obtaining access to 3D seismic for horizon integration

Tie profiles to regional control well [Empire Tract #1]

Characterized by Cherven (1983) and others

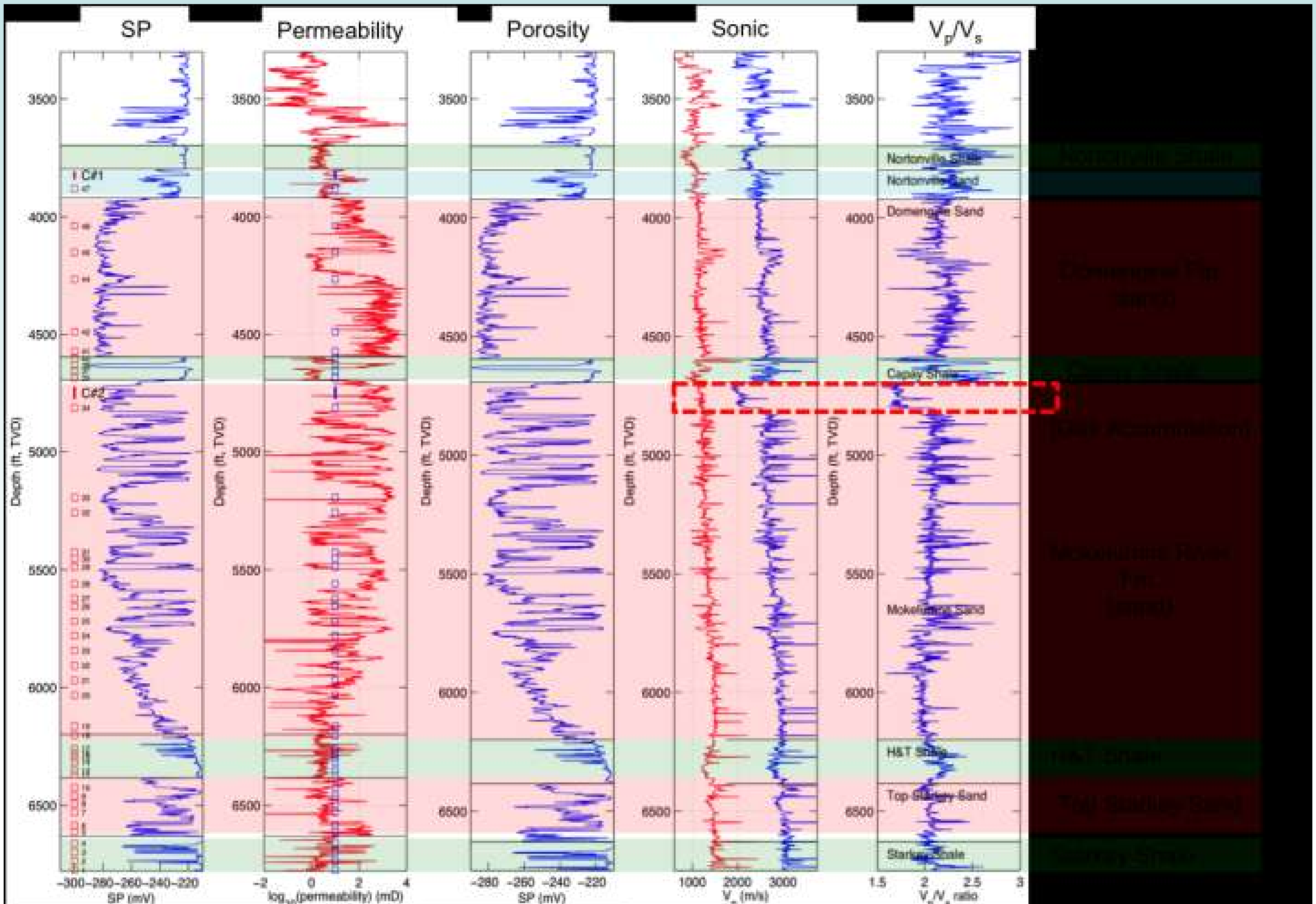
Regional Context : Southern Sacramento Basin

Test sedimentary column at King Island for GCS suitability
Assemble dataset for modeling $scCO_2$ flow, transport, & reaction in S. Sac. Basin

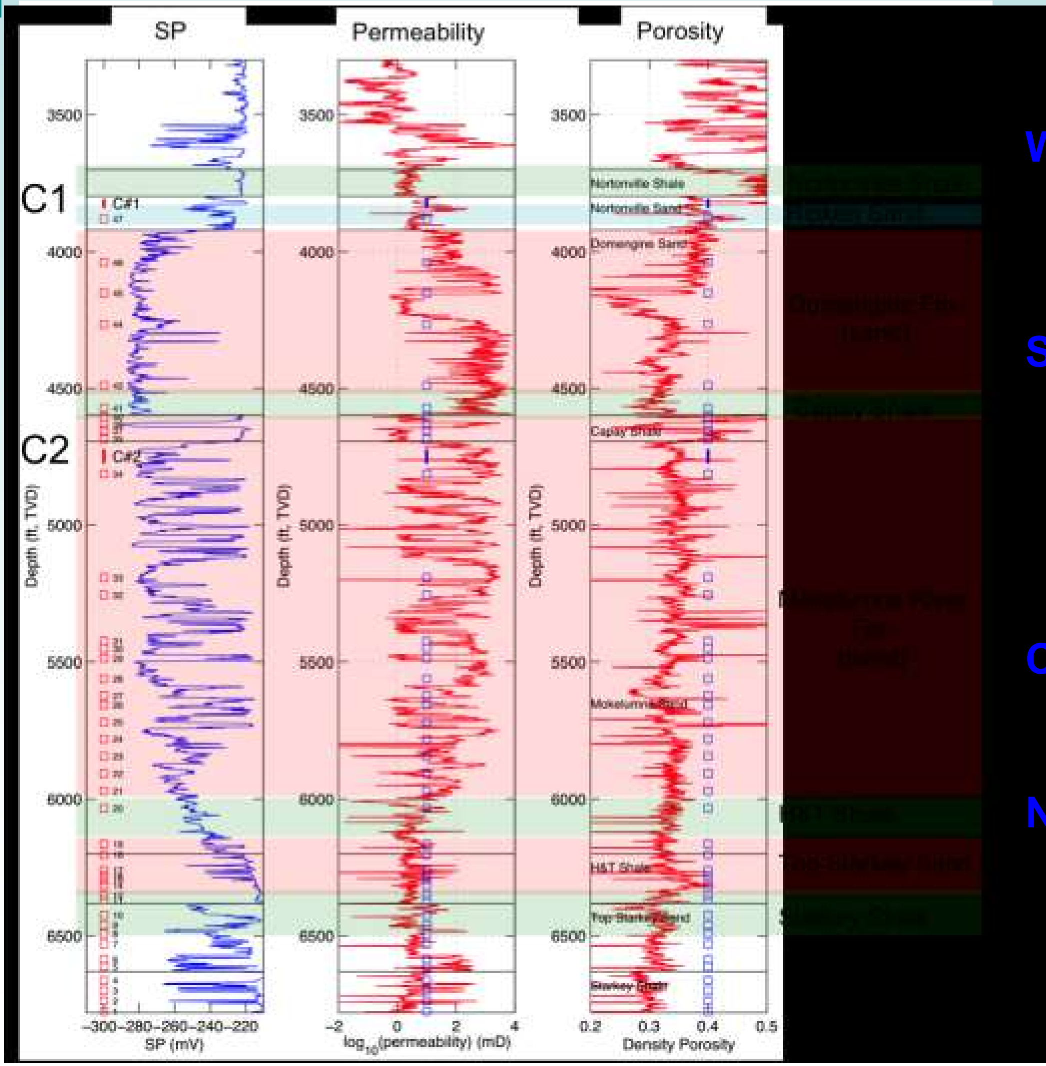


Citizen Green #1 Log Analysis

1. Acquired full logging suite (PEX, CMR, ECS, FMI, Sonic)
2. Gas column observed in the upper Mokelumne River Fm.
3. Several high quality reservoirs and seals identified.



Citizen Green Core Analysis



Whole Core :

1 : 20 ft, Nortonville/Ripken

2 : 50 ft, Upper Mokelumne River

Sidewall Samples :

7 acquired

wer 22 consolidated

rom lower Mokelumne River, H&T,

tarkey]

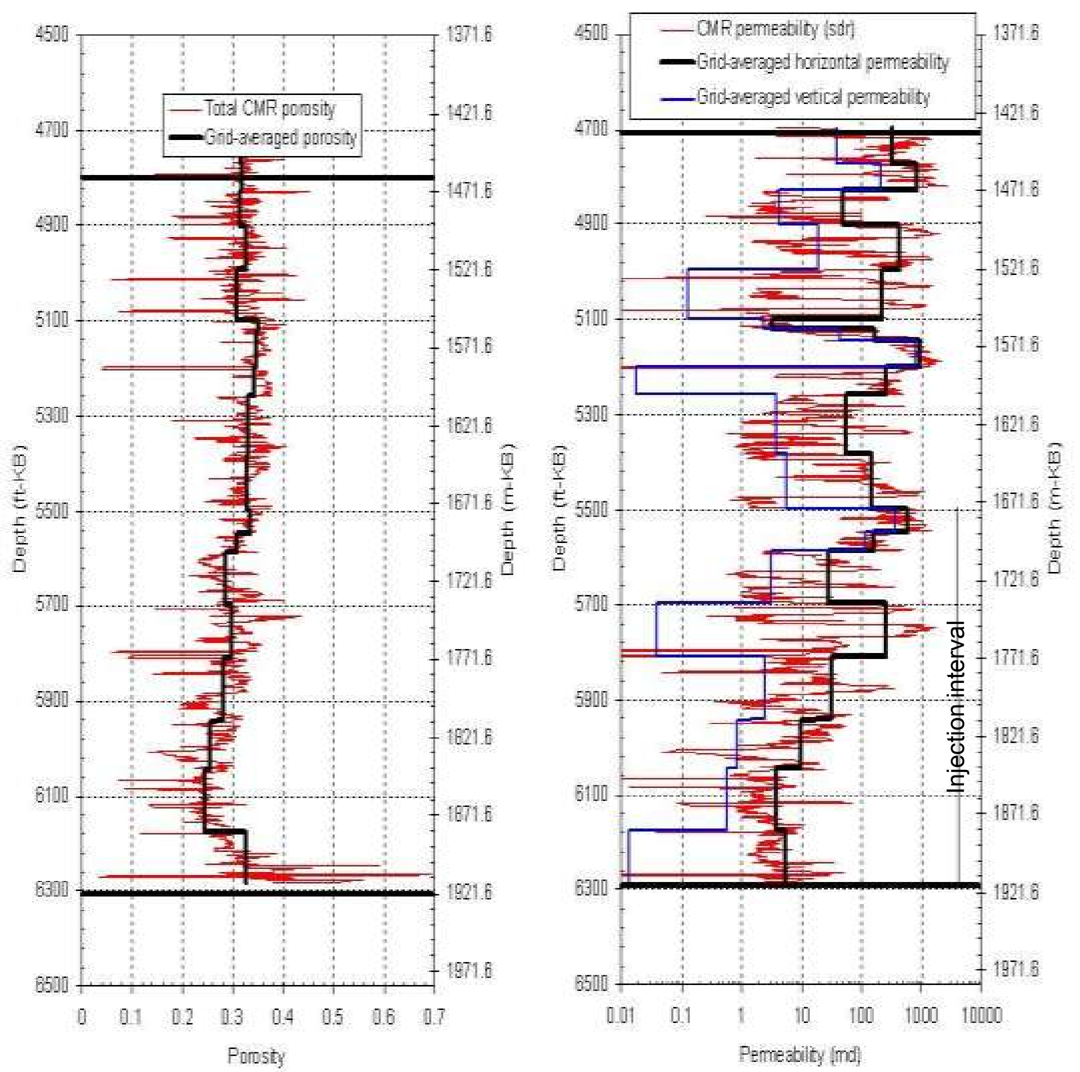
Cuttings :

agged every 30 ft

No Fluids :

ampling efforts in region planned

Blocked Flow Model for Mokelumne River Fm.



[w. Chris Doughty]

1. Modeling focus on Mokelumne River Fm.

2. Initial flow model developed before sidewall core measurements

3. CMR log blocked into 19 layers

4. Horizontal/vertical perms estimated using averaging

[continued in flow modeling talk]

Sidewall Evaluation of Lower Mokelumne River & Top Starkey Sand

Sample Number	Depth (ft)	Sample Length (in)	Perm (K_{air}) (mD)	Perm (K_{brine}) (mD)	Porosity (%)	Grain Density (g/cc)

Lower Mokelumne River

H&T Shale

Top Starkey Sand

Starkey

1. Lower Mokelumne River Sands confirmed as permeable (100 mD+)

2. Top Starkey also confirmed (100 mD+)

3. Both formations have high porosity (30%+)

4. Brine perm measurements marginal due to swelling + fines migration

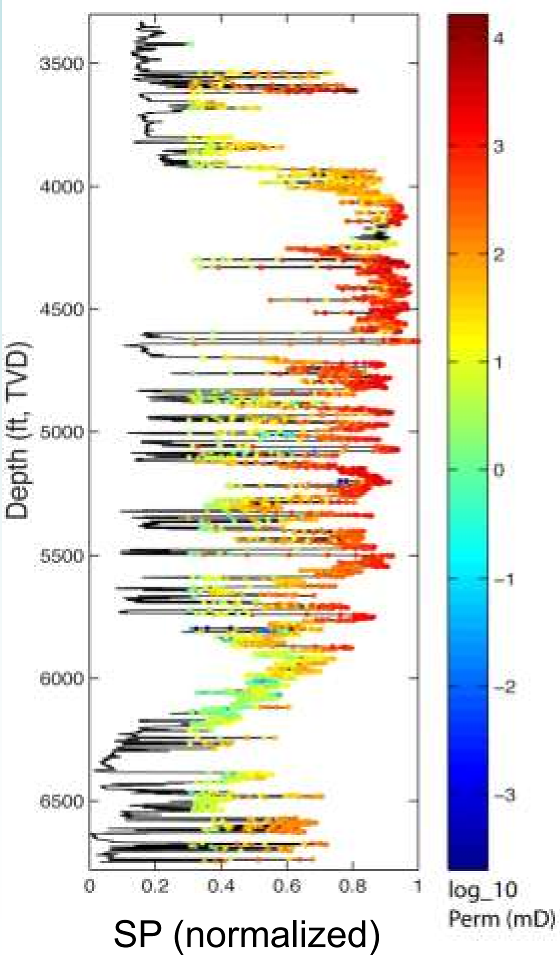
5. Samples currently at LBNL, being sub-sampled for secondary measurements (MICP, BET, microCT, SEM, XRD).

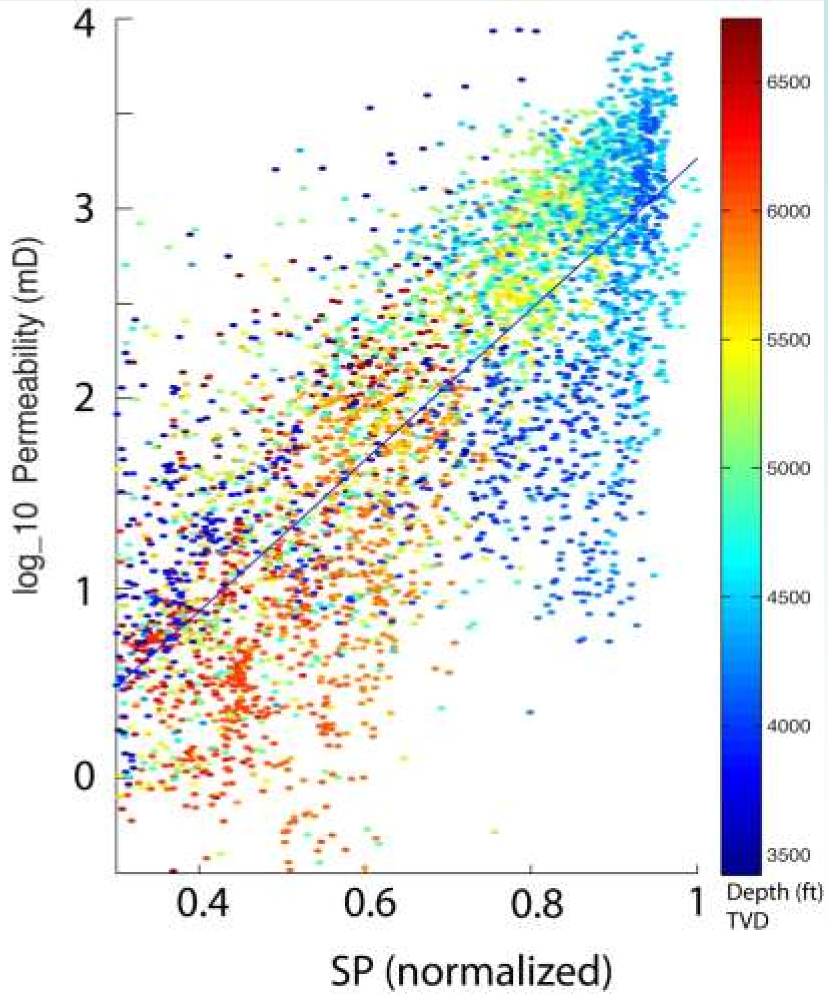
Broader Site Permeability Model

Current Effort : Extend permeability CG#1 information into broader model

Approach : Use SP/perm calibration + available logs & seismic horizons to extrapolate

Utility : Good correlation for sands, perm seems controlled by clay content



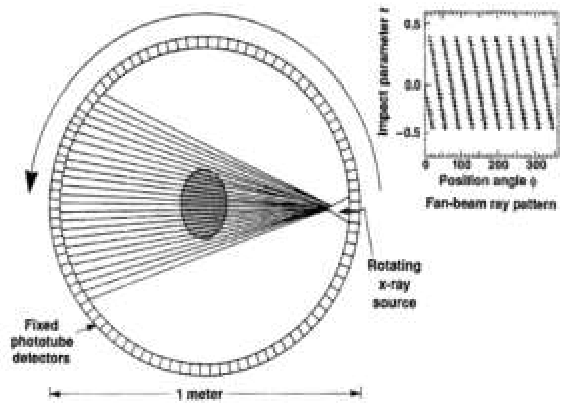


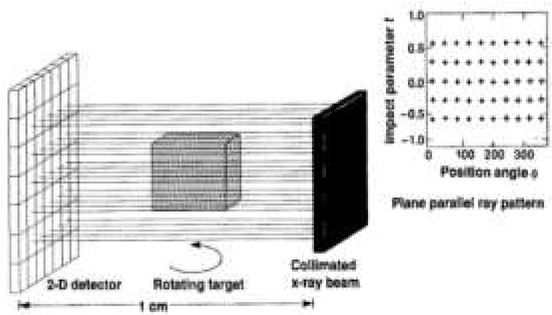
Aside : What Is X-Ray CT?

X-Ray Computed Tomography (CT)

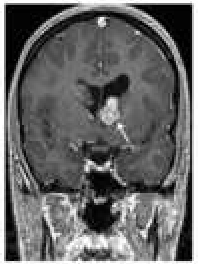
Build 3D images of x-ray absorption through a sequence of projections

[note : maps to density]





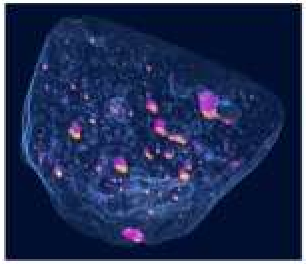
Flannery et.al. 1987



Biggest user : medicine

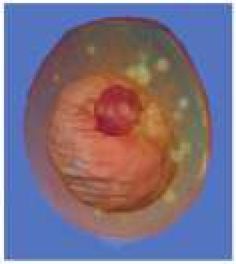
Now fully co-opted by geo/bioscientists!

[note : micro -> resolution on micron L]



Vesicles in a meterorite

Carlson 2006

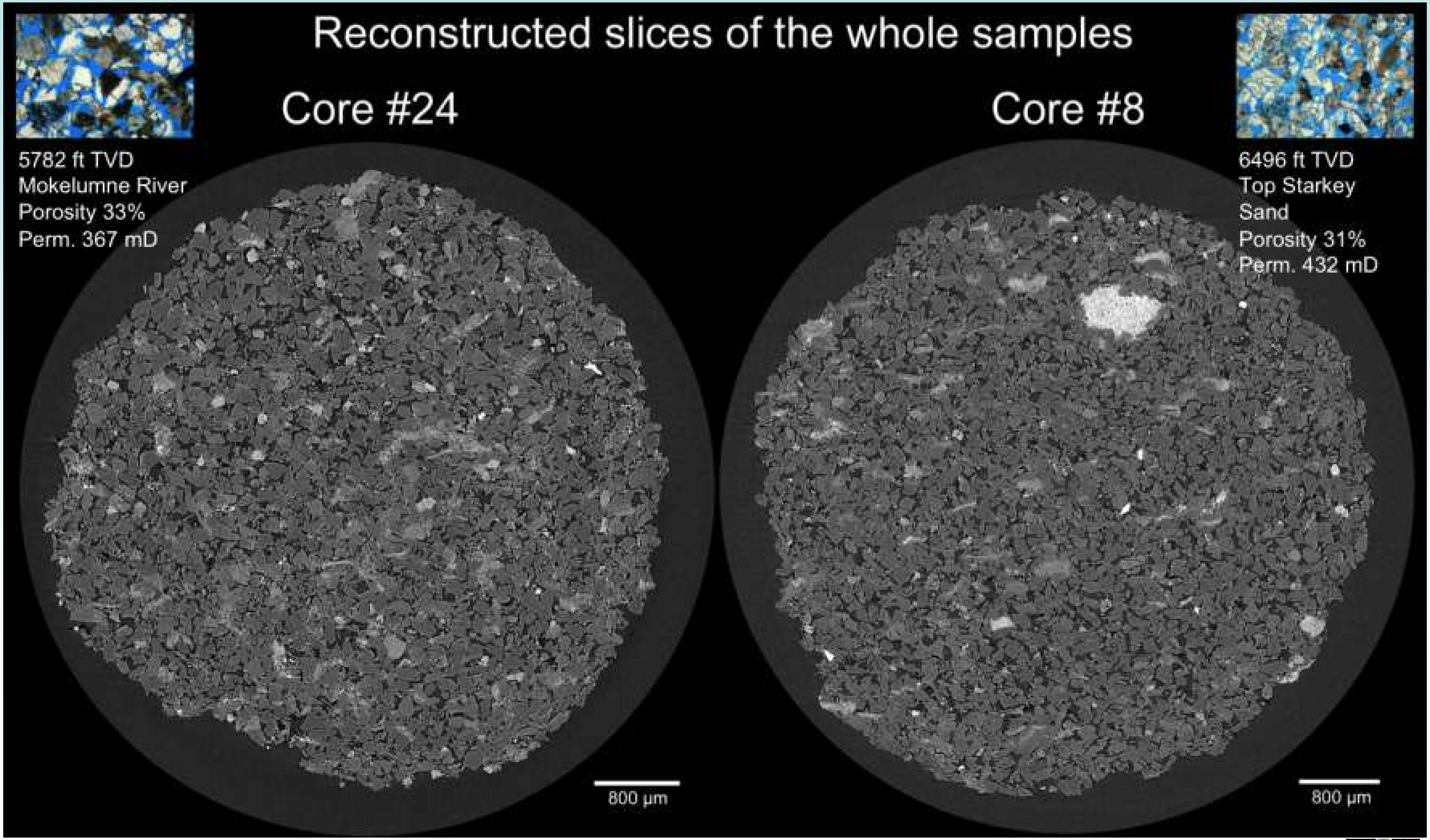


A single yeast cell

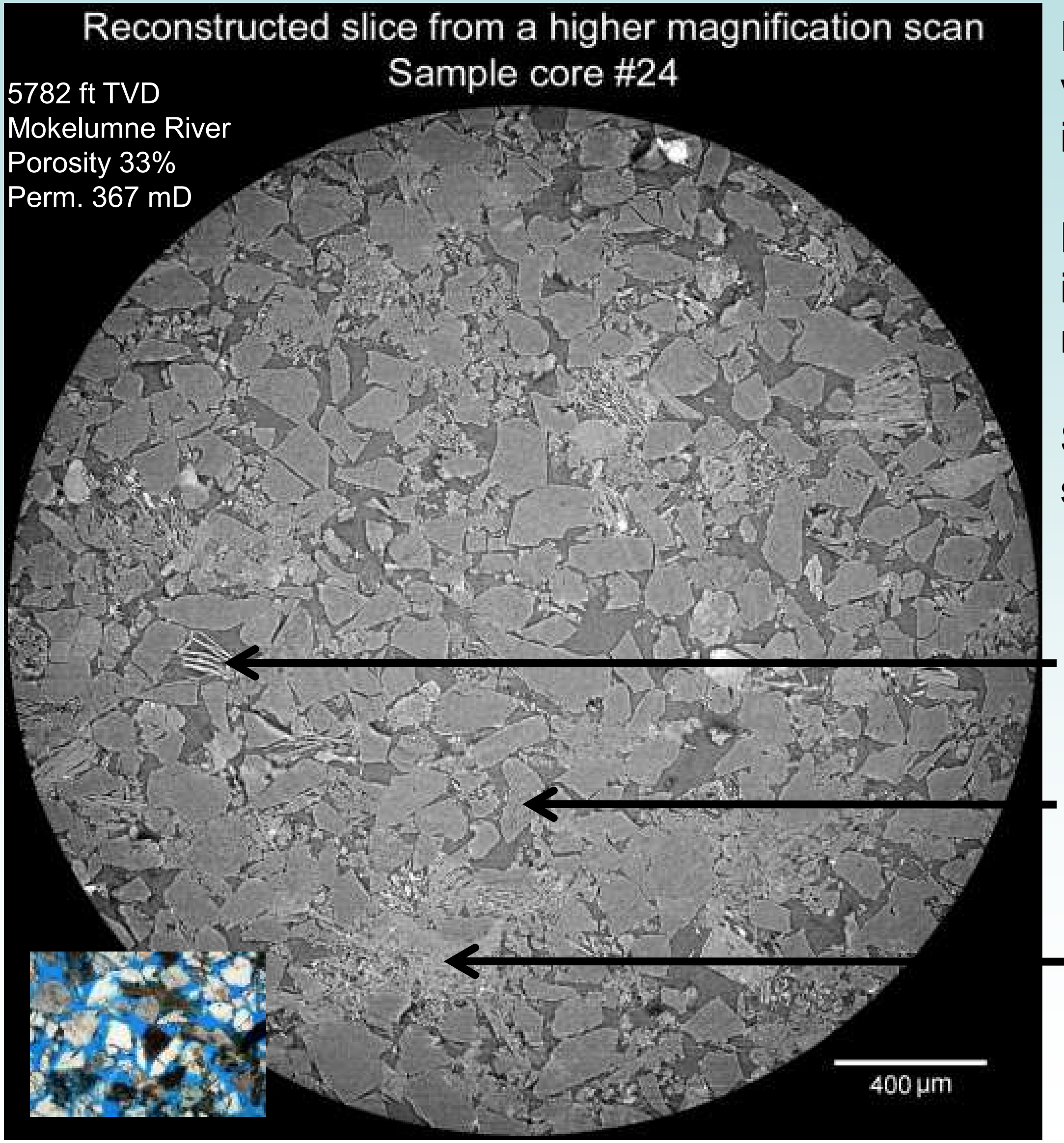
Atwood 2006

Preliminary Micro-CT Images : Moke & Starkey

Initial scans completed of Mokelumne River samples (upper & lower) as well as Top Starkey sand.



High-Resolution Scan : Mokelumne River #24



High-resolution scans (770 nm voxels) are akin to 3D thin-section imagery.

Detailed structure information but insufficient field-of-view for modeling multi-phase flow.

Scan to left from sidewall sub-section, 5782 ft TVD

Next Steps for MicroCT Characterization

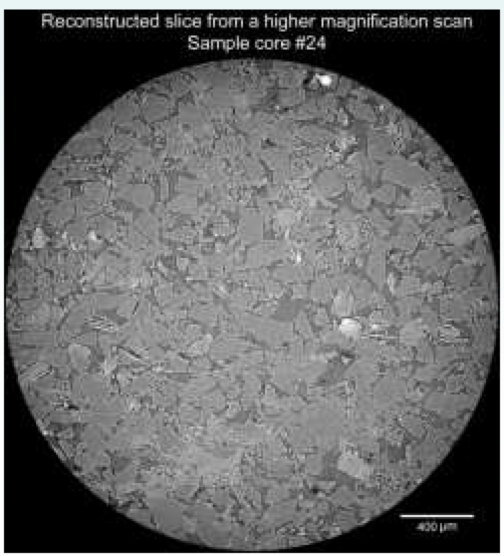
1. Complete scans (plan to scan 7 sidewall samples) – initial imagery promising

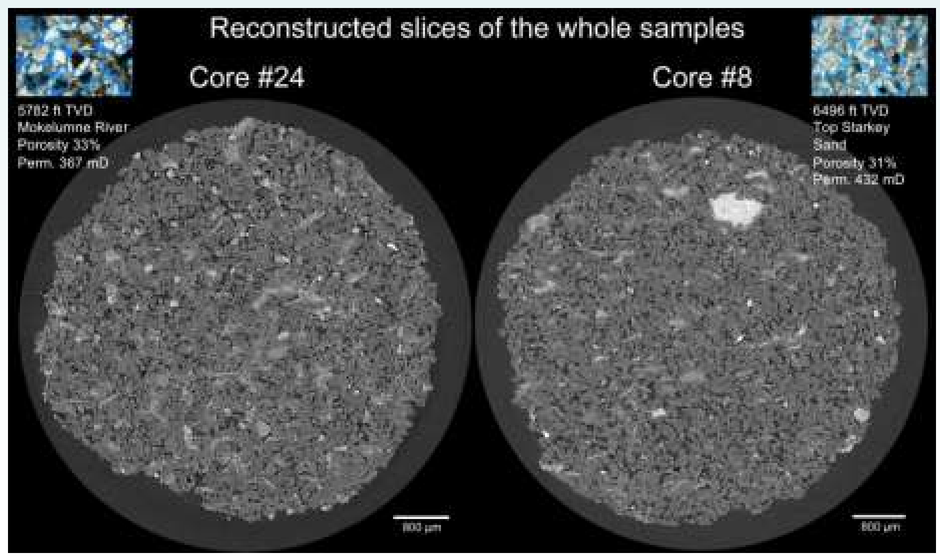
2. Perform segmentation and morphometric analysis (obtains sorting values)

3. Validate single-phase properties using Stokes solver (compare to sidewall val)

4. Predict multiphase flow properties using Maximum-Inscribed-Spheres (MIS) method (Silin et.al. 2010). Use results in TOUGH2 model.

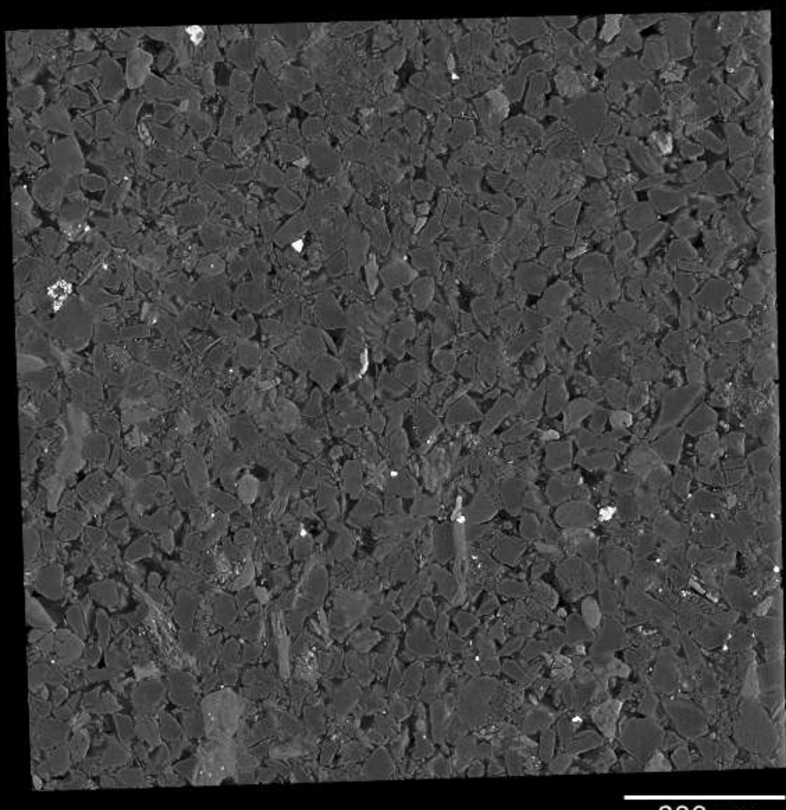
5. Predict effective diffusivity properties. Use in ToughREACT model.



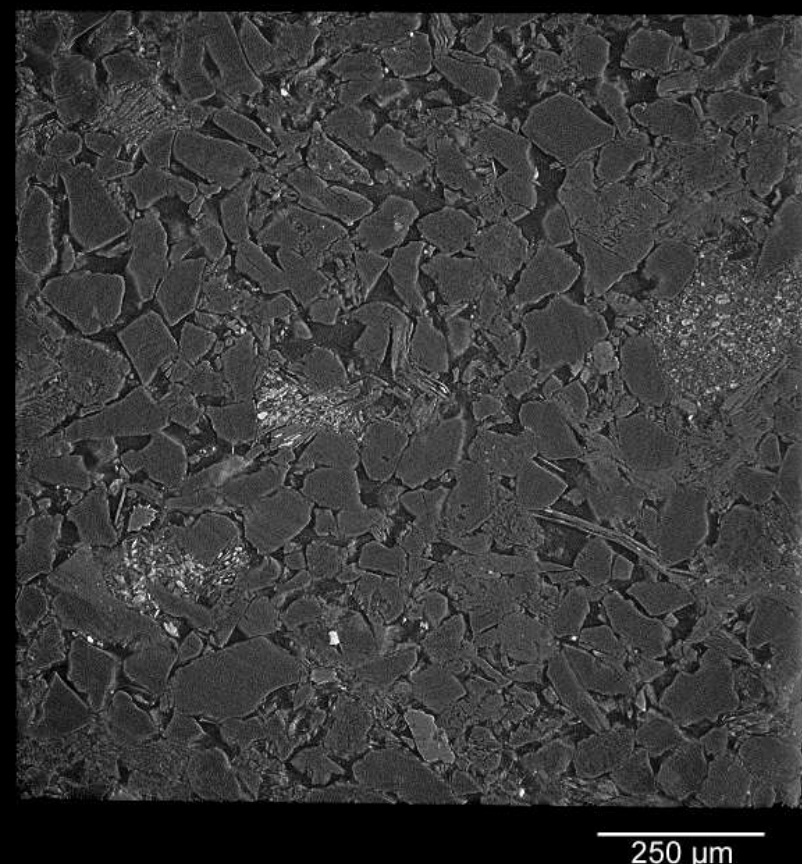


Preliminary Micro-CT Images : Moke & Starkey

Thin slab virtually cut from the core #24 sample showing the pore structure and the different mineral phases highlighted by their different XR absorption (grayvalues)

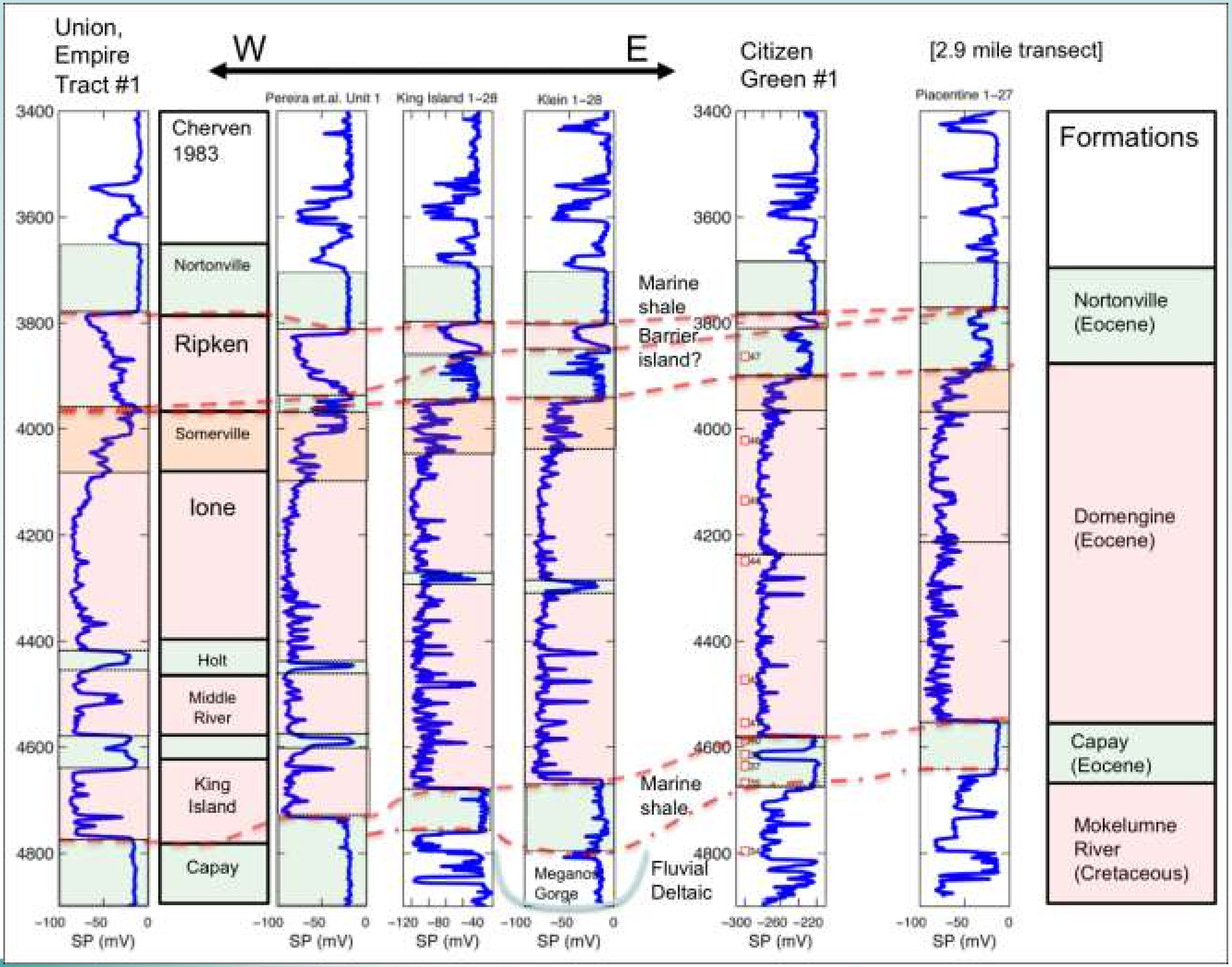


Thin slab from the higher mag setup, same sample (#24) While the FOV is smaller this setup permits to obtain important details e.g. on the clays microstructures.



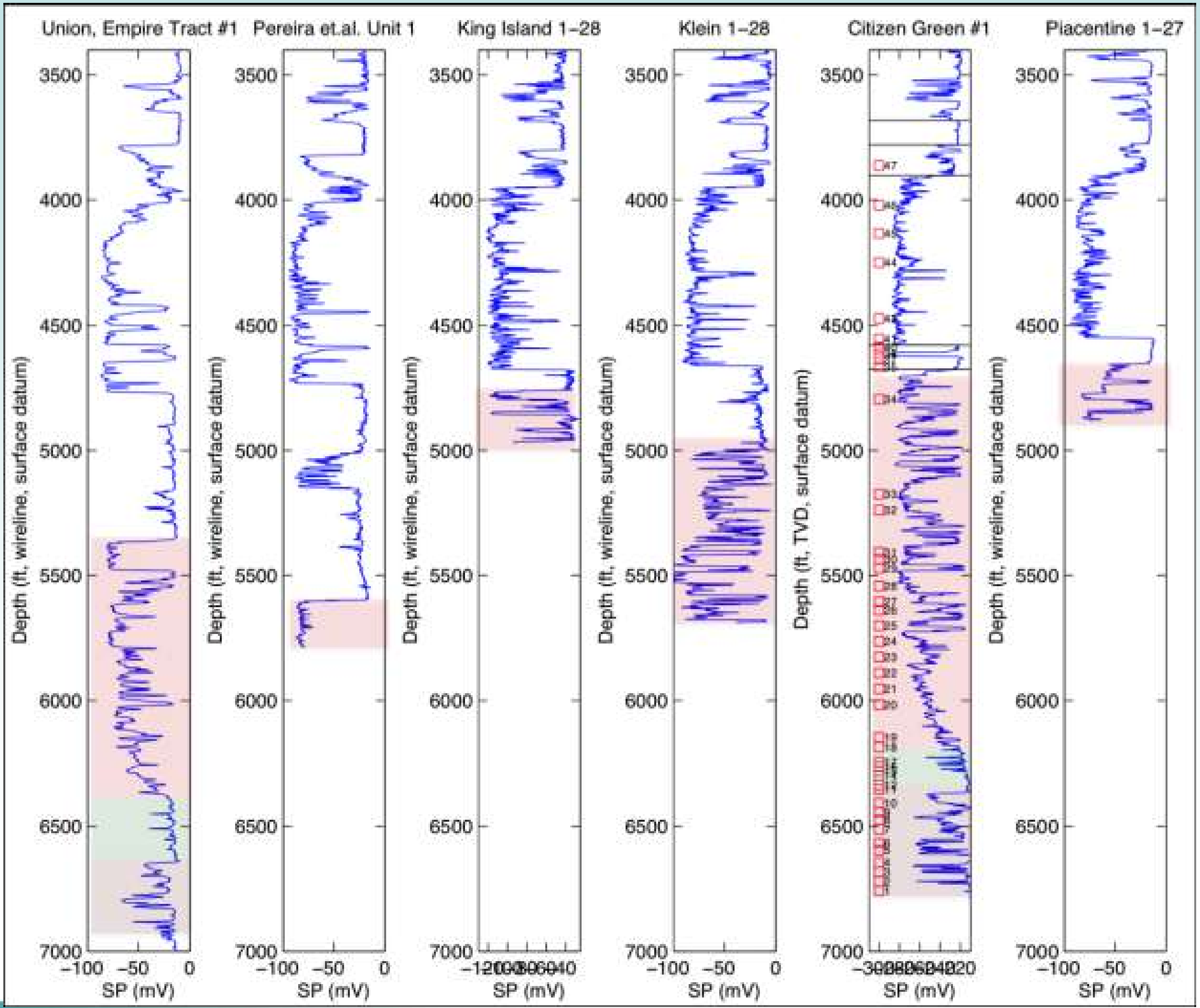
Nortonville & Domengine

Thick sands in the Domengine (Ione member) has good lateral continuity.
W/E trend towards massive sand (fewer shale stringers)
Nortonville (seal) has excellent continuity, top sands (Ripken) vary W/E



Mokelumne River & Starkey

Mokelumne River Fm highly variable, several sections missing due to Meganos Gorge.
CG#1's top Moke penetration is on a pinnacle, complicated boundary conditions.
Lower sands above/below H&T appear to be more continuous but reduced well control



Mokelumne River Fm

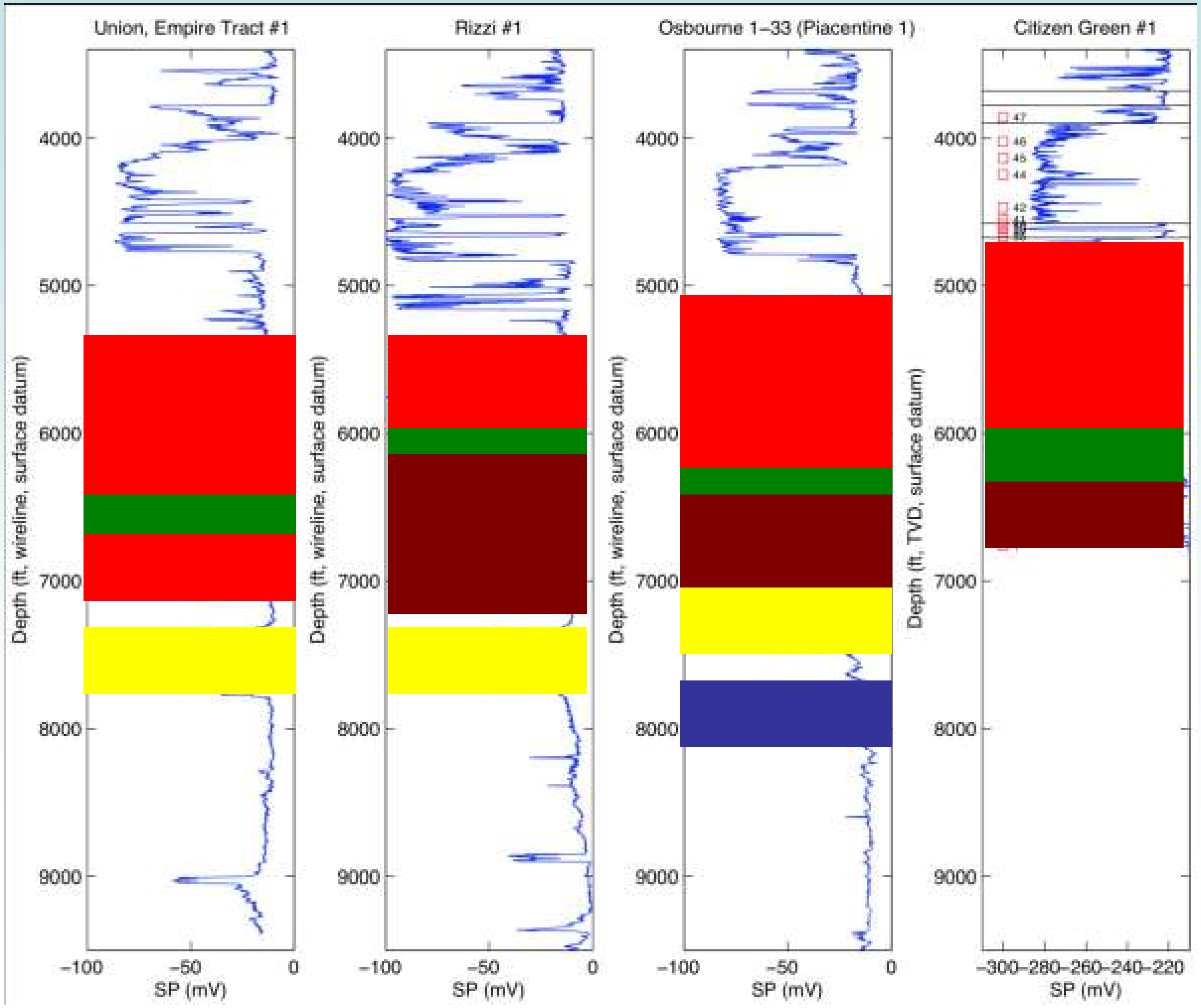
H&T Shale

Starkey

Lower Formations (Starkey/Peterson/Winters)

CG#1 terminates in top Starkey – thin sands

Poor well control for deeper horizons, but casting a wider net suggests that the Peterson Sand would be an excellent deep target.



Mokelumne River Fm

H&T Shale

Top Starkey

Peterson Sand

Winters

[Note : wells off profile]

Next Steps in Model Construction

Just Finished :

Digitized 23 local DOGGR wells to LAS for integration into 3D geomodel.

Plan :

Obtain 3D seismic horizons for integration into 3D geomodel.

Use SP/perm correlations from CG#1 to populate permeability

Integrate with core, microCT, & geochemistry to add multiphase & reactions

As dataset generated, newest components passed to modeling team to allow generation of “best estimate” throughout the development process.