GEOMECHANICAL PROPERTIES OF MESOZOIC RIFT BASINS: APPLICATIONS FOR GEOSEQUESTRATION

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U.S. Department of Energy

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Carbon Storage R&D Project Review Meeting
Transforming Technology through Integration and Collaboration

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Presentation Outline

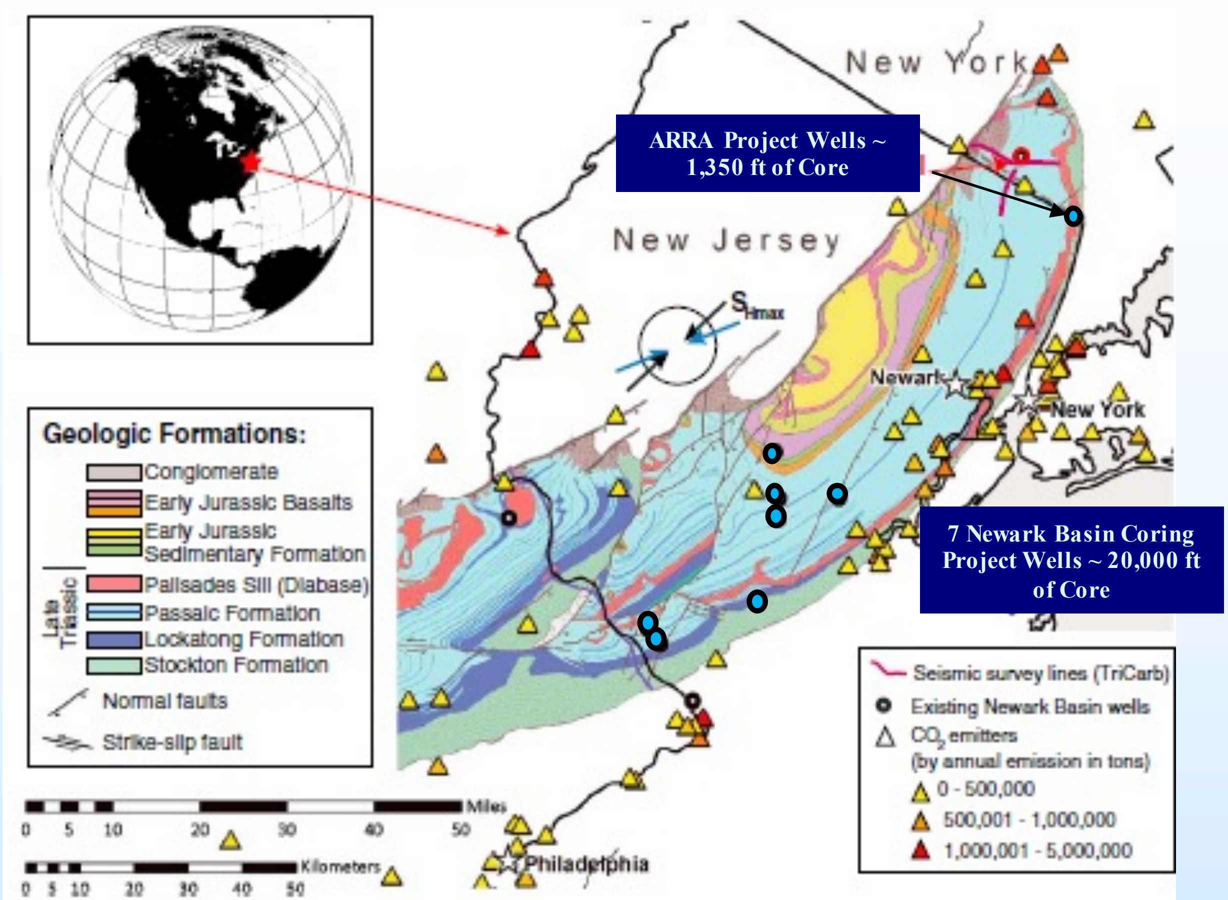
- Benefit to the Program
- Project Background
- Project Overview
- Technical Status
- Accomplishments to Date
- Synergy Opportunities
- Summary

- Appendix

Benefit to the Program

- One of the goals of the DOE Carbon Storage program includes reducing the risks associated with injection processes at potential carbon storage sites.
- A major risk associated with carbon storage comes from the possibility of reactivating preexisting faults and fractures due to injection induced a pore pressure increases in the reservoir.
- Understanding the induced seismic and leakage risks associated with a geological carbon storage site will substantially increase the security of injected fluids stored at that location and reduce the uncertainty, risk, and potential damages due to the injection process.
- The results of this “case” study may be widely applied to potential field-scale geological storage projects in the future.

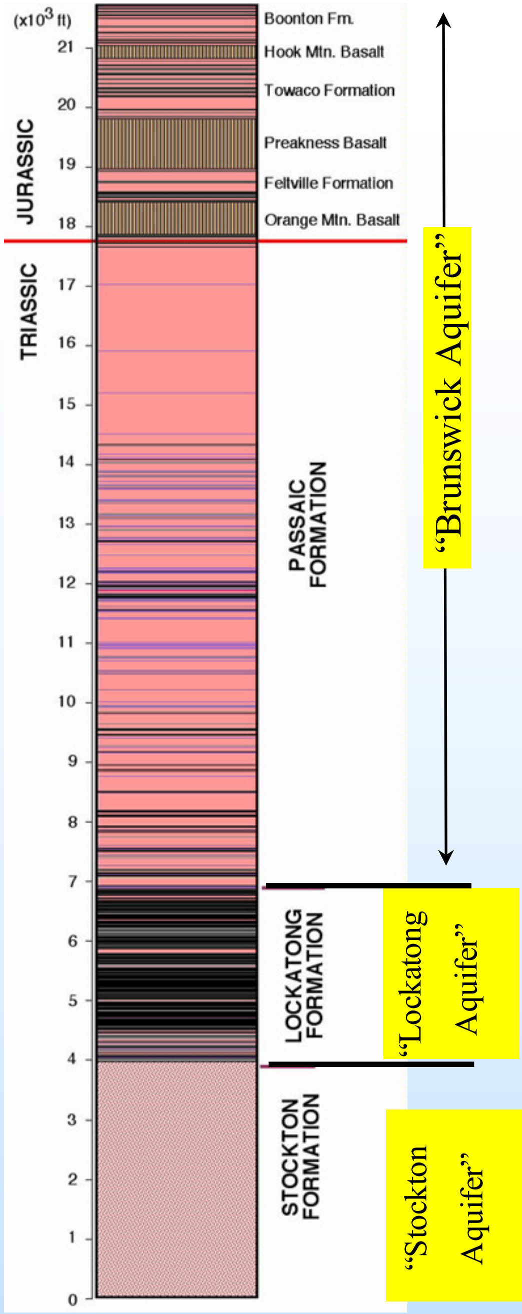
Physiogeographic Setting of the Newark Basin & Sources of Whole Core



Goldberg et al. [2003].

- Newark Basin stretches from Rockland County, New York, southwest across northern New Jersey, and into southeastern Pennsylvania (140 miles long by 32 miles wide)
- Geographic extent ~ 2,700 square miles
- The Newark Basin is in close proximity to large population areas and a heavily industrialized section of the country (28 MM tons/year CO_2 in closest NY/NJ counties)
- 1990s 7 Newark Basin Coring Project wells Central New Jersey ~3,500 ft deep – More than 20,000 feet of core
- ARRA Project drilled a Deep Borehole in 2011 with 150 feet of core and a Shallow Corehole in 2013 with 1,152 feet of core

Newark Basin Stratigraphy



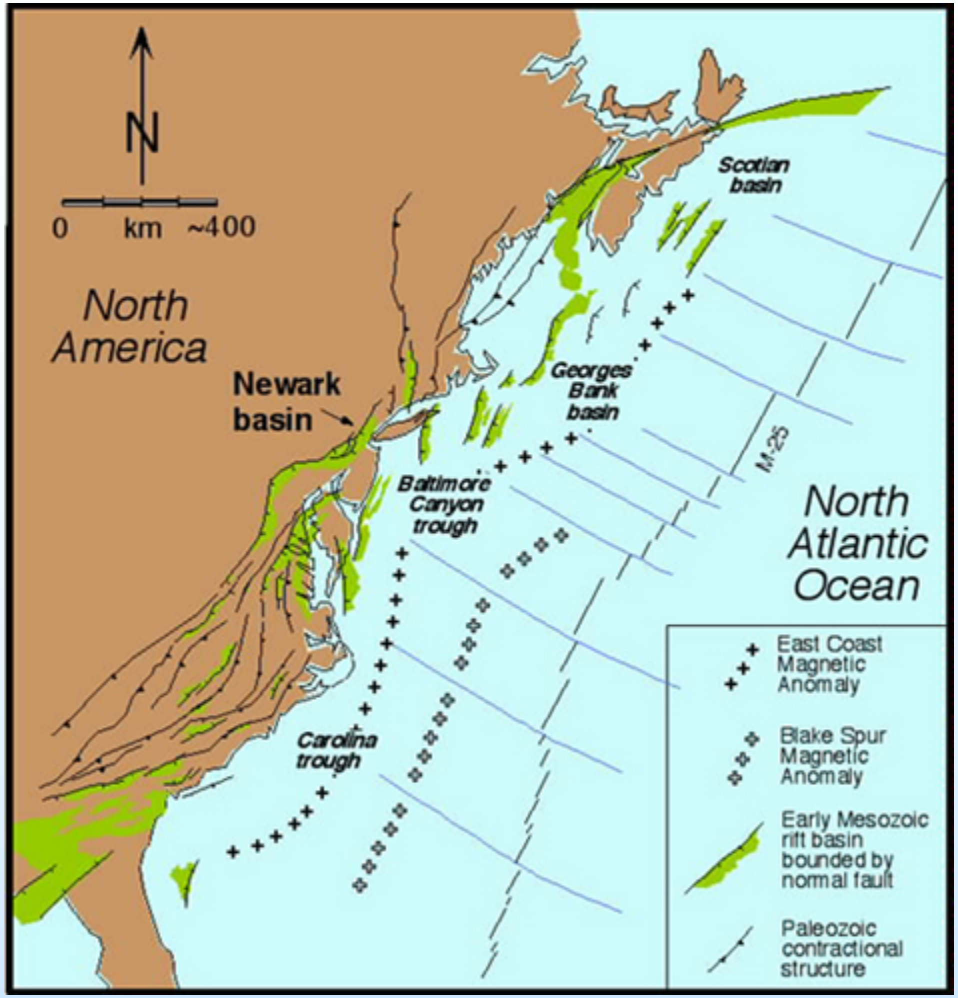
Half-graben clastic infill sequence

Playa lake and mudbank shales of the Passaic Fm provide secondary "seal" cap – up to 10,000 feet thick

Deep lake and shallow mudflat shales of the Lockatong Fm provide primary "seal" cap – up to 3,000 feet thick. Generally includes intrusive diabase "Palisades Sill"

Fluvial-alluvial sandstones and Mudstones of the Stockton Fm – up to 6,000 feet thick (or more along border fault)

One of a Series of Basins along Eastern North America



Withjack et al., 1998

- Includes both "exposed" and "buried" basins of Jurassic-Triassic Age (Newark Basin is exposed) and offshore basins
- Formed by the "breakup" & separation of North/South America from Europe and Africa
- Basins generally set up by a border fault (western)
- Sediment infilled the basin from adjoining areas

Project Overview: Goals and Objectives

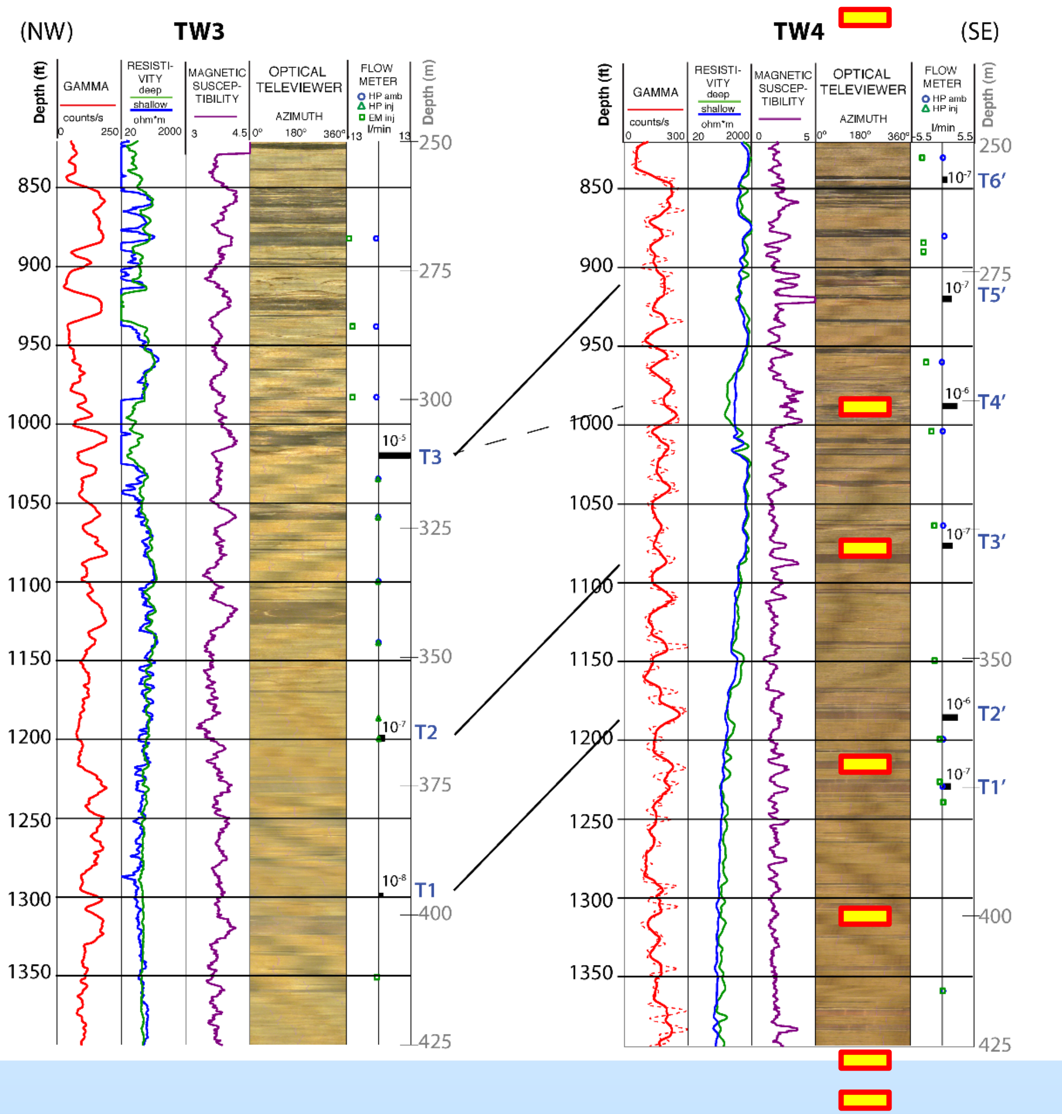
- Primary goal of the project is to detail formation caprock characteristics, stresses, and mechanical properties in Mesozoic Basins using a "case study" in the northern Newark Basin.
  - Preliminary work suggested significant variability in orientations and magnitude of the principal horizontal stress with respect to depth
  - Objective is to measure lab-scale properties (BP I) to field scale mechanical properties and stresses (BPII) using an extensive core library and an existing field test well.
  - Well testing includes innovative configuration of the Schlumberger Modular Dynamics Tester tool for use in consolidated formations of high strength

- Budget Period 1 Success Criteria is defined as successful characterization/geomechanics testing of at least 18 of the 25 core planned samples selected for testing.

Technical Status

- Budget Period 1 work involves leveraging the 1,350 feet of whole core collected in the Lamont Doherty Earth Observatory Test Well No. 4 with the +/-20,000 feet of Newark Basin Coring Project whole core, all maintained at the Rutgers University Repository
- Project Team selected +/- 25 core sections with different lithologies, concentrating on mudstones (confining materials)
- Core Sections were screened via CT Scanning and sample areas were identified for characterization and geomechanical testing.

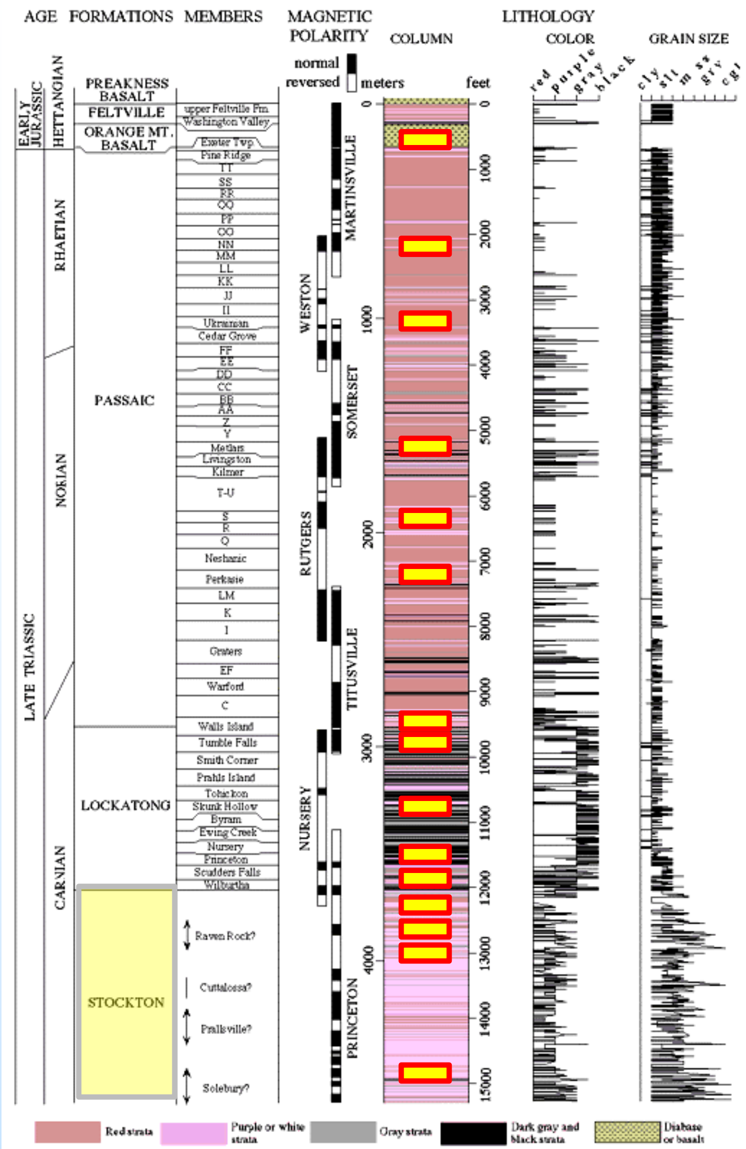
Newark Basin Characterization Project – LDEO Test Well No. 4 Whole Core



- Approximately 1,350 feet of core at Rutgers U. Repository
- Targeted mudstones throughout the stratigraphic section.
- Selected 8 core sections for CT scanning
- CT scans and whole core reviewed at TerraTek Lab in Salt Lake City to pick specific spots for plugging
- Geomechanical testing includes UCS, triaxial, multi-stress/multi-stage (anisotropy), and Brazilian

Geomechanical Sample Points

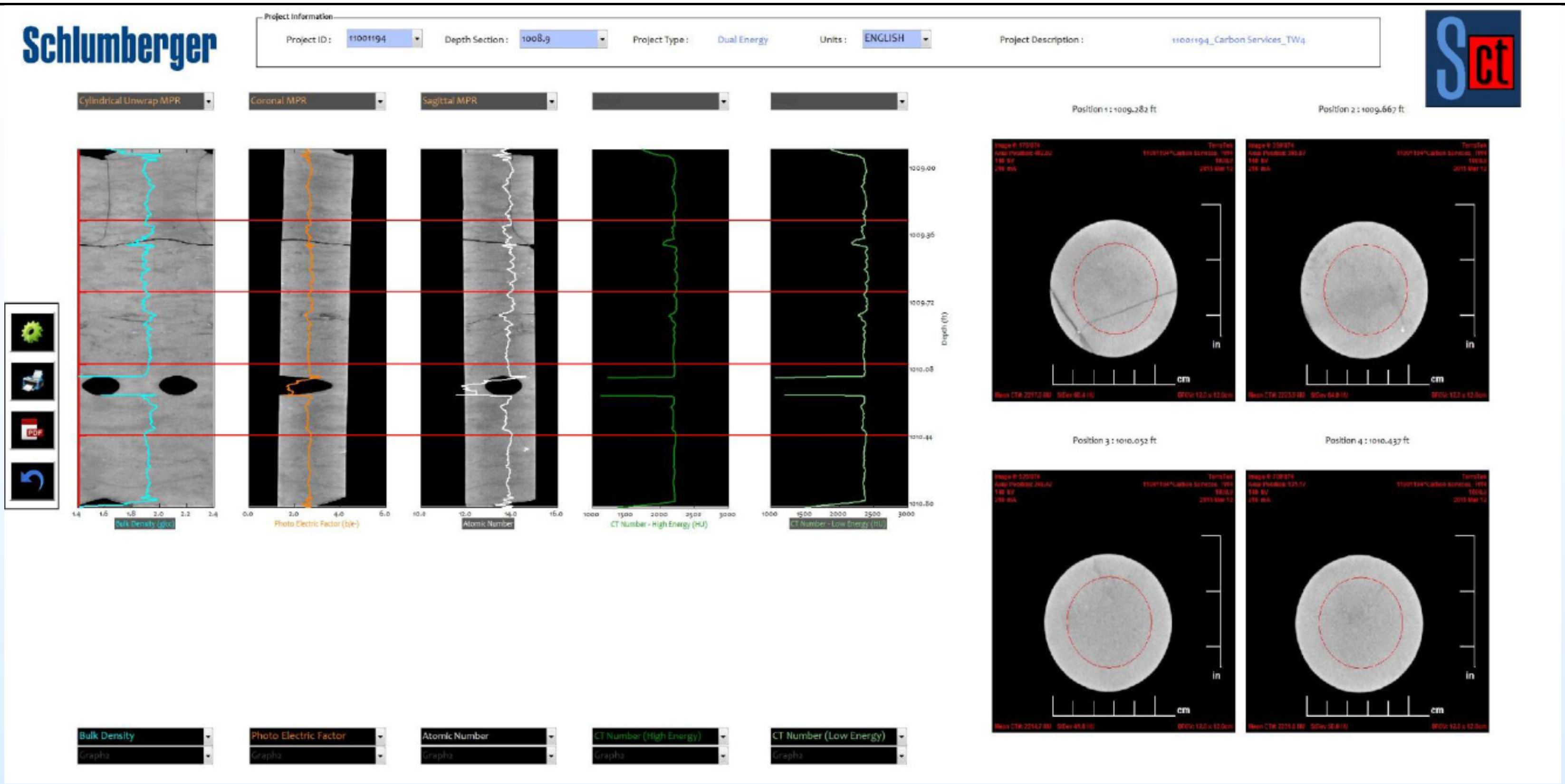
Newark Basin Coring Project – Whole Core



Geomechanical Sample Points

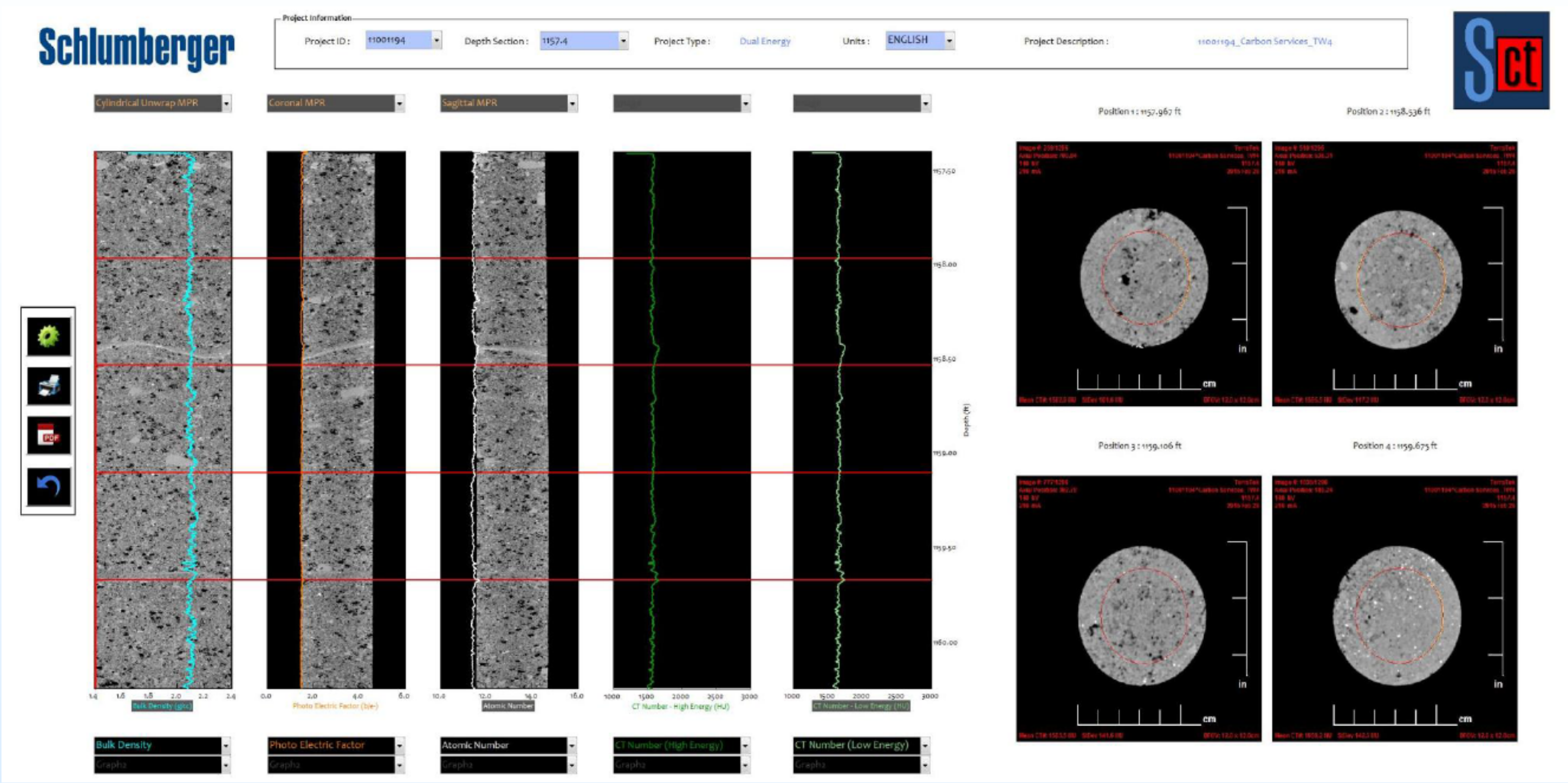
- Approximately 20,000 feet of core at Rutgers U. Repository.
- Targeted mudstones throughout the stratigraphic section with at least one sample per drill site.
- Selected 17 core sections for CT scanning
- CT scans and whole core reviewed at TerraTek Lab in Salt Lake City to pick specific spots for plugging
- Geomechanical testing included triaxial, multi-stress/multi-stage (anisotropy), Brazilian, and mobilized friction angle

CT Scan Example – Mudstone TW-4 Whole Core



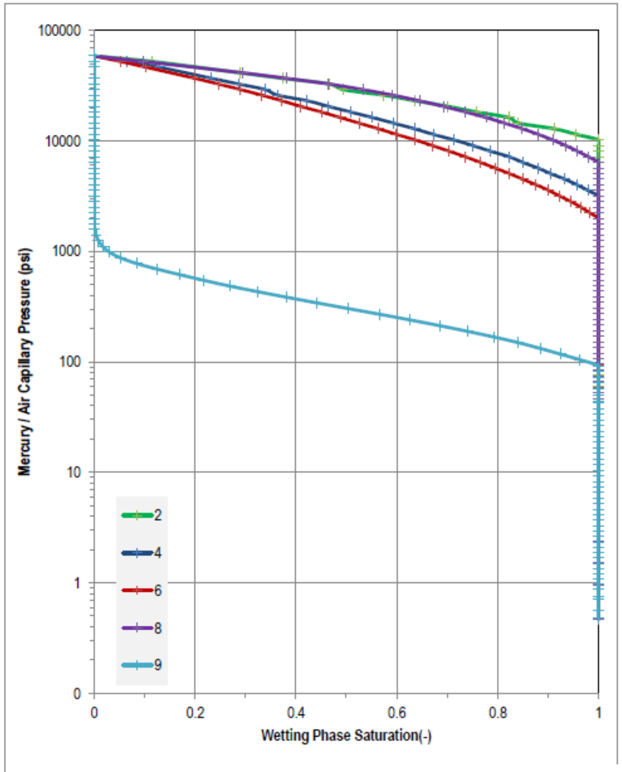
1008.9 to 1010.7 feet – Schlumberger CT Viewer Comprehensive report view highlighting each data track obtained through dual energy CT scanning of depth section –TW-4 Core. Images of the cylindrical unwrap and two longitudinally orthogonal reconstructions are displayed on left. Solid colored tracks of data provide values for atomic number (white), bulk density (light blue), high and low energy CT number (green and light green)and photo-electric factor (orange).Evenly spaced horizontal cross sections are displayed to the right and correspond to the four horizontal red lines dissecting the display..

CT Scan Example – Sandstone TW-4 Whole Core



1163.1 to 1165.0 feet – Schlumberger CT Viewer Comprehensive report view highlighting each data track obtained through dual energy CT scanning of depth section –TW-4 Core. Images of the cylindrical unwrap and two longitudinally orthogonal reconstructions are displayed on left. Solid colored tracks of data provide values for atomic number (white), bulk density (light blue), high and low energy CT number (green and light green)and photo-electric factor (orange).Evenly spaced horizontal cross sections are displayed to the right and correspond to the four horizontal red lines dissecting the display..

Mercury Injection Capillary Pressure Examples

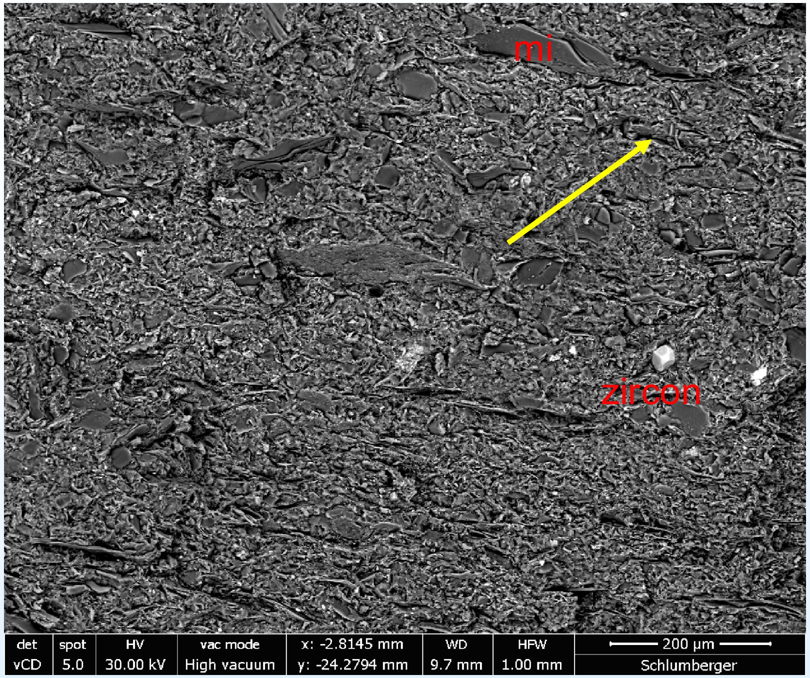


Mudstones in the LDEO Test Well No. 4 core show nanopore sized pore throats ranging in diameter between 1 nanometer to 1 micrometer with permeabilities less than 5.0E-0-8 darcies.

The arkosic sandstone contains both micropores and nanopores with median pore throats approaching 1 micron in diameter. Note that the tested sample is still low permeability (<1.0E-5 darcies).

Sample ID	Depth (ft)	Hg Inj Porosity (fraction)	Median Pore Throat Size (micron)	Pore Throat Types: Nanopores 1 nm<Dia<1 μm (%PV)	Micropores 1μm<Dia<62.5μm (%PV)	Mesopores 62.5μm<Dia<4mm (%PV)	Mercury/Air Entry Pressure (psi)	Air/Brine Entry Pressure (psi)	Swanson Permeability (mD)
2	1010.0	0.003	0.007	100	0.00	0.00	11454	2645	<0.000001
4	1217.0	0.013	0.012	100	0.00	0.00	3562	823	0.00001
6	1415.5	0.022	0.014	100	0.00	0.00	2234	516	0.00005
8	1685.5	0.026	0.007	100	0.00	0.00	7180	1658	0.00002
9	1162.5	0.043	0.706	68.5	31.5	0.00	104	24.1	0.093

SEM & EDX Example - Mudstone



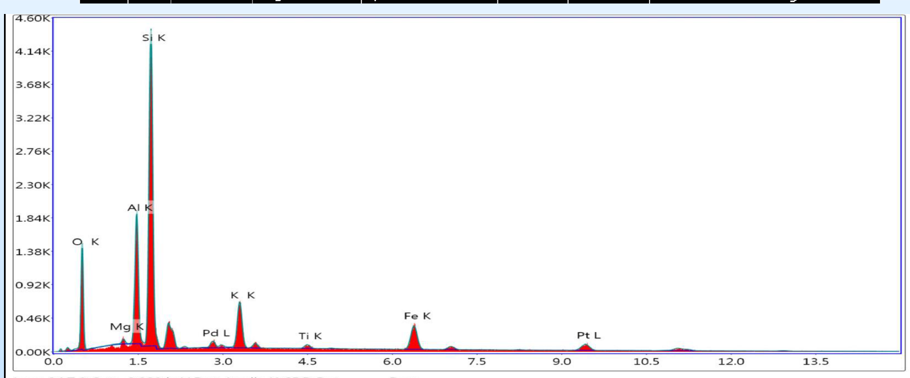
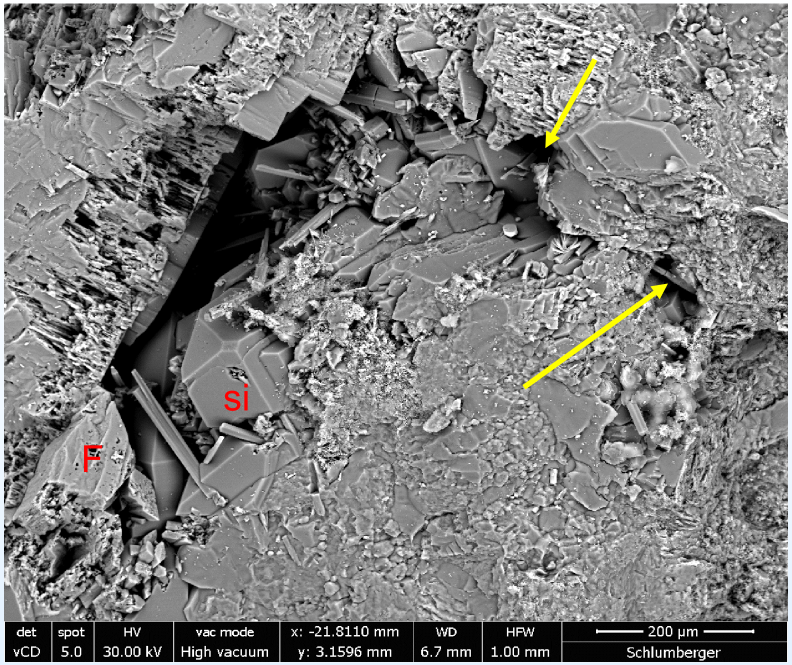


Plate 1. Sample 2 (1010.0 ft) SEM image and EDX spectrum. Clay particles and mica flakes (mi) such as biotite host narrow micropores (arrows).

Image B shows EDX results. Detrital silt, clays, and micas account for most of the major elements (Si, Al, O, K); iron oxides and biotite contribute most of the iron (Fe); and the SEM conductive coat contributes platinum (Pt) and palladium (Pd).

SEM & EDX Example - Sandstone



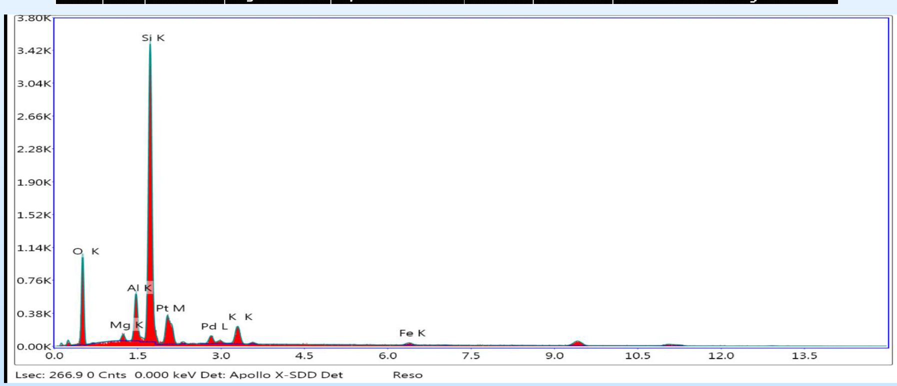
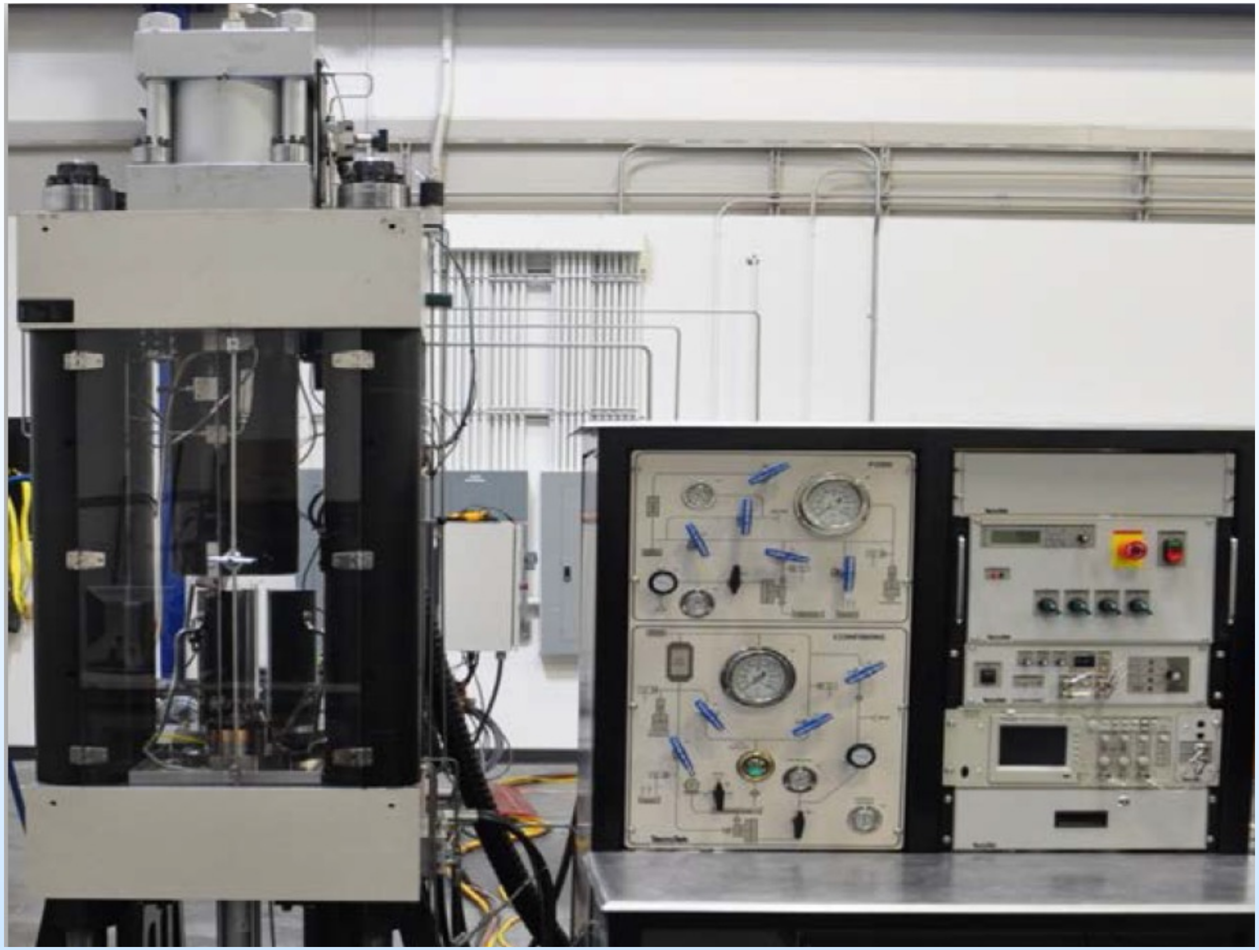


Plate 5. Sample 9 (1162.5 ft) SEM image and EDX spectrum. Authigenic clays and silica cement (si) occur in intergranular and dissolution pores (arrows) that are associated with altered feldspars (F).

Image B shows EDX results. Quartz accounts for most of the silicon (Si); feldspar and clays contribute most of the aluminum (Al) and potassium (K); and platinum (Pt) and palladium (Pd) are from the SEM conductive coat.

TerraTek Triaxial Testing Equipment

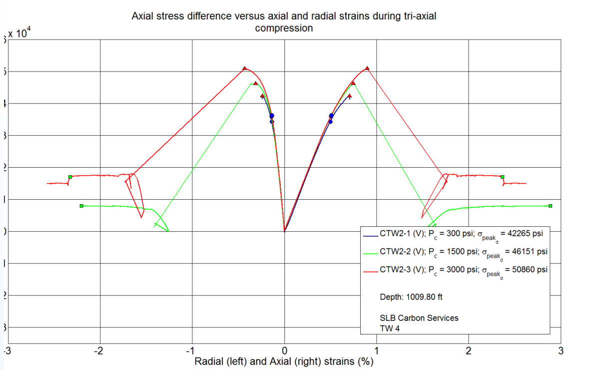


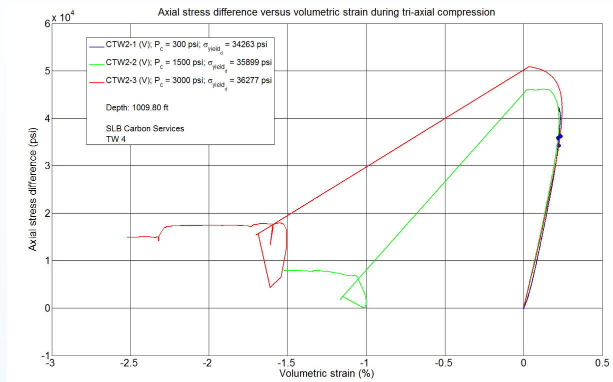
- 20k psi Triaxial Test System – Confining and Pore Pressure
- 230K lbs of axial load
- In-vessel instrumentation for measuring load and axial and radial deformations
- Automated Data Acquisition and Multi-Segment Test Control System.
- Ultra Sonic Velocity Measurements

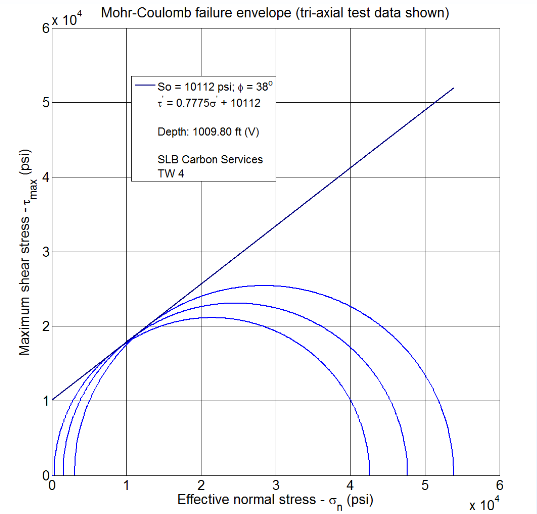
TerraTek Triaxial Testing Equipment (cont)

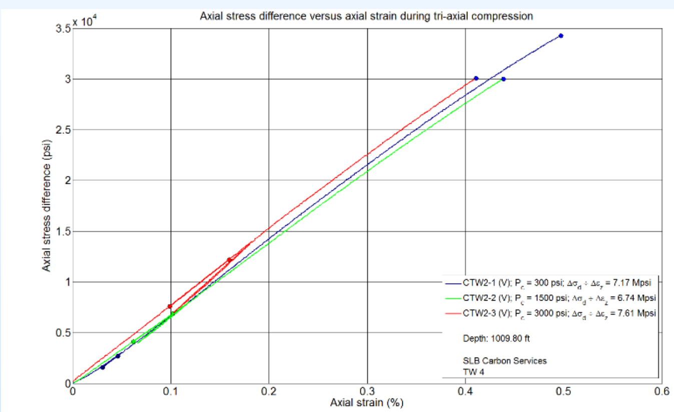
- Bank of 10k psi Triaxial Test Systems – Confining and Pore Pressure
- In-vessel instrumentation for measuring load and axial and radial deformations
- Automated Data Acquisition and Multi-Segment Test Control System.
- Ultra Sonic Velocity Measurements

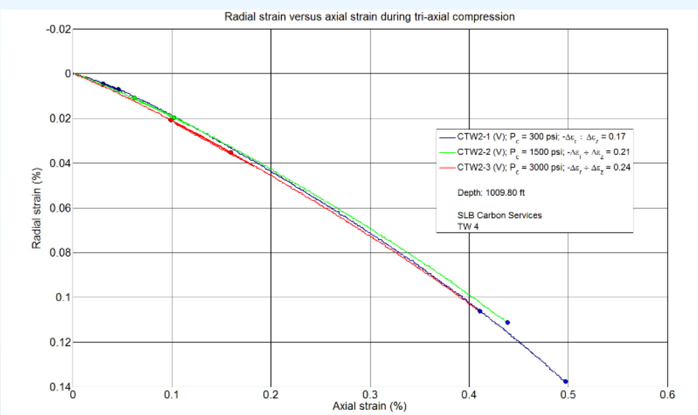
Geomechanics Testing Example 1,009.8 ft – TW-4 Well





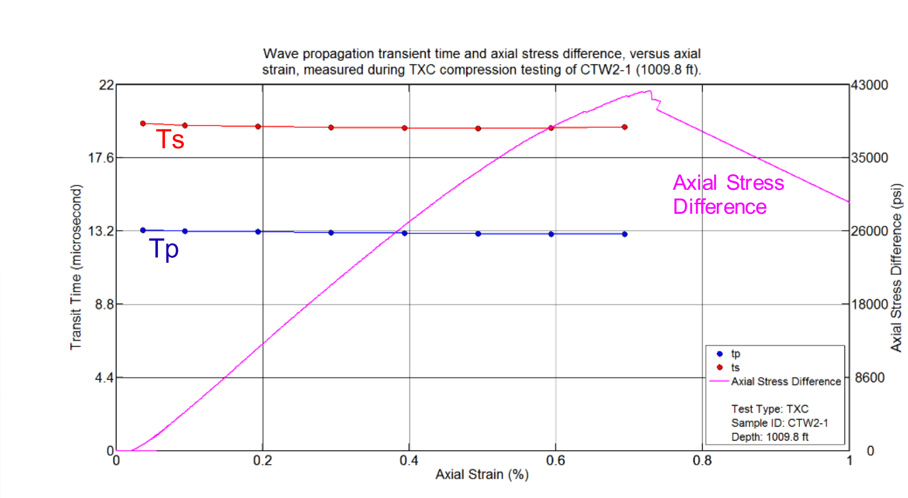


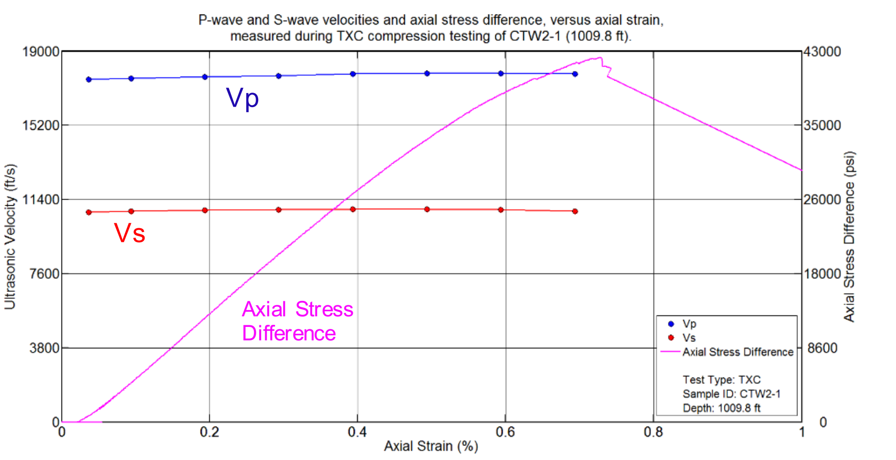


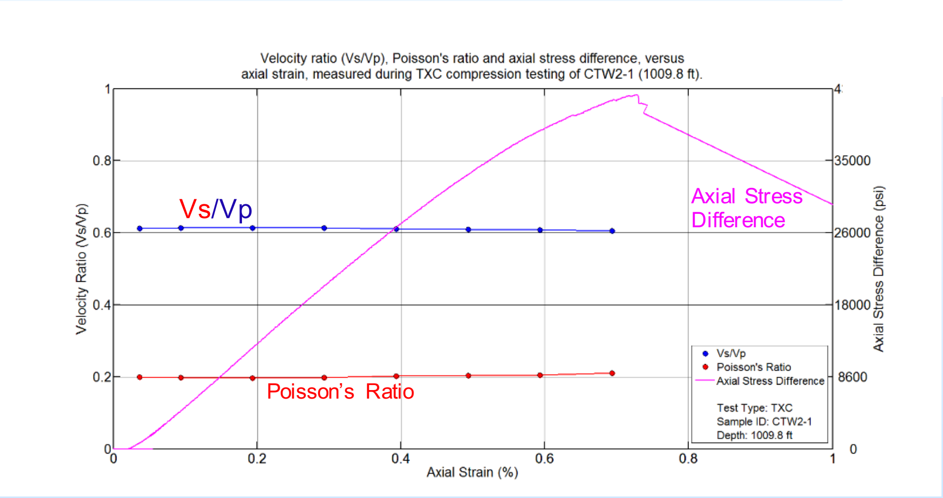


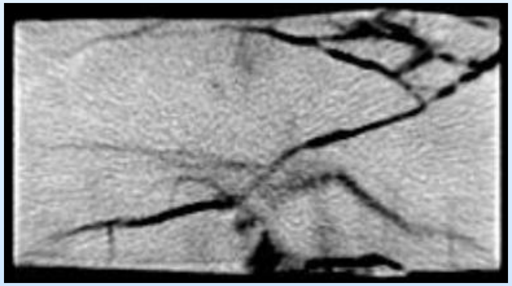
Silt-rich Mudstone

Ultrasonic Example 1,009.8 ft – TW-4 Well









1,009.8 ft Testing Summary

Sample ID	Orientation (deg)	Core Depth (ft)	Bulk Density (g/cc)	Effective Confining Pressure (psi)	Volumetric Yield Strength (psi)	Peak Strength (psi)	Residual Strength (psi)	Initial Young's Modulus (psi)	Initial Poisson's Ratio - 1	Initial Poisson's Ratio - 2
CTW2-1	V	1009.8	2.791	300	34,570	42,575	N/A	7.17E+06	0.17	0.17
CTW2-2	V	1009.8	2.79	1,500	37,402	47,655	9,426	6.74E+06	0.21	0.21
CTW2-3	V	1009.8	2.79	3,000	39,282	53,863	20,011	7.61E+06	0.24	0.24

Sample ID	Orientation (deg)	Core Depth (ft)	Bulk Density (g/cc)	Unload Young's Modulus (psi)	Unload Poisson's Ratio - 1	Unload Poisson's Ratio - 2	Reload Young's Modulus (psi)	Reload Poisson's Ratio - 1	Reload Poisson's Ratio - 2
CTW2-1	V	1009.8	2.791	7.18E+06	0.17	0.18	7.18E+06	0.21	0.21
CTW2-2	V	1009.8	2.79	7.70E+06	0.22	0.22	7.15E+06	0.24	0.24
CTW2-3	V	1009.8	2.79	8.76E+06	0.22	0.26	7.43E+06	0.26	0.26

Accomplishments to Date

- All core section samples have been selected and CT Core Section Scans have been completed
- Characterization of the LDEO Test Well No. 4 Core samples has been completed
- Geomechanical testing of the LDEO Test Well No. 4 Core samples has been completed
- Characterization and Geomechanical testing of the Newark Basin Coring Project Core is in progress – Complete in a few weeks!

Synergy Opportunities

– Project is collecting characterization and geomechanical dataset in lithified mudstones.

– Raw data can be shared with other projects

Summary

- Key Findings (so far):
  - The basin mudstones are very heterogeneous, with a range of strength and matrix properties

Summary

– Lessons Learned
  - Established working relationship since 2009 (Newark Basin Characterization Project (ARRA)) between project partners ensures a smooth project
  - No major surprises to date!
  - Project is progressing towards meeting Budget Period 1 goals

Summary

– Future Plans

- Complete geomechanical testing of NBCP Cores
- Compile Data into BP1 Report (*Report on Newark Basin Caprock Characterization and Laboratory Testing*)
- Anticipate completing Phase I at the end of September & Moving on to Phase II. First Phase II task is the late October 2015 Formation Microimaging of LDEO TW-3 borehole to help in selection of Wireline Well Testing locations in the Spring of 2016

Project Overview – Budget Period II

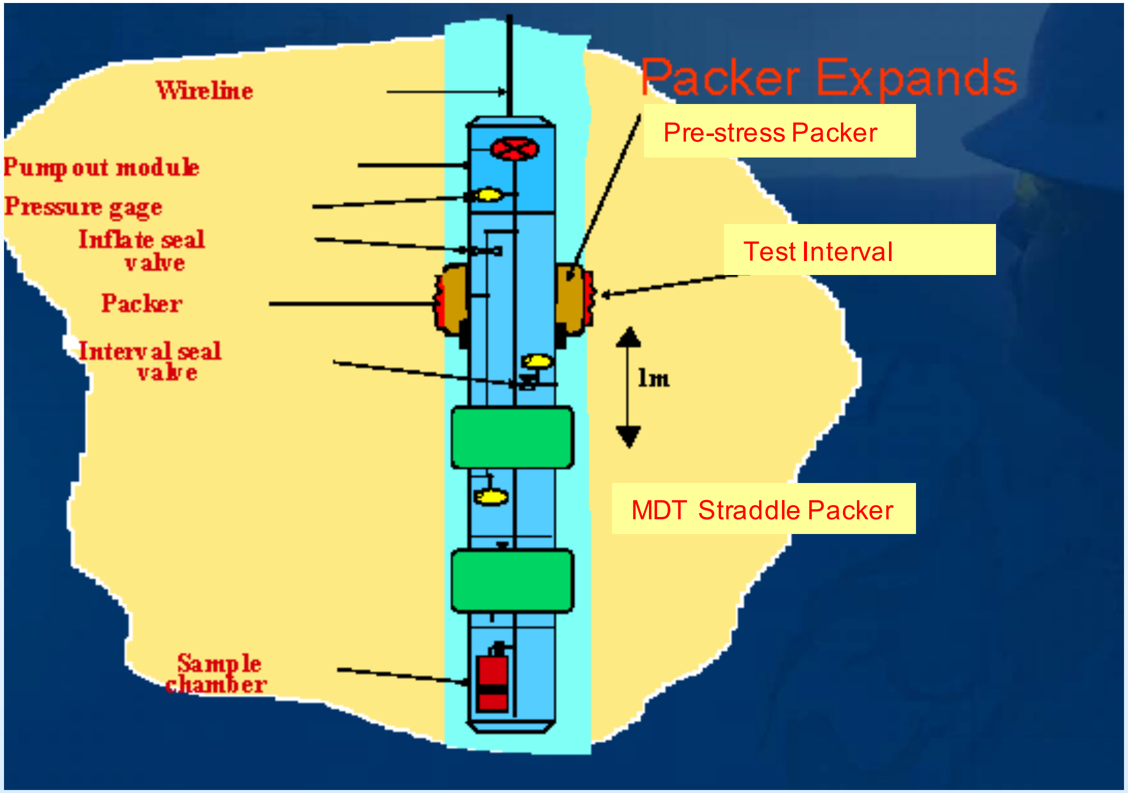
- We will use a novel wireline tool setup for performing the well testing portion of the project. Prior to 2013, the root cause of many field job failures was the inability to break down the formation.
  - In the deep ARRA Characterization well, formation breakdown tests were attempted at 3,510 ft (maximum pressure 5,700 psi) and 2,927 ft (maximum pressure 5,500 psi);
  - At the time, the tool packers could only hold ~4,000 psi differential pressure

- New/novel developments that enhance MDT formation breakdown testing include:
  - 1) packers that can perform at an 5,000 to 8,000 psi differential;
  - 2) tool pumps that have been modified to deliver a constant injection rate as the pressure varies;
  - 3) New software, custom built for MDT test observation and interpretation will used for this project, replacing the older Frac-Cade* software package that was designed for pumping services.

In Situ Testing Methodology – Modular Dynamics Tester with Pre-stress Packer (Continued)

- A more significant development is the addition of a second MDT packer module to the traditional tool string, which allows for pre-stressing the test interval;
- This additional packer is inflated across the test interval creating break in the formation using the force of the packer itself pushing against the borehole wall. As such, the packer is designed to hold a very high inflation pressure;
- Following formation breakdown, the pre-stress packer is deflated and the tool-string is moved up in order to straddle the test interval;
- Testing then proceeds using the traditional dual inflatable packer setup, which consists of injecting fluid to propagate the break in the formation, followed by a shut in period to determine fracture closure pressure.
- Field testing is under way with a pre-stress packer that can be inflated to 8,000 psi, testing the concept, pumps, and other equipment under field conditions. Development of additional packer sizes and configurations should be ready for deployment in time for our field program, including a packer that can undergo inflation to 12,000 psi to break down high-strength formations.

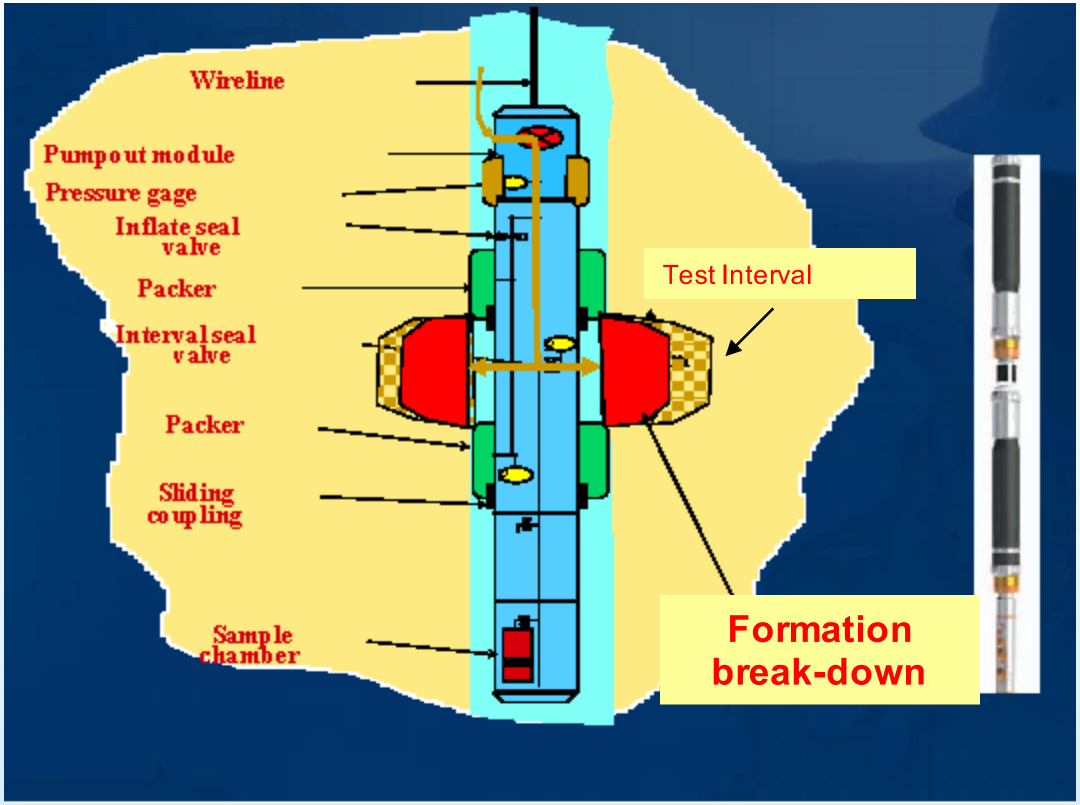
In Situ Testing Methodology – Modular Dynamics Tester with Pre-stress Packer



(Mishra, V., 2011)

- Innovative addition of an inflatable "pre-stress" packer on MDT tool allows for greater pressure to be placed on the test interval
- Pre-stress packer is deflated following initial stress event and MDT tool is placed straddling the pre-stressed test interval
- Standard formation breakdown test can then be run

In Situ Testing Methodology – Modular Dynamics Tester with Pre-stress Packer



(Mishra, V., 2011)

- MDT tool is placed straddling the pre-stressed test interval
- MDT pump module is used to further breakdown the formation, propagating the break a short distance out into the formation
- Tool allows for constant monitoring of pump rate and pressures with time during pumping and recovery

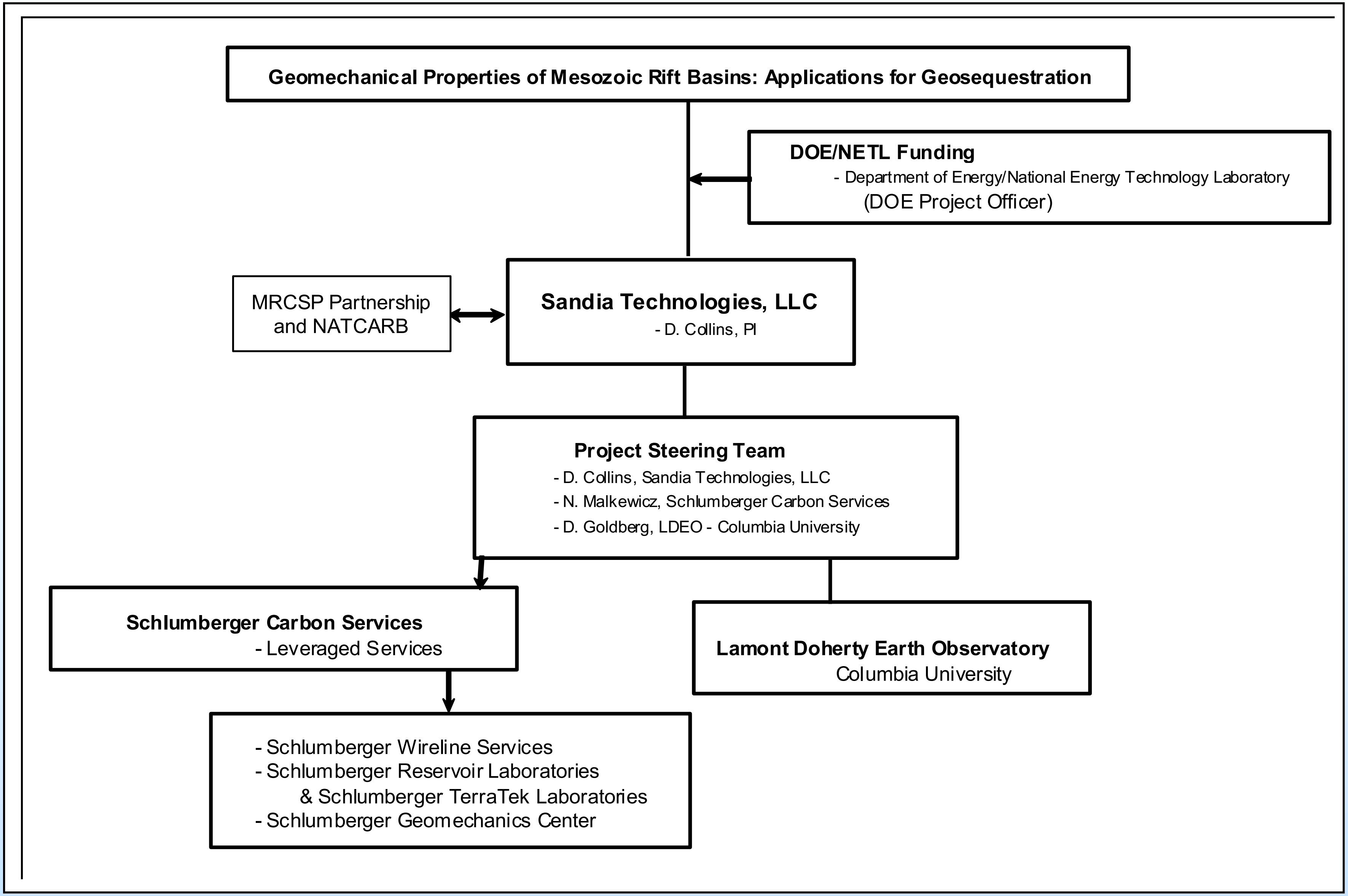
Questions?

End

Appendix

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

Project Organizational Chart

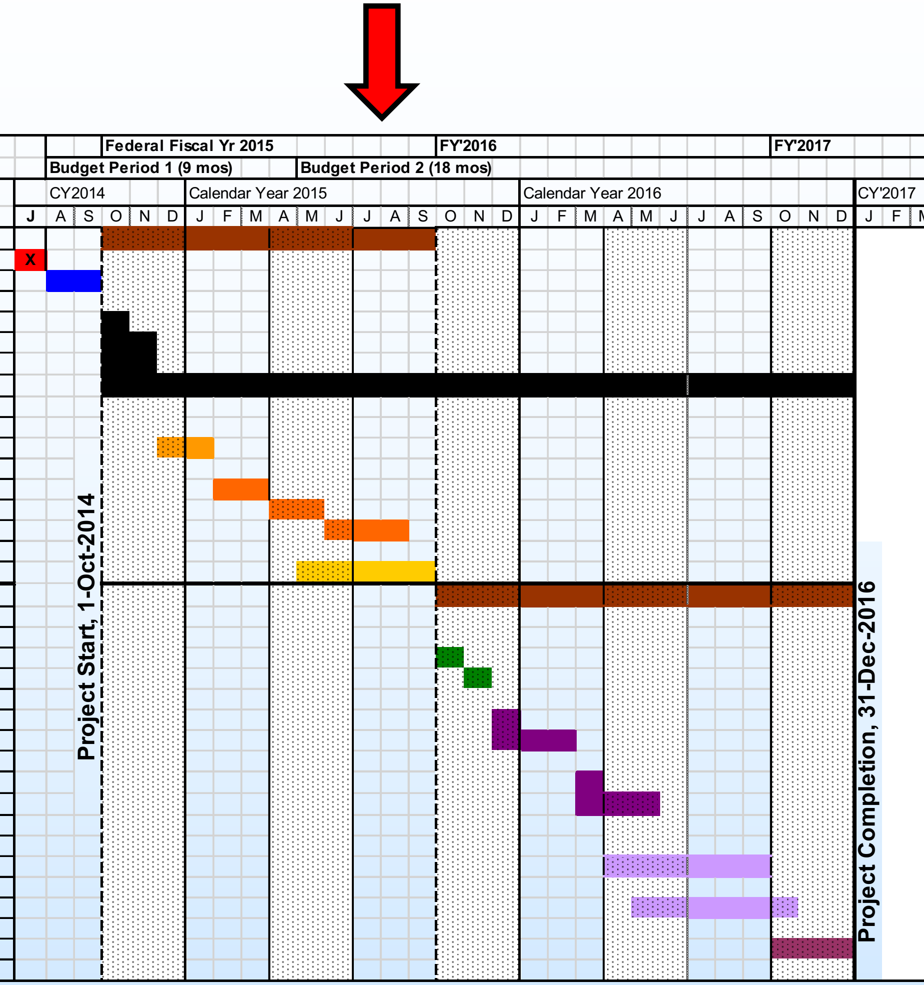


Project Organizational Chart – (continued)

- Schlumberger Carbon Services
  - Houston Rock Laboratory – routine and special core analyses
  - TerraTek Rock Mechanics lab – Salt Lake City
  - Wireline Services – Formation Microimager and Modular Dynamics Tester
  - Geomechanics Center – technical support in laboratory and field data evaluation/ analysis and modeling support to LDEO
- Lamont Doherty Earth Observatory
  - Research staff to support scientific efforts of the project, including primary data reduction/analysis, evaluation, and geomechanical modeling
  - Access to Newark Basin core library
  - Access to Test Well No. 3 for field testing program

Project Schedule – Gantt Chart

	Start Date	End Date	Dur. Mos.
Budget Period 1			12
Project Award - July 31 2014	7/31/2014	7/31/2014	
DOE/Sandia Contracting	8/1/2014	9/30/2014	2
Task 1.0 Project Management			
Revise Project Management plan	10/1/2014	10/31/2014	1
Final NEPA Preparation/Submittal/Approval	10/1/2014	11/30/2014	2
Contracting	10/1/2014	11/30/2014	2
Project Management	10/1/2014	12/31/2016	27
Task 2.0 – Core Sample Screening & Laboratory Testing			
Subtask 2.1 – Core Screening/Selection			
Core Screening & Sample Selection	12/1/2014	1/31/2014	2
Subtask 2.2 – Laboratory Testing			
Laboratory Prep and Screening (CT/Plugging/Photo)	2/1/2015	3/31/2015	2
Core Characterization (Routine/SEM/XRD/MICP/Thin Sections)	4/1/2015	5/31/2015	2
Rock Mechanics (Compressive Strength/Acoustic/Tensile)	6/1/2015	8/31/2015	3
Subtask 2.3 – Evaluation of Laboratory Testing			
Analysis and Reporting of Laboratory Results	5/1/2015	9/31/2015	5
Budget Period 2			
Task 3.0 – Field Data Acquisition			
Subtask 3.1 – Well Test Planning and Permitting			
Prepare Well Test Program	10/1/2015	10/31/2015	1
Secure Necessary Permits	10/1/2015	11/30/2015	2
Subtask 3.2 – Field Work			
Baseline Formation MicroImager Survey	12/1/2015	12/4/2015	0.2
Process & Evaluate Baseline Formation Microimager	12/7/2015	2/29/2016	2.8
Subtask 3.3 – Formation Fracture Testing			
Run Minifracs with novel Modular Dynamics Tester Setup & Post Formation Microimager	3/7/2016	3/11/2016	0.2
Analyze Modular Dynamics Tester Minifrac Tests and Formation Microimager	3/14/2016	5/31/2016	2.5
Task 4.0 – Data Reduction, Analysis & Reporting			
Subtask 4.1 – Data Reduction & Analysis			
Data Integration and Interpretation	4/1/2016	9/30/2016	6
Subtask 4.2 – Geomechanical Modeling			
Data Integration and Interpretation	5/1/2016	10/31/2016	6
Subtask 4.2 - Final Project Data Analysis & Reporting			
Prepare Final Project Report	10/1/2016	12/31/2016	3



Bibliography

List peer reviewed publications generated from the project per the format of the examples below

- AGU Presentation:
  - Zakharova, N., Goldberg, D., Collins, D., and Malkewicz, N., 2015, Geomechanical and petrophysical properties of rift basin mudstones: American Geophysical Union Fall Meeting, San Francisco. (Submitted)