Mudrock & Tight Oil Characterization Consortium (MUDTOC)

Industry Consortium Proposal

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Other Investigators may be added as project evolves

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Summary

Mudrocks (shales and chalks), tight oil, and halo reservoirs contain significant hydrocarbon resources. The term “mudrock” as used in this proposal includes shales, chalks and marls. Mudrocks generally consist of kerogen, clay and silt-sized particles. Total organic carbon content (TOC) of many successful mudrock plays ranges from 2-11 wt. %. The type of organic matter is dominantly a Type II kerogen. The mineralogy of successful mudrock plays is variable but generally consists of less than 50% clay and over 50% of carbonate and/or siliciclastic material. Lower clay content of successful mudrock systems generally increases the brittleness of the units, making them more amenable to hydraulic fracturing.

Mudrocks in the past were considered to be both source rocks and seals. Tight-oil reservoirs are low porosity and permeability reservoirs that are generally adjacent to organic-rich source rocks. For example, the Middle Bakken is a tight reservoir adjacent to organic-rich shales. The chalk beds in the Niobrara Formation (targets of horizontal drilling) are adjacent to organic-rich marl beds. Mudrock and tight oil plays have been successfully developed using the combined technologies of horizontal drilling and multi-stage hydraulic fracturing.

Halo reservoirs are the tight zones surrounding conventional oil fields. These areas in the past were considered to be the seal for the conventional hydrocarbon accumulation. Halo reservoirs have also recently been developed using horizontal drilling and multi-stage hydraulic fracture stimulation.

Successful mudrock and tight oil plays (to date) include the following formations: Bakken, Three Forks, Niobrara, Eagle Ford, Austin Chalk, Vaca Muerta, parts of the Barnett, etc. New halo reservoir plays include the Parkman, Teapot, Turner, Sussex and Shannon of the Powder River Basin. Similar halo plays exist in other Rocky Mountain basins. Of primary importance in developing these reservoirs is an understanding of low porosity pore systems, natural fractures, and hydrocarbon fluid properties (e.g., gravity, viscosity, GORs, etc.).

Mudrock and Tight Oil Characterization Consortium Objectives:

Proposed research objectives for MUDTOC include:

- Better define the **petroleum systems** and the genetically related petroleum accumulations surrounding **mudrock, tight oil and halo oil** fields;
- Characterize both the conventional and unconventional accumulations in terms of porosity, permeability, and other reservoir parameters;
- Image pore systems using state-of-the-science petrographic techniques, SEM, CT scans, etc.;
- Measure permeabilities using MICP, nitrogen adsorption, water immersion methods;
- Determine *in situ* stress and pore pressure characteristics;
- Characterize facies and mineralogy (Including XRD, XRF, FE SEM);
- Characterize geologic, geochemical, geophysical, geomechanical, and operational parameters;
- Develop methods to accurately assess the potential of shale and tight reservoirs for hydrocarbon production from common industry petrophysical measurements;
- Develop petrophysical models for source rock maturity and identification of pay;
- Accurately delineate natural fracture systems (for guiding horizontal wells to intersect a large number of open fractures);
- Conduct studies to understand trapping mechanisms;
- Conduct subsurface pressure analyses;
- Conduct coupled geomechanics, acoustic and permeability measurements to determine reservoir and seal characteristics;
- Develop geomechanical models;
- Conduct preliminary studies of novel concepts for unconventional oil and gas development in shale hydrocarbon resources, and for the initial assessment of the potential of frontier shale gas/oil resources, and;
- Develop geo-models and reservoir models where applicable.

Participating companies will help define the research objectives.

Potential Impact of the Project

Industry will benefit from this project in a number of important ways:

- This study will establish a new predictive stratigraphic framework and conceptual reservoir model for the mudrock and tight oil intervals that will improve play and prospect assessment, reservoir characterization, and allow a more accurate estimate of reserve volumes.
- Improved understanding of mudrock and tight oil producibility will reduce drilling risk and provide more accurate resource estimates.

Potential Mudrock, Tight Oil, and Halo Reservoirs for this Project

This project will be industry driven. Mudrock, tight oil, and halo reservoirs worked on will be chosen with industry input.

Potential mudrock and tight oil plays for the project include but are not limited to the following: Bakken (Williston Basin), Eagle Ford (Gulf Coast), Mowry (Rockies Region), Skull Creek (Rockies Region), Wolfcamp (Permian Basin), Haynesville (Gulf Coast), Marcellus/Utica (Appalachian Basin) and Vaca Muerta (Neuquén Basin Argentina).

Potential halo reservoirs include the Muddy, Shannon, Sussex, Parkman, and Teapot reservoirs of the Powder River Basin. Similar halo reservoirs exist in other Rocky Mountain basins and may be added to the study.

Participating companies will help define focus areas for this study.

Background and Existing Technologies/Methodologies

Mudrocks (shales, marls, and chalks), tight oil, and halo reservoirs contain significant hydrocarbons. Mudrocks generally consist of kerogen, clay and silt sized particles. Figure 1 illustrates the current mudrock and tight oil plays and potential plays in North America. These plays have had a dramatic impact on US oil production (Figure 2).

Tight oil and mudrock plays have very small pore diameters (Figure 3). Prior to production being established in the Bakken, the pore systems were thought to be too small for production to occur. Natural fractures also contribute to the total pore system.

Successful mudrock and tight oil plays (to date) include the following formations: Bakken, Three Forks, Niobrara, Eagle Ford, Austin Chalk, Vaca Muerta, parts of the Barnett, etc. Table 1 compares some of the plays.

The total organic carbon content (TOC) of many successful mudrock plays ranges from 2-11 wt. %. The type of organic matter is dominantly a Type II kerogen. The mineralogy of successful mudrock plays is variable but generally consists of less than 50% clay and over 50% of carbonate and siliciclastic material. The low clay content generally increases the brittleness of the units. Figure 4 compares the mineralogy between several shale plays.

Mudrocks in the past were considered to be source rocks and seals. Tight-oil reservoirs are low porosity and permeability reservoirs that are generally adjacent to organic-rich source rocks. For example, the Middle Bakken is a tight reservoir adjacent to organic-rich shales. The chalk beds in the Niobrara Formation (targets of horizontal drilling) are adjacent to organic-rich marl beds. Mudrock and tight oil plays have been successfully developed using the combined technologies of horizontal drilling and multi-stage hydraulic fracturing.

Halo reservoirs are the tight zones surrounding conventional oil fields. These areas in the past were considered the seals for the conventional pools. Halo reservoirs have also recently been developed using horizontal drilling and multi-stage hydraulic fracture stimulation. New halo reservoir plays include the Parkman, Teapot, Turner, Sussex and Shannon of the Powder River Basin. Similar halo plays exist in other Rocky Mountain basins.

Of primary importance in developing these reservoirs is an understanding of low porosity pore systems, natural fractures, and hydrocarbon fluid properties (e.g., gravity, viscosity, GORs, etc.).

Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI.
Updated: May 9, 2011

Figure 1. Location map showing current and prospective shale gas and oil plays in North America. Many of these "shale" plays contain reservoirs that are not shale, so they might be considered as hybrid plays.

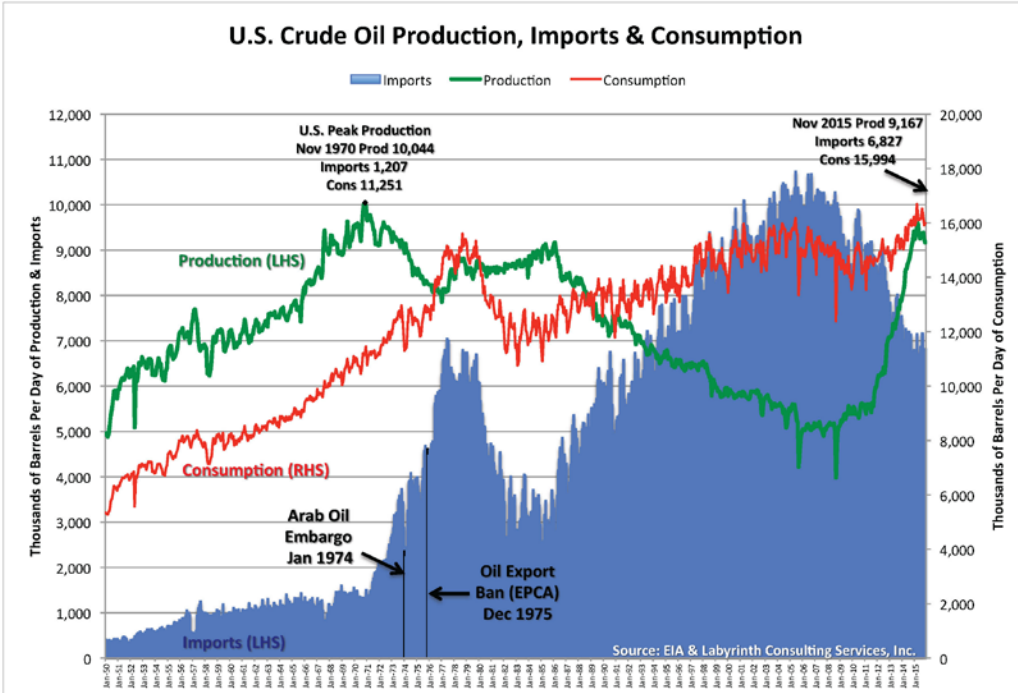


Figure 2. US crude oil production and import data. The impact that tight oil production has had on US total production is significant. Current US production is over 9 million barrels per day. (Berman, 2015)

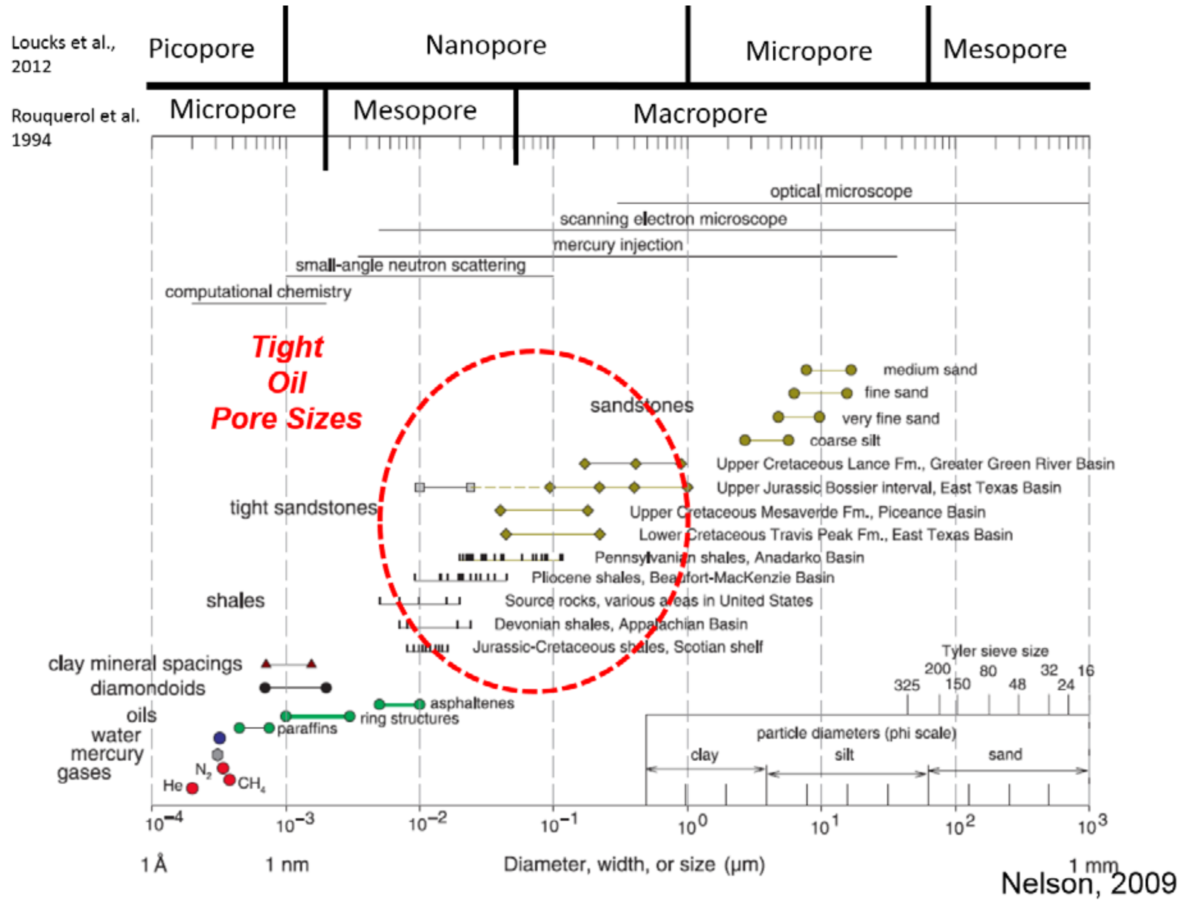
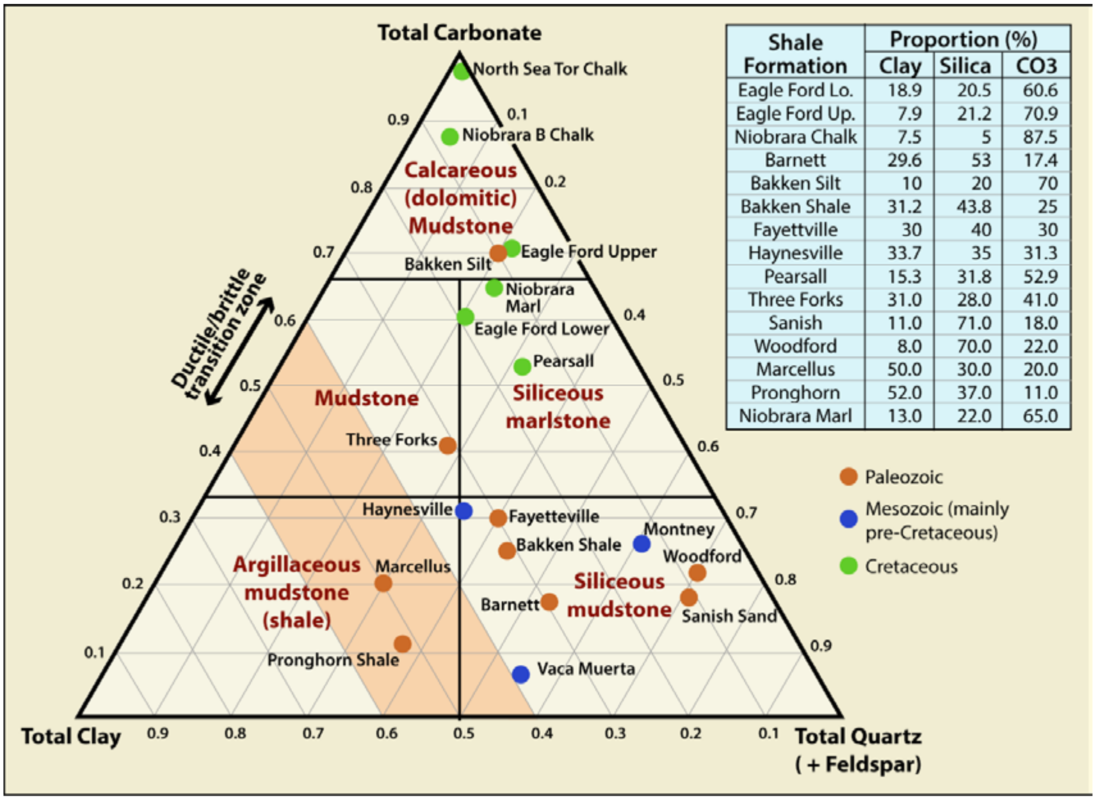


Figure 3. Sizes of molecules and pore throats in siliciclastic rocks. Measurement methods shown in top of graph (Nelson, 2009). Terminology for pore sizes shown in upper part of diagram from Loucks (2012).

What do the Rocks Look Like				
Formation	**Vaca Muerta**	**Bakken**	**Niobrara**	**Eagle Ford**
Hydrocarbon	**Oil/Gas**	**Oil/Gas**	**Oil/Gas**	**Oil/Gas**
Age	**Jurassic/Cretaceous**	**Upper Devonian**	**Cretaceous**	**Cretaceous**
Depth (TVD ft)	**8,000-11,000**	**8,000-11,000**	**6,000-9,000**	**5,000-11,000**
Thickness (ft	**150-1,000**	**<140**	**300-450**	**80-175**
Porosity (%)	**6-10.**	**5-9.0**	**8-10.0**	**9-11.0**
TOC	**2-9.**	**11.00**	**4-8.0**	**3-6.0**
Pressure Gradient (ppg)	**9.4-17.3**	**9-12.**	**9-11.**	**9.6-12**
EUR (MBOE)	**300-750**	**300-750**	**300-600**	**200+**

Table 1. Comparison of Mudrock plays.

The mineralogy of mudrock systems generally falls into the carbonate or siliciclastic regimes (Figure 4).



Shale Formation	Proportion (%)		
	Clay	Silica	CO3
Eagle Ford Lo.	18.9	20.5	60.6
Eagle Ford Up.	7.9	21.2	70.9
Niobrara Chalk	7.5	5	87.5
Barnett	29.6	53	17.4
Bakken Silt	10	20	70
Bakken Shale	31.2	43.8	25
Fayettville	30	40	30
Haynesville	33.7	35	31.3
Pearsall	15.3	31.8	52.9
Three Forks	31.0	28.0	41.0
Sanish	11.0	71.0	18.0
Woodford	8.0	70.0	22.0
Marcellus	50.0	30.0	20.0
Pronghorn	52.0	37.0	11.0
Niobrara Marl	13.0	22.0	65.0

Figure 4. Mineralogy comparison of the mudrock plays with other producing shale systems. High carbonate and silica content of shales generally contribute to brittleness of source rocks. Case studies from North America: AAPG Search and Discovery Article # 80354 (2014).

TECHNICAL APPROACH

Scope of Work

The stratigraphy and reservoir characterization components of the project will include compilation of a subsurface database, and an initial assessment of various petroleum systems from current literature. This will be followed by documentation of regional outcrop stratigraphy, integration with regional and 3-D seismic data to allow construction of a sequence stratigraphic framework for the multiple regions. Outcrops of the various petroleum systems will be integrated with subsurface data in the basin. Reservoir characterization of key reservoir intervals using cores and outcrops will be accomplished within this stratigraphic framework. The project plans to use high-resolution quantitative mineralogical analysis of samples from outcrop and core, combined with standard petrographic techniques and inorganic geochemical analyses of samples, to characterize mineralogy and diagenesis, to help quantify the pore systems, and to integrate that data with larger-scale flow unit compartments and connectors. The results of these efforts will allow the research team to document and map the lateral and vertical heterogeneity of reservoirs in outcrop and at the inter-well scale.

The second project objective will be a sub-regional tectonic and structural analysis to define the natural fracture systems for the plays chosen for this study. This will include analysis of outcrop and core description to document both open and closed fracture systems, and to construct a 3-D model of this sub-regional system. In conjunction with the fracture characterization study, the *in situ* stress and pore pressure will be determined and a 3D *in situ* stress and geomechanical model will be developed based on the integrated study findings.

The third project objective is to investigate and develop criteria for mapping reservoir and source rock characteristics. Rock physics analysis of outcrop, well log and core data will be used to calibrate available seismic data. This detailed integrated subsurface mapping of the depositional and fracture systems using seismic attributes and sequence stratigraphic analysis will be integrated with source rock and oil geochemistry, and thermal maturation / migration modeling. This work will include analysis of closely-spaced rock samples in well-characterized stratigraphic transects for total organic carbon and organic matter composition (pyrolysis); correlation of organic carbon content and type to well logs; correlation of source rocks to produced oils and gases; development of regional models for source rock quality and thermal maturity; and integration of pore-system characterization into a hydrocarbon migration model.

The fourth project objective is to develop an integrated model of the stratigraphy, fracture analysis, and petrophysics characteristics of Mudrock, Tight Oil and Halo Oil systems and test this model over multiple regions.

Additional areas of investigation that may be explored are listed below:

Mineralogical Analyses

Petrographic analyses, along with XRD, and XRF data gathering and analyses will be obtained in each study area. These data will help with provenance and environment of deposition analysis, mechanical stratigraphy studies, and source bed studies.

Fracture Analysis

Construct a model that explains distribution of fractures in the basins studied.

Documentation of Fracture Systems

Perform fieldwork at outcrops, and study core descriptions of wells in the various basins studied to document fracture systems. This documentation shall include, but not be limited to, fracture size distribution of macro- and micro- fractures.

Sub-regional Tectonic and Structural Analysis

Perform a sub-regional tectonic and structural analysis to understand the natural fracture systems. Mapping will be accomplished using 3-D seismic and borehole image logs from various basins studied. The most useful attributes will be extracted at the appropriate seismic time-slice.

Source and Migration Model

Geochemistry

Characterize mudrock organic geochemistry in several detailed stratigraphic sections (outcrop / core / cuttings). Correlate organic geochemical character to well-log petrophysics. Source rock analysis will involve both pyrolysis analysis and XRF sample analysis.

Hydrocarbon Characterization

Correlate source rocks to producing oil and gas fields.

Source and Maturation Model

Develop regional model for controls on source rock character, and develop hydrocarbon migration model at local and regional scales. A basin model for each studied area will be developed.

Data Integration and Predictive Exploration Model

Develop a fully integrated exploration model that can be tested outside the sub-regional area of this project. This model will integrate the stratigraphic framework; with the fracture analysis, and with the rock physics calibrated seismic attribute analysis, to predict high potential fairways and traps for the studied hydrocarbon systems.

Coupled Mechanical and Acoustic Properties and Permeability Core Measurements

The UNGI Geomechanics laboratory in Petroleum Engineering Department has been established at the Petroleum Engineering Department by Dr. Tutuncu and a custom-designed MTS load frame equipped with elastomer technology has been used that enables us to conduct low seismic frequency (up to 200 Hz) and ultrasonic frequencies (100 KHz and 1 MHz) measurements along with triaxial deformation and failure tests to simultaneously measure/simulate realistic *in situ* stress and elevated pore pressure and temperature conditions. The core measurements using the coupled geomechanics assembly will provide us realistic acoustic, mechanical, permeability and strength characteristics of multiple mudrock and tight oil reservoirs and associated seal formations. Nano-scale SEM, AFM, CT-Scan, NMR and XRD measurements will be upscaled into large-scale models. Laboratory-measured quantities will be compared to the log-derived moduli and attenuation measurements for investigating the deformation and dispersion characteristics of the reservoir formations and their seals and key controlling factors impacting production in our studies.

Geomechanical Models and Wellbore Stability

The goal here is to determine local variations in *in situ* stress conditions, pore pressure, and deformation characteristics, and obtain stress dependence of mechanical, acoustic properties, porosity and permeability by conducting coupled laboratory core measurements under true *in situ* stress and elevated pore pressure conditions. These will contribute to a better understanding of reservoir characteristics, static and dynamic moduli differences, and their stress dependence that are critical input for building accurate fully integrated geomechanical models. Further, our studies will address wellbore stability and wellpath optimization, hydraulic fracture design, and execution and production portfolio management. We will couple fracture network analyses into the geomechanical models to further constrain wellbore stability and wellpath optimization analysis. Offset drilling well data, well logs and seismic data, along with representative core and cutting measurements, will be used to calibrate the *in situ* stress state in the basins of study. Taken together, these will provide recommendations for optimized drilling, completion, and critical input for fracture design.

Hydraulic Fracture Stimulation Model

We will also be developing hydraulic fracture stimulation model(s) for the zone(s) targeted during geologic analysis. The focus of this component will be the optimum placement and design of the treatments. Although fracture stimulation is a key component in unconventional reservoir development, the specific characteristics of the reservoir dictate the actual design. Required fracture conductivity and fluid selection for the zones of interest will be evaluated. Additionally, the optimum spacing of the treatments will be evaluated. These spacing requirements will be closely integrated with the drilling technology component of this proposal, along with completion technologies (e.g., plug-n-perf methods versus packer/ball systems). Fracture conductivity, which is critical to long-term production, will be integrated with the rock mechanical and stratigraphic models. The brittle versus ductile behavior of unconventional systems is proving to be significant in such evaluations. Deliverables from this component will be stimulation models and associated design sensitivities.

Reservoir Models

Two models will be developed to evaluate the production behavior of the studied reservoirs. The first model will be an analytical model based on the theoretical behavior of the transient flow regime in the formation. Due to the ultra-low permeability, the transient conditions are likely to continue for a significant portion of the production. This model will evaluate how flow behavior is influenced by reservoir permeability and hydraulic fractures.

The second model will be a commercial numerical reservoir simulation model. It will be a sector model for a study area of the reservoir. Data for developing the model will come from the geologic exploration model. This model will be used to evaluate the long-term production trends and to optimize the well and hydraulic fracture spacing.

Upon field operations and implementation, the team would analyze field results and determine efficiencies as they occur. The team would also identify those problems that need resolution for future consortium activity.

Deliverables

Digital data will be available to sponsors for the cost of reproduction. A single digital copy of meeting reports and of graduate student theses will be available to each sponsor via our password-protected website. Additional copies can be prepared for each sponsor who requests them, for the cost of reproduction.

At the current time: sponsoring members have access to all current MUDTOC and previously completed Bakken, Eagle Ford, Niobrara and Vaca Muerta theses and studies.

The MUDTOC project is designed to be a multi-year, multi-phase study. Companies are encouraged to join the consortium for the three-year period, but can elect to join one year at a time.

Cost and Technology Transfer

The cost of participation in the CSM MUDTOC consortium is $35,000 per year. Payment structure is $35,000 payable by January 1 of each calendar year. Company participation can be one year at a time with no obligation to join the following years. Donation of 3-D seismic data, cores, geophysical log data or other types of data may partially reduce the cost of participation in the study.

Project duration for Phase 1 of this project is from January 1, 2016, to December 31st 2018. The project is expected to have multiple phases. Companies may join at any time during the project subject to membership agreement terms.

Semi-annual Sponsors Meetings will be held during this project phase.

Companies wishing to become members should make the check out to the Colorado School of Mines and send the check via instructions below. Please reference MUDTOC Consortium and/or Invoice # on your check.

Mail Checks To:

ATTN: ORA Consortia Manager
Colorado School of Mines
Grants - Dept 1911
Denver, CO
80291

Wire Transfer Info:

Bank Name:	Wells Fargo Bank West
Address:	P.O. Box 5247 Denver, CO
Account Name:	Colorado School of Mines
Routing Number:	102000076
Account Number:	867605115
International Transfers:	WFBIUS6S
EIN Number:	84-6000551

Membership Agreement

The participation in this consortium will be subject to a membership agreement (Appendix I) and Membership Bylaws (Appendix II).

Timetable (Phase 1)

2016 January 1	Start of project
2016 Spring/Fall	Semi-annual Sponsor Meeting and Research Updates
2017 Spring/Fall	Semi-annual Sponsor Meetings and Research Updates
2018 Spring/Fall	Semi-annual Sponsor Meetings and Research Updates

Timetable (Phase 2)

2019 January 1	Start of project
2019 Spring/Fall	Semi-annual Sponsor Meeting and Research Updates
2020 Spring/Fall	Semi-annual Sponsor Meetings and Research Updates
2021 Spring/Fall	Semi-annual Sponsor Meetings and Research Updates

Personnel

This project is a consortium research project is a shared research project at Colorado School of Mines. The Principle Investigator is Dr. Stephen A. Sonnenberg. Other Co-project investigators will be determined as the project develops and needs determined.

It is anticipated that approximately 10-15 graduate students will be working on this project at any given time.

Administration and coordination will be handled through the Department of Geology and the Office of Research Administration.

TECHNICAL AND MANAGEMENT CAPABILITIES

Qualifications of Key Personnel (PI's)

Dr. Steve Sonnenberg is a Professor and holds the Charles Boettcher Distinguished Chair in Petroleum Geology at the Colorado School of Mines. He specializes in sequence stratigraphy, tectonic influence on sedimentation, and petroleum geology. A native of Billings, Montana, Sonnenberg received BS and MS degrees in geology from Texas A&M University and a Ph.D. degree in geology from the Colorado School of Mines. He has over twenty-five years experience. Steve has served as President of several organizations including the American Association of Petroleum Geologists, Rocky Mountain Association of Geologists, and Colorado Scientific Society. He also served on the Colorado Oil and Gas Conservation Commission from 1997-2003 and was the Chair of the Commission from 1999-2003. Sonnenberg has previously been in management positions at PanCanadian/EnCana, and Westport/Kerr McGee/Anadarko.

Dr. Sonnenberg has experience managing teams of engineers, geologists, and landmen in several exploration and exploitation projects in the Rocky Mountain region. His teams typically managed budgets in the 30 to 80 million dollar range. *He is currently managing the CSM Bakken and Niobrara Consortia.*

Other potential Project Investigators:

Dr. Jennifer L. Miskimins is an Associate Professor and the Associate Department Head in the Petroleum Engineering Department at the Colorado School of Mines. Dr. Miskimins holds BS, MS, and PhD degrees in petroleum engineering and has over 25 years of experience in the petroleum industry. Between her BS and graduate degrees, she worked for Marathon Oil Company in a variety of locations as a production engineer and supervisor. Dr. Miskimins started teaching at CSM in 2002 and was full-time until 2013 when she returned to industry. From 2013-2016, she continued to hold a part-time appointment at CSM, advising research and graduate students, while working for Barree & Associates. In 2016, she returned full-time to the university.

Dr. Miskimins specializes in well completions, stimulation, hydraulic fracturing, and associated production issues. She is the founder and current Director of the Fracturing, Acidizing, Stimulation Technology (FAST) Consortium and also co-directs the Center for Earth Materials, Mechanics, and Characterization (CEMMC). Her research interest focus on the optimization of stimulation treatments and the importance of such on associated recovery efficiencies.

Dr. Miskimins is currently the Completions Technical Director on the SPE International Board of Directors. She was an SPE Distinguished Lecturer in 2010-2011 and 2013-2014 on hydraulic fracturing in unconventional reservoirs. Dr. Miskimins serves on a variety of conference organizing committees and as a technical editor for various journals. She is a registered Professional Engineer in the State of Colorado (License #36193).

Quality and Suitability of Facilities, Equipment and Materials

CSM is strategically located in the center of the Rocky Mountain region, and has traditionally had easy access, and made excellent use of the rich outcrop and subsurface database available in the region. CSM has a long history of research in reservoir characterization. Researchers in the Geology and Geological Engineering, Geophysics, and Petroleum Engineering Departments have made a habit of collaboration in their research and teaching. As a result, CSM advanced degree graduates are strong contributors to the oil and gas industry.

CSM operates cutting edge technical and analytical facilities. Computer labs have modern geophysical workstations, and current up-to-date geological and geophysical interpretation software. In addition, CSM has a $2M advanced mineralogy research center, that has been operational since April, 2008. This is one of the few university-based centers in the US, dedicated to research in mineral image and compositional analysis on the nano- through macro-scale. The center features QEMSCAN® analytical instrumentation for automated mineralogical and rock fabric analysis, and has recently added additional state-of-the-science quantitative mineralogical instrumentation using x-ray analysis Additional facilities in Geology and Geological Engineering include a Scintag XDS 2000 powder x-ray diffractometer, a source rock analysis laboratory, a light stable isotope laboratory (H, C, N, O, S isotopes), epi-fluorescence and hot-cathode cathodoluminescence microscope capabilities, a brand new field-emissions scanning electron microscope facility, heating/freezing stage for fluid-inclusion microscopy and analysis, a hand held x-ray fluorescence instrument (XRF), a hand held Bambino for rock mechanics, and a general geochemistry laboratory.

The Geomechanics Laboratory at the Petroleum Engineering department has experimental capability for conducting coupled core measurements of deformation, anisotropy, mechanical, acoustic, petrophysical, failure and transport properties in gas shale, shale oil, oil shale and tight gas sand unconventional reservoirs with true *in situ* stress, elevated pore pressure and temperature conditions. Core measurements are incorporated with modeling studies for improving uncertainties in rock property input parameters into geomechanical models, as well as better coupling of the geomechanics and fluid flow simulators for reserve analysis, field development and production management.

Our geomechanics system has capability of measuring stress-deformation, acoustic, seismic, velocity anisotropy, directional attenuation, porosity and directional permeability using custom designed MTS load frame equipped with elastomer technology allowing low seismic frequency (from zero to 200 Hz) and ultrasonic frequency measurements (100 KHz and 1 MHz) and simultaneous triaxial deformation measurements under *in situ* stress and elevated pore pressure and temperature conditions to determine realistic acoustic, mechanical and strength characteristics in sand and shale reservoirs and their seal formations. The confining and pore pressure levels can be controlled within +/- 0.001 psi accuracy. Temperatures up to 250ºF can be measured. SEM, CT-Scan, XRD and dielectric measurements are also integrated into core analysis of the coupled measurements to incorporate the mineralogy and heterogeneity effect on the measurements and better up-scaling characteristics.

Industry Participation

CSM is actively soliciting industry participation in this consortium project.
A list of sponsoring companies is available on the MUDTOC website.
http://geology.mines.edu/MUDTOC/index.html

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Nelson, P.H., 2009, Pore throat sizes in sandstone, tight gas sandstones and shales: AAPG Bulletin, v. 93/3, p. 329-340.