UCRL-JRNL-217774

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December 16, 2005

Environmental Geoscience

Disclaimer

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Abstract

Naval Petroleum Reserve No. 3 (NPR-3), better known as the Teapot Dome oil field, is the last U.S. federally-owned and -operated oil field. This provides a unique opportunity for experiments to provide scientific and technical insight into CO_2-enhanced oil recovery (EOR) and other topics involving subsurface fluid behavior. Towards that end, a combination of federal, academic, and industrial support has produced outstanding characterizations of important oil- and brine-bearing reservoirs there. This effort provides an unparalleled opportunity for industry and others to use the site. Data sets include geological, geophysical, geochemical, geomechanical, and operational data over a wide range of geological boundary conditions. Importantly, these data, many in digital form, are available in the public domain due to NPR-3's federal status. Many institutions are already using portions of the Teapot Dome data set as the basis for a variety of geoscience, modeling, and other research efforts.

Fifteen units, 9 oil-bearing and 6 brine-bearing, have been studied to varying degrees. Over 1200 wells in the field are active or accessible, and over 400 of these penetrate 11 formations located below the depth that corresponds to the supercritical point for CO_2. Studies include siliciclastic and carbonate reservoirs; shale, carbonate, and anhydrite cap rocks; fractured and unfractured units; and over-pressured and under-pressured zones. Geophysical data include 3D seismic and vertical seismic profiles. Reservoir data include stratigraphic, sedimentological, petrologic, petrographic, porosity, and permeability data. These have served as the basis for preliminary 3D flow simulations. Geomechanical data include fractures (natural and drilling induced), in-situ stress determination, pressure, and production history. Geochemical data include soil gas, noble gas, organic, and other measures. The conditions of these reservoirs directly or indirectly represent many reservoirs in the U.S., Canada, and overseas.

Introduction

Carbon capture and storage (CCS), or carbon sequestration, has emerged as a critical technology pathway to reduce atmospheric greenhouse gas emissions. Specifically, storage of carbon dioxide in geological reservoirs has become a primary focus of industrial, academic, and government research (e.g., U.S. DOE, 2005; IEA GHG, 2002; IPIECA, 2003). Due to economic, policy, and engineering concerns, a great deal of effort has focused on these sectors. However, concerns about the fate of injected CO_2 and uncertainties associated with subsurface operations and risks have prompted efforts to generate new knowledge that would help demonstrate the safety, ease, cost, and efficacy of geological carbon storage (e.g., Klara et al., 2003; Hawkins, 2003).

Ultimately, much of this new knowledge will come from the study of large field projects (Friedmann, in press). Some of these are active demonstration projects, such as Sleipner and Weyburn (e.g., Torp & Gale, 2003; Preston, 2003). The primary project goal of these large-scale efforts is to store large CO_2 volumes. In that context, scientific and technological research proceeds in the context of project economic and operational concerns. Some CO_2 sequestration projects are intimately linked to industry-driven enhanced oil recovery; in those cases both injection scenarios and monitoring technologies are focused on optimization of oil production. Other projects are field experiments, such as the Frio Brine Pilot (Hovorka et al., 2005). The goal in these is to develop knowledge through scientific experimentation. In that context, the primary limits to investigation come from geological constraints, budget, ownership, and the regulatory framework.

In order to maximize new knowledge covering a variety of settings and contexts, the U.S. Department of Energy (DOE) has built a research program aimed at understanding better both carbon storage and enhanced oil recovery (e.g., U.S. DOE, 2005). This has led to the work at the Frio Brine Pilot, the establishment of the Regional Sequestration Partnership programs, and designs for the zero-emission FutureGen power plant. To help maximize learnings around subsurface CO_2 injection, the Teapot Dome oil field is an ideal location for site characterization and CO_2 storage studies (Figure 1). This is the only oil field currently owned and operated by the U.S. federal government, which makes it possible to propose and carry out scientific experiments and technical development programs within a long-term, stable business context, free of the commercial drivers of a privately-owned oil field.

Background and Data Character

The Teapot Dome research program presents a unique opportunity to conduct CO_2 -storage experiments, largely as a consequence of its history (Friedmann et al., 2004). The public-domain data set is key to mapping structural and stratigraphic attributes and heterogeneities at depth (Table 1). The field covers nearly 10,000 acres (40.5 km^2) and contains over 2200 wells total, of which over 1200 may be accessed (Figure 2). Of these, ~600 are currently producing (~600 non-producing) and more than 400 penetrate to a depth greater than 2700 ft (823 m). All cores, well logs, mud logs, completion descriptions, and production data from these wells are in the public domain. In addition, the Rocky Mountain Oilfield Testing Center (RMOTC), co-located with DOE's office that manages and operates the field, acquired a full-field 3D seismic volume in 2000, which is also in the public domain.

Field infrastructure includes roads, pipelines, water lines, water treatment facilities, a gas processing plant, workover rig, several buildings, telephone lines, and dedicated internet connections. Currently, RMOTC owns and operates one drilling rig and 600 pump jacks of varying sizes. Drilling costs for certain work are covered by RMOTC, and an internal committee of scientists and engineers approves drilling programs in coordination with all other efforts (e.g., the current site characterization / CO_2 program). As of September 2005, there is no dedicated CO_2 pipeline into Teapot Dome. However, Anadarko Petroleum Corporation recently completed a new CO_2 pipeline to their Salt Creek field, immediately adjacent to Teapot Dome's northern field boundary (Figure 1). The pipeline configuration provides for 250 million ft^3/day (7.1 million m^3) of anthropogenic CO_2, which originates at the Shute Creek gas processing facility (owned by ExxonMobil) located in western Wyoming. RMOTC and the DOE are currently discussing the pipeline right-of-way, interim trucked delivery and compression of CO_2, and CO_2 price with Anadarko and other private companies. Given this, the earliest likely date for initial CO_2 injection into Teapot would be with trucked delivery in 2006; pipeline delivery of CO_2 could not begin until 2007 or ’08.

Recently, RMOTC digitized data from over 400 deep wells and placed them in a newly acquired Landmark-based data environment. These data include wireline logs, lithology curves, and limited porosity and permeability data. By mid-2006, these data should all be publicly available and ready to be loaded into typical subsurface geology packages.

Site Characterization

The CO_2 effort formally began at RMOTC in 2003. At that time, site characterization began in order to modernize and fill gaps in the field data set, to enhance the understanding of Teapot Dome’s complex subsurface, and to build the scientific foundation necessary to support future CO_2 injection experiments. This work took advantage of the field’s abundant data, the recently acquired 3D seismic volume, and prior field characterization work. The program has since expanded, and many aspects of the field geology in both hydrocarbon- and brine-bearing units are now well understood.

Stratigraphy and Sedimentology

The main stratigraphic units at Teapot Dome were identified early in the 20th century. They include Devonian to Upper Cretaceous units that occur widely throughout the intermountain West (Thom and Spieker, 1931). Within the field, they comprise nine oil-bearing and six water-bearing units, and include terrestrial sandstones, marine and lacustrine carbonates, and shallow shelf siliciclastics (Figure 4). On the whole, relative fluctuations in base level interleaved porous and permeable units with impermeable rocks that serve as seals (Table 2). Both oil-bearing and brine-bearing strata at Teapot Dome hold hydrocarbon accumulations elsewhere in Wyoming, Montana, and Colorado. Many of these are excellent targets for CO_2 EOR (Nummedal et al., 2003). Although various studies present the stratigraphy and sedimentology of many field strata, only two reservoir and cap-rock pairs are discussed in this paper: The Pennsylvanian Tensleep Sandstone and overlying Goose Egg Formation, and the Upper Cretaceous Second Wall Creek Sandstone with overlying shales of the Frontier Formation. These two reservoir-cap-rock pairs are addressed in this paper because the Tensleep has been selected by the project team as the first and most promising reservoir target for specific proposed CO_2 injection experiments. Thus it and the Goose Egg cap rock have been the primary focus of recent characterization and pre-CO_2 baseline studies. The Second Wall Creek is also considered an excellent injection target for specific experiments currently under consideration, and is the first and largest zone being CO_2 flooded in the neighboring Salt Creek EOR project initiated by Anadarko Petroleum in 2004. A preliminary CO_2 EOR screening study performed by RMOTC (Giangiacomo, 2001) laid the groundwork for additional, more thorough review of both of these reservoirs. Other zones at Teapot Dome are also being considered for possible future injection, but will not be covered in this paper.

Tensleep Sandstone

The Pennsylvanian Tensleep Sandstone represents an enormous rock volume suitable for CO_2 storage, both in saline aquifers and oil-bearing zones. It covers large areas of Wyoming, Montana, and Colorado (Figure 5a,b) and is the primary oil-bearing unit at Rangely in Colorado (the Weber Sandstone is equivalent) and Lost Soldier and Wertz Fields in Wyoming, all three of which have received continuous CO_2 injections for roughly 20 years. It holds two-thirds of Wyoming's oil (Nummedal et al., 2003), and is a thick, continuous, porous and permeable sandstone aquifer where oil is not trapped. Within NPR-3, about 35 wells have penetrated the Tensleep Sandstone, including 13 cored wells. All have traditional well-log suites, with six recent wells having FMI (Formation Micro Imaging) logs. Core samples and special core tests provide porosity and permeability information (Table 3; Figure 6b), petrographic samples, and petrophysical characterizations. Within the field, multiple cores have been recovered and described for both sedimentary and fracture characterizations (Figure 7).

The Tensleep Sandstone consists predominantly of thick-bedded porous and permeable aeolian sandstones. Average porosity is 8% with 80 mD permeability, although data vary widely as a function of depositional sub-environment and degree of local cementation. Within the field, the thickest and most continuous of these bodies is the "B" sand, which is well over 100 ft (30.5 m) thick; permeable zones include the overlying "A" sand and underlying "C" sands. These are separated by thin sabkha carbonates, minor evaporites (mostly anhydrite), and thin but widespread extensive beds of very low permeability dolomicrites. These units represent periods of relative sea level rise (transgression) followed by exposure and unconformity; they also represent low-permeability zones that act as flow baffles or barriers (Figure 6a, Figure 7).

The overlying cap rock is the Permian Phosphoria Formation, locally called the Goose Egg Shale, which consists of over 300 ft (91.4 m) of shale, carbonate, and anhydrite cap rock in the field. This is the primary regional seal allowing for large hydrocarbon accumulations. The longest of these is the 48-x-28 well (May 2004) from which over 150 feet (45.7 m) of core were recovered and described in detail. At Teapot Dome, this seal trapped more than 35 million barrels (5.6 million m^3) of oil and dissolved natural gas, demonstrating its effectiveness.

Within the Tensleep Sandstone, 14 wells penetrate a small closure and hydrocarbon accumulation in Section 10 near the southern end of the field (Figure 2). The closure has a structural crest at 5500 ft (1676 m) depth. The closure is bounded by an oblique-slip fault to the north that is part of the S1 fault network (Figure 2; see below). To the south, the closure dips away from the structural crest, covering an area of roughly 0.4 mi^2 (1 km^2). It is small enough to be managed well yet large enough to capture most critical reservoir aspects, including heterogeneities, seal characteristics, and pressure response. Baseline characterization to date serves as the basis for the static geological model and full-field flow simulation.

Second Wall Creek Sandstone

The Second Wall Creek Sandstone is one of a series of fluvial/deltaic tongues within the Frontier Formation. These were deposited in a tectonically active basin within the Cretaceous interior seaway in Wyoming during the early Upper Cretaceous. This unit is the source of a large percentage of production within Wyoming and is the largest oil-bearing unit in Salt Creek field, and the second-largest (after the Shannon sandstone) in NPR-3. It is qualitatively similar to the Etive and Ness formations within the Brent Group of the North Sea in terms of connectivity, overall reservoir geometry, sequence stratigraphic characteristics, and relative permeability. Within NPR-3, the sandstone is relatively thin (60 ft, 18.3 m) but massively bedded, fairly quartzose and homogeneous in composition. It may represent a low-stand fluvial/estuarine depositional environment deposited above a regional sequence boundary.

In anticipation of and during waterflooding in NPR-3, over 45 cores from the Second Wall Creek were collected and analyzed, including special analyses from 37 cores. Average porosity is high at 15% with average permeability of 100 mD. The variance in permeability is a function of both patchy cements and variation in grain size (e.g., Dutton et al., 2002).

The overlying cap rock is a shale tongue within the Frontier Formation. It consists of approximately 250 ft (76 m) of shale and mudstone, and represents the primary regional seal trapping hydrocarbons within the Powder River basin. The trapping of more than 57 million barrels (9 million m^3) of oil and 45 billion scf (1.3 billion m^3) natural gas at Teapot Dome has demonstrated its effectiveness.

The Second Wall Creek Reservoir at Teapot Dome is divided into a Northern and Southern Reservoir by a sealing northeast-southwest trending strike-slip fault (S2 fault network) which cuts across Sections 33 and 34. Geological and reservoir studies on the Northern Second Wall Creek waterflood were conducted by Lawrence-Allison & Associates (1987) on behalf of DOE. The flood initiated in 1979; details of its characterization and likely production effects can be found in the report.

Basic field geology and static geomodels

Various studies have described key aspects of the site-specific field geology for almost 100 years (e.g., Wegemann, 1918; Thom and Spieker, 1931). Since then, surface geology, wells, and 3D seismic have defined unambiguously the large-scale field structure, depth to key horizons, major unit thickness, and secondary fault networks (Figure 3). Recent mapping by McCutcheon Energy has produced high-precision time-structure and depth-structure maps of key horizons (e.g., top Tensleep Sandstone, top Second Wall Creek Sandstone). These data serve as a basis for large 3D static geomodels (e.g., Wagoner et al., 2005), which can be populated with detailed reservoir information.

Main structural elements

The main structural elements of Teapot Dome are a SW verging anticline that developed above a Laramide-style thrust fault. This thick-skinned fault offsets Precambrian igneous and metamorphic basement mapped in outcrop in adjacent ranges. Deformation timing is interpreted to be broadly coeval with Laramide shortening (Late Cretaceous to Late Paleocene). This faulting produced an asymmetric anticline with shallow dips (<20°) on the east flank and fairly steep dips (20-50°) on the west.

Several large NE-SW trending faults transect NPR-3. These faults can be mapped both at the surface and subsurface (Fig. 2) and have been noted by many workers (Wegemann 1918; Horn 1959; McCutcheon 2003). These faults offset the basement (Fig. 2b,c) and are parallel to both the vergence direction of the main fold and basement foliation in neighboring outcrops. They have locally complex geometries (e.g., Friedmann et al. 2004) and generally have steep dips. At the surface, these faults have apparent lateral offsets and are characterized by sub-horizontal or oblique-slip striations (e.g., Cooper et al., 2003). For all these reasons, they are commonly interpreted as oblique-slip or lateral slip fault networks that reactivate older basement fabrics, acting as tear faults or accommodation faults during major deformation (e.g., Harding, 1985). Their timing is interpreted to be broadly coeval with Laramide shortening (Late Cretaceous to Late Paleocene), but thickness changes across the faults in Paleozoic and Mesozoic strata suggest that there was some earlier fault slip and growth strata (Friedmann et al. 2004).

Reservoir Characterization

Substantial characterization of NPR-3 reservoirs exists beyond the stratigraphic and sedimentological characterization described above. McCutcheon Energy has investigated the acoustic response of various units to interpret hydrocarbon, porosity, and stratigraphic signatures (T. McCutcheon, pers. comm.). More detailed data and assessments are discussed below.

Hydrocarbon character:

Over the years, operators and the United States Geological Survey (USGS) built datasets of basic information on the hydrocarbon character (e.g., API gravity), original oil-water contact, and initial gas saturation. Recently, the USGS has undertaken more detailed analyses of the hydrocarbon system at both Teapot Dome and Salt Creek (Brennan et al., 2005; Dennen et al., 2005), including whole gas chromatography, source-rock kerogen characterization, and fluid-inclusion analyses of cements. These data support interpretations regarding the degree of microbial degradation, reservoir compartmentalization and communication, and leakage risk. Primary conclusions suggest that the Tensleep Sandstone hydrocarbon system appears to be connected between Salt

Creek and Teapot Dome, but that the Cretaceous oils are not connected. Moreover, variable degrees of biodegradation in the Upper Cretaceous oils suggest fault compartmentalization of the Second Wall Creek and other oil-bearing units, which may indicate long-term isolation. Finally, hydrocarbon minerals encountered at the present-day ground surface in NPR-3 appear to have formed at depth, suggesting that hydrocarbon leakage at the field is not active today and thus may not reflect current geological leakage potential.

Inorganic Geochemistry

Basic compositional descriptions and petrography on all lithologic units have been completed. This includes the framework and matrix composition for all coarse-grained units. Yin (2005) organized much of the specific petrography of the key reservoirs. Some work has even focused on the reactive chemistry of the Tensleep Sandstone (Shiraki and Dunn, 2000). In addition to the rock system, RMOTC has collected a database of brine composition and temperature for all producing units and some saline aquifers. These data commonly consist of TDS and major element constituents. One saline aquifer of particular interest is the Crow Mountain aquifer, at approximately 4500 ft (1372 m) depth, which contains three permitted EPA Class 2 water disposal wells at NPR-3.

Fractures

The key producing reservoirs at Teapot Dome, and much of the Rocky Mountains, are fractured. Substantial fracture permeability has resulted in dual porosity networks that are difficult to characterize and integrate into flow simulations. At Teapot Dome, several of the producing zones are from fractured shales, including the Niobrara and Steele Shales (Figure 4), and zones of high fracture density have been targets for enhanced production.

Several historical or current studies at Teapot Dome have focused on discrete characterization of the fracture trends. Cooper et al. (2004) studied both outcrop and surface fracture distribution in order to generate predictions of subsurface fracture density (Figure 8). They identified orthogonal fracture trends that were used in history matching simulations performed at both the field scale and within Section 10, for the purposes of preliminary design and performance predictions of the proposed Section 10 CO_2 project described below (Lorenz and Cooper, 2004). Based on their azimuths, striations, and cementation patterns, these probably formed during Laramide shortening. This interpretation is supported by curvature analyses on individual seismic reflections that reveals anomalies with azimuths and locations parallel to surface oblique faults (Figure 8a). Additional studies by Wadleigh (Aflotech) on characterizing Tensleep natural fractures in dual porosity, dual permeability reservoir models, and fracture aperture and geometry data gathered by CT scans of actual fractures in the Teapot Dome 48-x-28 core by Schechter (Texas A&M) are still in progress and not yet published. Gilbertson and Hurley (2005) studied Tensleep Sandstone outcrops in the nearby Alcova anticline using LIDAR (Light Imaging Detection and Ranging) outcrop mapping. The LIDAR survey was designed to collect sufficient data points (10's of millions) to resolve fracture planes $\geq 1\ m^2$ in area (Figure 9). Additionally, high-resolution photomosaics were draped over the data set. Fracture planes were detected using automated and handpicking approaches. One goal of the study was to populate a 3D geological model with a fracture network.

Extracted fracture data from the LIDAR dataset determine the parameters used to seed the fracture-generating model.

The fracture and fault networks of the Tensleep Sandstone, and their role in controlling oil production, are currently being investigated at West Virginia University (T. Wilson, personal communication). One of the goals is to verify FMI (Formation Micro Imaging) fracture data against actual fractures in the core. Summer 2005 field work included recording Tensleep Sandstone fracture spacing, character and orientation on the homoclinal section in Fremont Canyon and the anticlinal section at Alcova Dam (Figure 9), both sites located roughly 30 miles (48.3 km) southwest of Teapot Dome, and studying the entire rock section from the Precambrian basement through Cretaceous sedimentary rocks as exposed along the shorelines. Much of the fieldwork focused on fracture characterization of the Tensleep Sandstone section at Fremont Canyon. Fracture orientation, intensity, and aperture measurements from the FMI logs and 3D seismic data will be incorporated into the characterization and future flow simulations. These new understandings will be of immense value in any Tensleep Sandstone CO_2 injection effort. The natural fractures seen in both the Tensleep Formation sandstones and dolomites impact performance and reservoir flow. The fractures form a high fluid-conductivity network that has supplied producing completions with over 166 million barrels of water with no measurable drop in reservoir pressure. Five Tensleep Sandstone completions in Section 10 have achieved cumulative water production in excess of 16 million barrels of water per well. A recent reservoir pressure measured in one of these wells (44-1-TPX-10) indicated a 3 psi (20.7 kPa) pressure, which reflects the subtle reservoir pressure increase as wells have been shut in. The 1.8 million barrels (0.29 million m^3) of recovered Tensleep Sandstone oil represent less than 20% recovery of the original oil-in-place as the water readily bypasses the oil by flowing along the least resistance fracture pathways between the aquifer and the producing wells. These studies suggest that the Tensleep Sandstone is a good analog for fractured reservoir systems suitable for either CO_2 flooding or storage.

Previous reservoir production and floods

Nine producing units provide data on original oil-in-place, production history, and response to various reservoir floods. We focus here on production from the Tensleep Sandstone and water-flooding of the Second Wall Creek. Other floods in the field have included a large steam flood of the Shannon Sandstone, an in-situ combustion project, polymer test, and others.

Tensleep Sandstone: The small closure in Section 10 south of the S1 fault network (Figure 2) originally contained 3.8 million barrels (0.6 million m3) of 32 API gravity oil and 11 million scf (0.31 million m^3) of natural gas. To date, over 1.8 million barrels (0.29 million m^3) have been produced and over 170 million barrels (27 million m^3) of water, in large part due to the strong bottom water drive. Reservoir pressure remains high at 2350 psi (16.2 mPa) and the reservoir temperature is 190 ^oF (88 ^oC). The expected reservoir temperature at this depth (5500 ft, 1676 m) would be roughly 125 ^oF (52 ^oC), assuming a regional geothermal gradient of about 1 ^oF per 100 ft. Initial CO_2 swelling tests show excellent response to CO_2, including substantial swelling, interfacial tension reduction of 90%, and five-fold viscosity reduction (Hycal, 2004). This suggests that a Tensleep Sandstone CO_2 flood would be miscible or near miscible, and modeling predicts good EOR response.

Second Wall Creek water flood:

Waterflooding and produced gas re-injection were both initiated in 1979 to help slow rapid production decline. Objectives of this publication do not include a thorough review of the 1987 geological and reservoir studies that focused on those floods. Rather it is sufficient to note that the waterflood was discontinued in 1992, and during its operation experienced many challenges related to the complex geology, faulted and fractured reservoir, low matrix permeability, aging wells (some dating back to the 1920s), well spacing issues and limited budgets (Lawrence-Allison, 1987). Though the reservoir is now in a pressure-depleted state, several wells continue production, gas cycling is still conducted, and produced natural gas liquids are stripped out at the NPR-3 gas plant and sold with the NPR-3 oil. Ultimate recovery from the reservoir is estimated at approximately 18.4% of original oil in place (US DOE, 2004).

Reservoir flow simulation

A series of computer reservoir simulations has been performed for the Tensleep Sandstone in Section 10 to confirm high reservoir fracture connectivity, and as part of the design work for a proposal in progress for a CO_2 EOR/storage pilot project. A sensitivity study, using the best estimate of sandstone matrix properties in a simulated dual-porosity solution of matrix and fracture flow, confirmed that fractures provide 20-100 times better flow capacity than the rock matrix. The high flow capacity of the fractures essentially equalized the pressure around the matrix pore volume, where most of the oil remains.

Simulations indicated good probability for using precise pressure measurements to determine the flow path of water as it moves to operating completions. Pressure observation while activating and idling producing wells was also shown to be a means for simulator validation by matching field and reservoir simulation pressure characteristics.

The reservoir simulation was tuned with equation-of-state parameters, matched to the 2004 oil laboratory testing of base and CO_2-enhanced fluid properties. Lab results indicated that the injection of CO_2 would result in swelling of the oil by over 20%, a significant reduction in oil viscosity, and a 95% reduction in interfacial tension (Hycal, 2004). This near-miscible fluid characteristic was accounted for in simulations to quantify enhanced oil recovery potential. Carbon dioxide injection could improve oil recovery by 30-40%.

The substantial recovery improvement would result from excluding the water from the fracture flow system high within the reservoir structure as the carbon dioxide replaces the water. The carbon dioxide would then process oil in the exposed blocks of matrix pores. The oil would swell, reduce in both viscosity and interfacial tension, and then drain into the fracture system for production at completions lower within the reservoir structure.

Simulations have demonstrated the potential for rapid testing of carbon dioxide for EOR in the pilot area. Conversion of one crestal well for injection of trucked carbon dioxide could mobilize oil for rapid response along the fractures to several down-structure producing “observation” wells operated to observe and capture the oil response. This gravity-stable project design would demonstrate a low-cost EOR operation applicable to many fractured reservoirs with high structural relief (Wadleigh, personal communication).

Current Status of Baseline Monitoring

RMOTC and partner institutions commenced baseline monitoring programs in late 2003 as part of the comprehensive site characterization necessary to support proposed CO_2 injection and other experiments. Work includes noble gas characterization (University of Manchester), soil gas surveys (Colorado School of Mines), vertical seismic profiling, including extended techniques (Lawrence Berkeley National Laboratory), electrical resistance tomography (Lawrence Livermore National Laboratory), and hyperspectral airborne surveys (Lawrence Livermore National Laboratory). Some of the results are presented here.

Noble gas tracing:

The University of Manchester is investigating the use of noble gases (helium, argon, etc.) as tracers for CO_2 movement in both EOR and carbon storage applications. These gases exist in low concentrations in the CO_2 supply stream provided by the Anadarko CO_2 pipeline. Field sampling and analysis of produced fluid samples from both the Salt Creek EOR project and Teapot Dome began in May 2005. Initial results are encouraging, but analysis and interpretation of the results are still in the early stages.

Soil Gas:

Soil gas composition and gas flux baseline conditions field-wide at NPR-3 were established over two years of study, beginning in fall 2003 and documented in two annual reports (e.g., Klusman, 2004 and 2005). Surface and shallow soil gas and gas fluxes measured from 40 locations field-wide, and samples from five 10-meter wells of gases from one to 10 meters depth provide C-13/C-12 ratio, methane, CO_2, and C-14 content of baseline CO_2 (Klusman, 2005). The monitoring phase of this work is planned to begin with initiation of CO_2 injection. Carbon dioxide fluxes averaged 227.1 mg CO_2 m^{-2} day^{-1} and a standard deviation of 186.9 mg m^{-2} day^{-1}. Methane fluxes averaged 0.137 mg CH_4 m^{-2} day^{-1} and a standard deviation of 0.326 mg m^{-2} day^{-1}. Isotopic and soil-gas concentration data suggested that increased CO_2 concentrations with depth were due to biological oxidation of soil organic matter.

Shallow Geophysics:

A VSP (vertical seismic profile) project to develop “designer seismic” monitoring is underway at Teapot Dome in collaboration with Lawrence Berkeley National Laboratory. This project is focused on using shallow microholes (provided through an experimental drilling program jointly pursued by the National Energy Technology Laboratory (NETL), Los Alamos National Laboratory (LANL) and RMOTC) specifically drilled and completed to be used as receivers, and attempting to image deeper horizons (three to four times the depth of the microholes) for CO_2 monitoring; these lines require processing. At the same location, researchers from Brigham Young University have conducted shallow reflection seismic profiles to compare with projected fault predictions, shallow well-log correlations, and the VSP work.

Airborne hyperspectral mapping:

The method uses high-resolution hyperspectral imagery to detect and map the effects of elevated CO_2 soil concentrations on the roots of the local plants (Pickles and Coven, 2005). The method also detects subtle or hidden faulting systems that localize the CO_2 pathways to the surface. As part of an induced natural gas pipeline leakage detection study at RMOTC in fall 2004, hyperspectral data were collected both as a baseline for CH_4 effect detection and for future CO_2 monitoring.

Leakage Risk Characterization

Fault zone fluid migration:

In addition to the USGS work (Brennan et al, 2005; Dennen et al, 2005) on organic chemistry of surface hydrocarbon minerals, RMOTC undertook work to directly investigate the leakage potential of faults within the field. Towards that end, RMOTC dug two shallow trenches across the S2 fault network in 2004-05 in order to look for direct evidence of prior or current fluid migration. To date, there is no evidence of current or recent migration of fluids from reservoir depth. However, chemical analysis of effluorescence pans along fault strands may indicate shallow groundwater recirculation along the fault (Klusman, 2005).

In order to better predict the risks associated with fault reactivation due to fluid injection and pressure transients, new studies have begun to characterize the fault geometry and in-situ stress patterns near the proposed Section 10 injection site. The predictions will follow well-established methodologies for fault fluid-migration risk (e.g., Wiprut and Zoback, 2002). This work is based on RMOTC data, interpretation of the 3D seismic volume and well logs, and new analyses by Stanford University.

Well-bore and cement integrity:

Public direct access to wells and lack of a strong production driver provides an unprecedented potential for analysis of well-bore integrity at Teapot Dome. In 2004, researchers from Princeton gathered direct well-bore cement samples from multiple horizons within a Section 10 Tensleep Sandstone well to assess the baseline character of the vintage cement prior to CO_2 injection. Samples ranged from relatively pristine to degraded. Physical and chemical measurements of these samples have served as a basis for synthetic models of aged cement for experimental analysis (IEA GHG 2005; G. Scherer, pers. comm.). Flow through experiments on the samples and these models indicated that calcium was removed and silicon reduced in a zone around the outer margin of the cement rod (iron remained largely unchanged). This corrosion was accelerated by low pH and high temperatures. As a maximum rate of reaction if fresh CO2 and carbonic acid flowed over the cement in place, as much as 2-3 mm of month might be removed.

Discussion

Over the past two years, substantial scientific resources were committed to the characterization of NPR-3 to prepare for possible CO_2 injection. This characterization is richer in data density, breadth, and character than that of many other potential CO_2 injection sites. Cores, well logs, 3D seismic, and surface geological data served as a template on which to place geochemical, geophysical, and structural interpretations. Additional production history data, high-resolution well tools, and simulations help to confirm the initial predictions, and baseline monitoring suites will serve as a basis for comparison once injection begins. Importantly, these data are all within the public domain, which allows future researchers to gain access to the prior data and interpretations for their own use. Similarly, independent researchers who have specific research questions can use the site to test and verify their approach while adding new characterization to the site pre-injection. Although it is a U.S. federal facility, NPR-3 may serve as a site for increased international collaboration. Researchers from the University of Manchester (U.K.) have already worked at the site, and other international groups have expressed an interest in testing their equipment and techniques as well.

The current state of reservoir characterizations provides an excellent baseline for certain kinds of studies. For example, the USGS work on reservoir segmentation and lack of communication in certain reservoirs would provide a technical basis for studying geomechanical effects and pressure build-up characterizations; aspects of this problem will be the focus of a new Stanford Ph.D. study. Similarly, given the ease of access to cement samples and well bores, the field is an ideal site for well-bore integrity studies. The abundance of accessible and non-producing wells also creates a natural facility to test and deploy monitoring arrays with great density. Finally, the abundance of well-constrained geological information, including geochemical and petrophysical data, could provide a community model for intercomparison of codes between different research groups in a predictive (forward) context. As CO_2 injection activities are scheduled in the field, there will be new opportunities to investigate these and other scientific and technical questions.

Acknowledgements

The authors would like to acknowledge the technical contributions of the following individuals: Mark Milliken, Tom Anderson, Brian Black, Dag Nummedal, Peigui Yin, Neil Hurley, Nathan Gilbertson, Gene Wadleigh, Tim McCutcheon, Ronald

Klusman, Scott Cooper, John Lorenz, Ernie Majer, Mike Hoversten, Mark Zoback, Laura Chiaramonte, Tom Wilson, Robert Burruss, Sean Brennan, Kristen Dennen, Chris Ballentine, Sarah Mackintosh, David Schechter, George Scherer, Andrew Duguid, Jeff Wagoner, Tor Nilsen, and Leo Giangiacomo. Special thanks to Doug Tunison and Jim States who helped gain approval for this manuscript. The Lawrence Livermore National Laboratory is operated by the University of California for the U.S. Department of Energy under contract W-7405-Eng-48.

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Tables

Table 1: Data types and formats available of Teapot Dome

Data Type	Format	Accessibility
3D Seismic Volume	Digital	Direct
3D seismic interpretations, including horizons & faults	Digital	Indirect through vendor
Wireline logs: 423 deep wells (>2700')	Digital	Direct
Wireline logs: 800 shallow wells	Paper/raster format	Direct and indirect (WOGCC)
Cores	Boxed samples	Direct and indirect
Core descriptions	Reports, paper and raster	Direct and indirect
Formation tops and picks	Digital and paper	Direct and indirect
Well completion reports	Paper	Direct
Well and formation production data	Paper and raster	Direct
Reports on field experiments and studies	Raster	Direct
Production tests	Raster	Direct
Geochemical analyses, incl. hydrocarbon and brine composition	Paper and raster	Direct
Full 3D flow simulations	Digital and raster	Indirect
Static geomodels of Tensleep Sandstone, Section 10	Digital	Indirect

Table 2: Key oil-bearing and brine-bearing reservoir targets

Unit	**Age**	**Lithology; Depositional Environment**	**Depth/ Thickness ft (m)**	**Seal**	**Pore fluid**
Shannon Sandstone	Upper Cretaceous	Sandstone; fluvial/tidal	515 (157)/ 120 (37)	Carlisle Shale	Oil
1st Wall Creek Sandstone	Upper Cretaceous	Sandstone; deltaic	2650 (808)/ 160 (49)	Frontier shale	Brine
2nd Wall Creek	Upper Cretaceous	Sandstone; fluvial/deltaic	3086 (941)/ 65 (20)	Frontier shale	Oil
3rd Wall Creek	Upper Cretaceous	Sandstone; deltaic	3325(1013) / 5 (1.5)	Frontier shale	Oil
Muddy Sandstone	Lower Cretaceous	Sandstone; shoreface	3840(1170) / 15 (4.6)	Mowry Shale	Oil
Dakota Sandstone	Lower Cretaceous	Sandstone; fluvial	3975(1212) / 85 (26)	Thermopolis Shale	Oil
Lakota Sandstone	Lower Cretaceous	Conglomeratic sandstone; fluvial	4060(1237) / 10 (3)	Thermopolis Shale	Oil
Sundance Sandstone	Jurassic	Sandstone; shoreface	4340(1323) / 95 (29)	Morrison Fm. Shales	Brine
Crow Mt.	Triassic	Sandstone; fluvial	4585(1378) / 80 (24)	Lower Sundance shales	Brine
Tensleep Sandstone	Pennsylvanian	Sandstone & dolostone; eolianite & sabkha	5205(1586) / 320 (98)	Goose Egg shales & evaporites	Oil
Amsden Fm.	Pennsylvanian	Limestone; carbonate platform	5845(1782) / 160 (49)	Dolomicrites	Brine
Madison Fm.	Mississippian	Limestone; carbonate platform	6005(1830) / 300 (91)	Dolomicrites & evaporites	Brine
“Flathead” Sandstone	Devonian	Sandstone; braided fluvial	6865(2092) / 200 (61)	Devonian shales	Brine

Table 3: Tensleep Sandstone Characteristics at NPR-3

	Average	2σ range
Porosity (ϕ)	8	1 – 19
Permeability (mD)	80	0 – 110
Thickness (ft, m)	320 (97.5 m)	300-350 (91.4-107 m)
Salinity (mg/L)	3100	2600-3600
Gravity (API units)	32	32-40
Cap rock thickness (ft, m)	300 (91.4 m)	310-330 (94.5-101 m)

Figure Captions:

Figure 1: Location for Teapot Dome. (Left) Shaded relief map of Wyoming with location of CO_2 pipelines. Orange line (Bairoil to Salt Creek) was completed in early 2004. Red areas are large gas fields, and green areas are large oil fields. Image is courtesy of Anadarko Petroleum Corporation. (Right) Structure map on the top Second Wall Creek Sandstone at the Salt Creek and Teapot Dome oil fields. Heavy outline shows NPR-3 field boundary. Small squares (sections) = 1 mi^2 (2.6 km^2). Distance from Casper to Teapot Dome is roughly 40 miles; field outline of Teapot Dome extends roughly 7 miles from northern to southern end.

Figure 2: (a) Map of NPR-3 surface geology, including surface faults and projections of fault networks from depth (McCutcheon, 2003; after Horn, 1959). Light red zones are surface projections of faults mapped at depth based on 3D seismic interpretations; darker red lines are mapped locations of faults at surface. Dark green lines in center of field are Sussex Sandstone outcrops. The S1 and S2 fault networks are marked. Red box in lower field center is section 10. Thin blue line shows field outline; black dots are wells. (b) Time-structure map of the basement. Note parallel structure to surface (c) Contoured time-structure map of basement (Stamp et al. 2004)

Figure 3: 3D seismic visualization showing the top of the Second Wall Creek Sandstone viewed towards the northeast. Sticks represent the main faults within the S2 fault network.

Figure 4: Stratigraphic column for the Teapot Dome field. Dark-grey boxes on the far right represent oil-bearing zones, and light-grey units represent brine-bearing zones.

Figure 5. (a) Paleogeographic map of early Permian Tensleep extent; dark area represents area of thickest deposition. After Miller (1992) (b) Stratigraphic correlation diagram for the late Paleozoic in Wyoming. The Tensleep Formation is shown in the center. Revised from WGA guidebook, 2000. (c) Core from 48-x-28. Note the oil staining in the upper (left) core sandstone and the underlying brine aquifer in the lower (right) core.

Figure 6. (a) Diagram of depositional boundaries within the Tensleep at Bighorn Mountain. The thick blue lines are marine carbonates that overlie the terrestrial dune deposits of the main sandstones. Black lines are boundaries between migrating dunes, and thin brown lines show the original stratal inclination of the dune foreset beds. (b) Tensleep porosity and permeability by sedimentological unit: DUC=dune uncemented; DC = dune cemented; DDC = dune dolomite cemented; IDUC = interdune uncemented; IDC = interdune cemented.

Figure 7. Core description, environmental interpretation, and sequence stratigraphic architecture of Tensleep well 54-TPX-10 from within section 10. Note the variable permeability in the “A” and “B” sandstones as a function of cementation and sub-environment.

Figure 8: Fracture systems within NPR-3. (a) Curvature analysis of the 2nd Wall Creek Horizon. Note NE-SW trends. Dashed black line is the fold axis. (b, c) Outcrop fractures of the Parkman Sandstone (Cooper et al., 2003) around the end of the field. (b) fractures parallel to surface faults interpreted as tear faults; (c) fractures at a high angle to surface faults. (d) Rosette diagram of natural fractures within the Tensleep Sandstone as imaged by FMI logs, well 48-x-28. (e) Photo of segment of 25 ft. (7m) long cemented fracture in Tensleep reservoir.

Figure 9: Outcrop fracture studies on the Tensleep Sandstone along an analogous structure: the Alcova Anticline. (a) Outcrop photomosaic of the north side of the canyon. (b) LIDAR 3D projection of point cloud of the same outcrop. The inset rosettes show the fracture trends derived from the LIDAR point clouds. (c) Close-up segment of the NE side of the northern canyon wall. Inset blow-up shows details of digitally derived strike and dip maps and derived fracture geometries. From Gilbertson and Hurley (2005).

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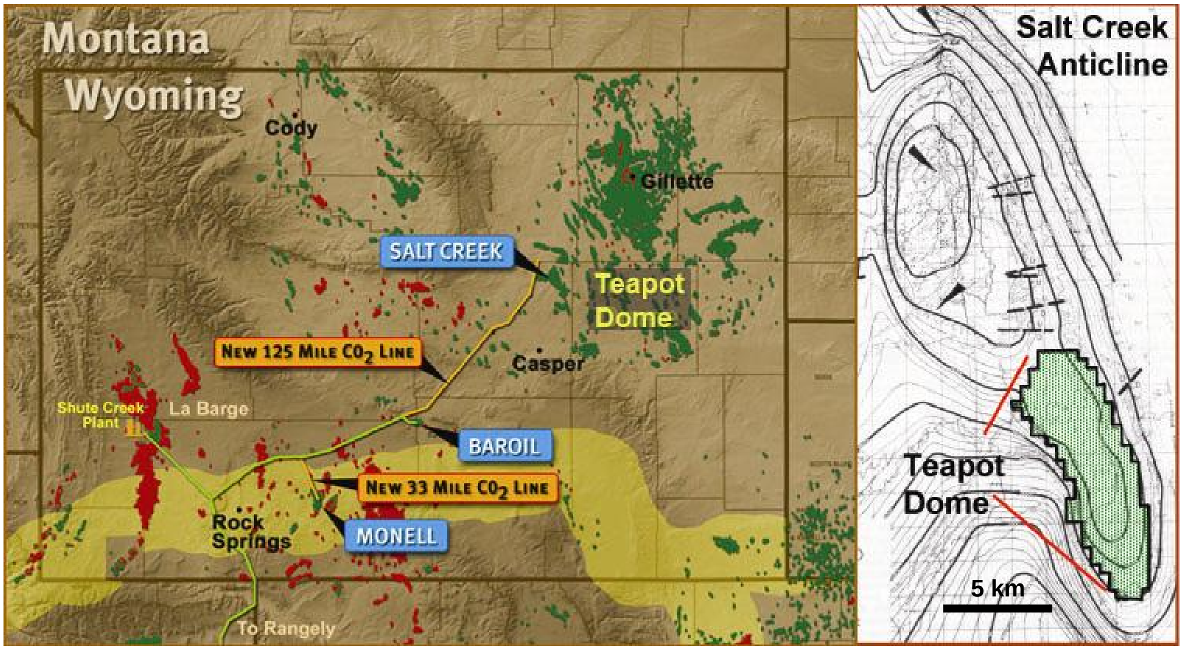

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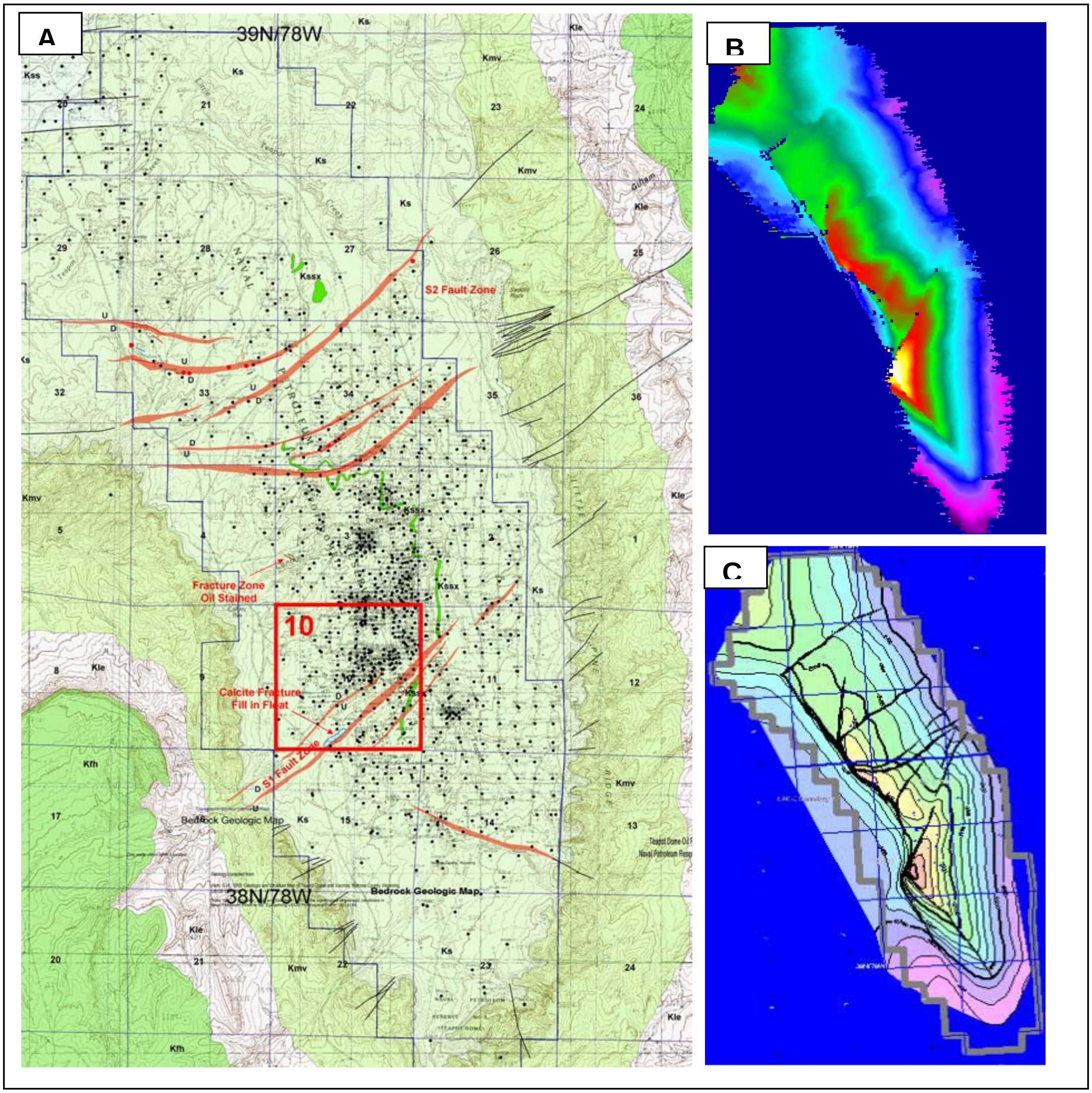

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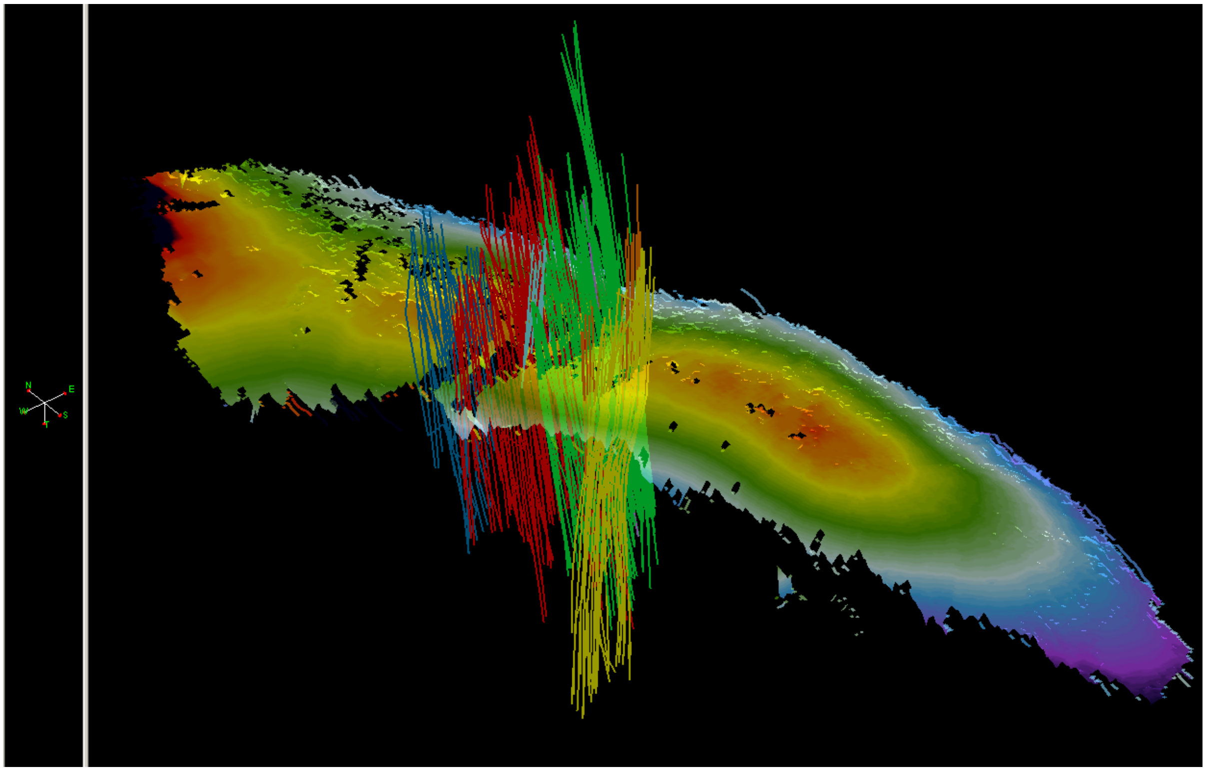

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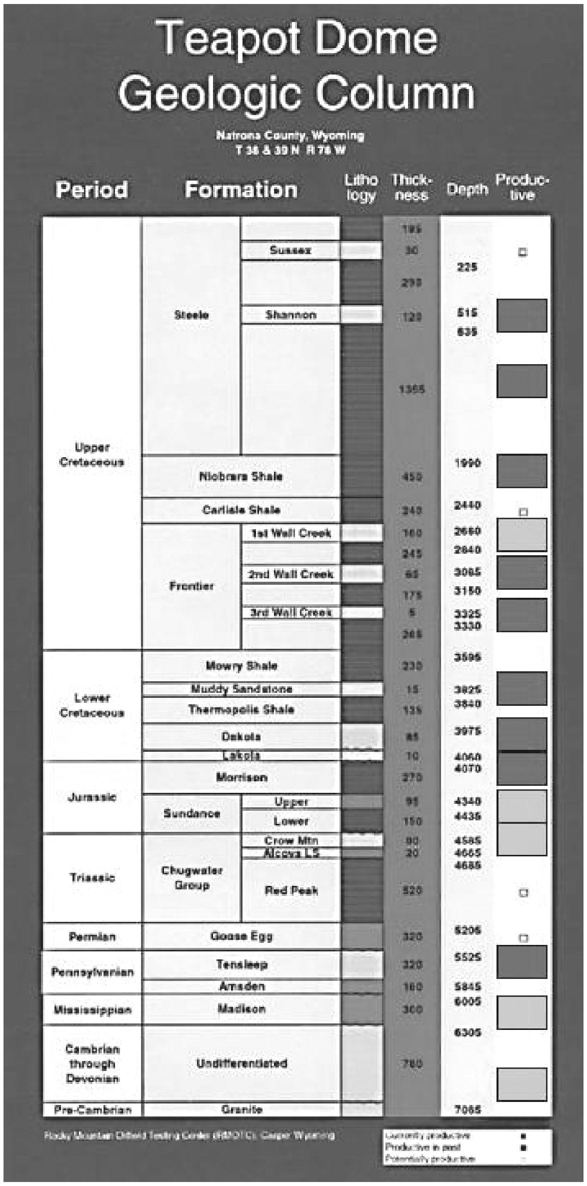

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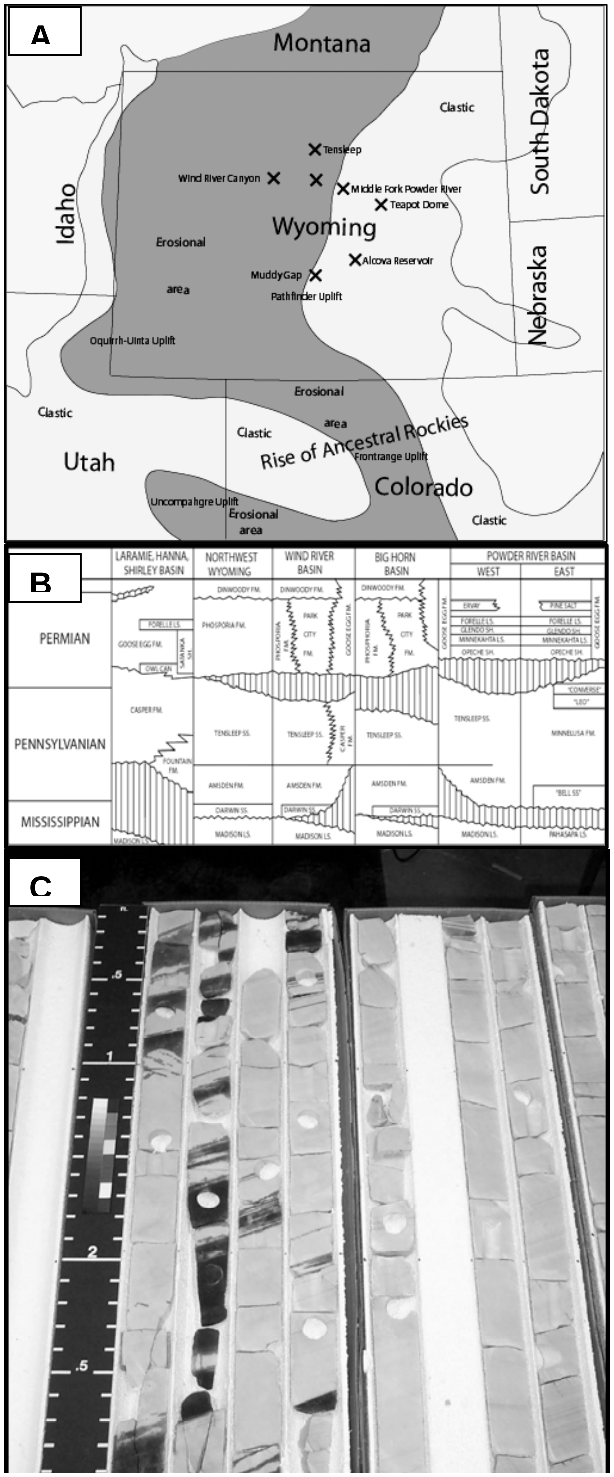

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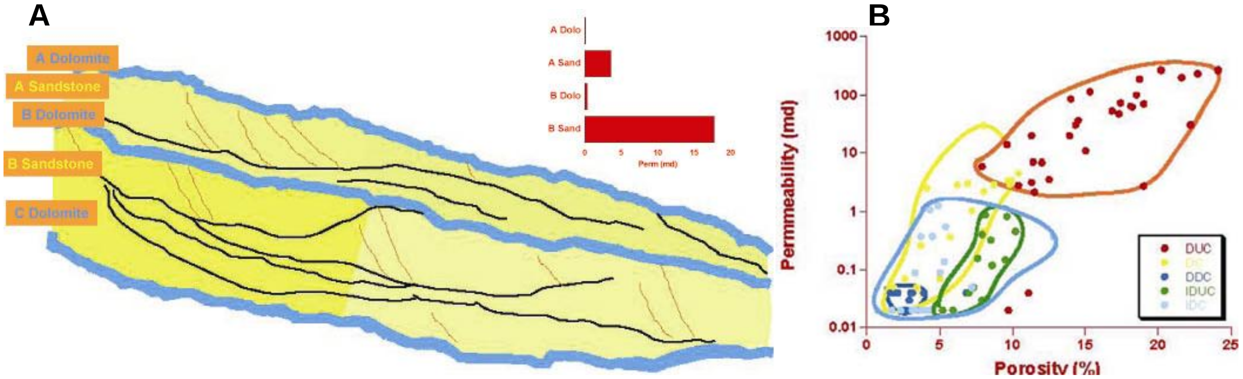

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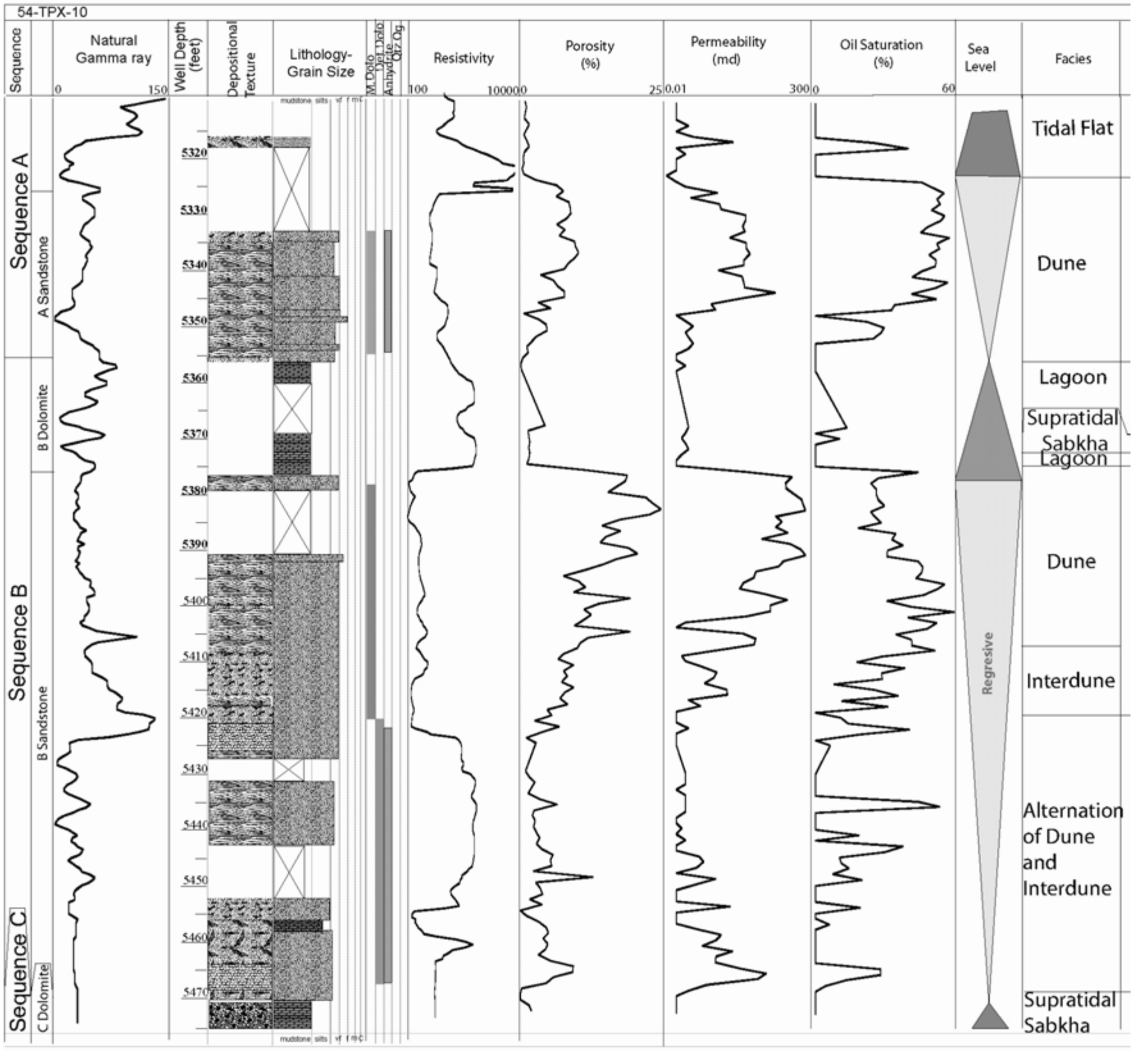

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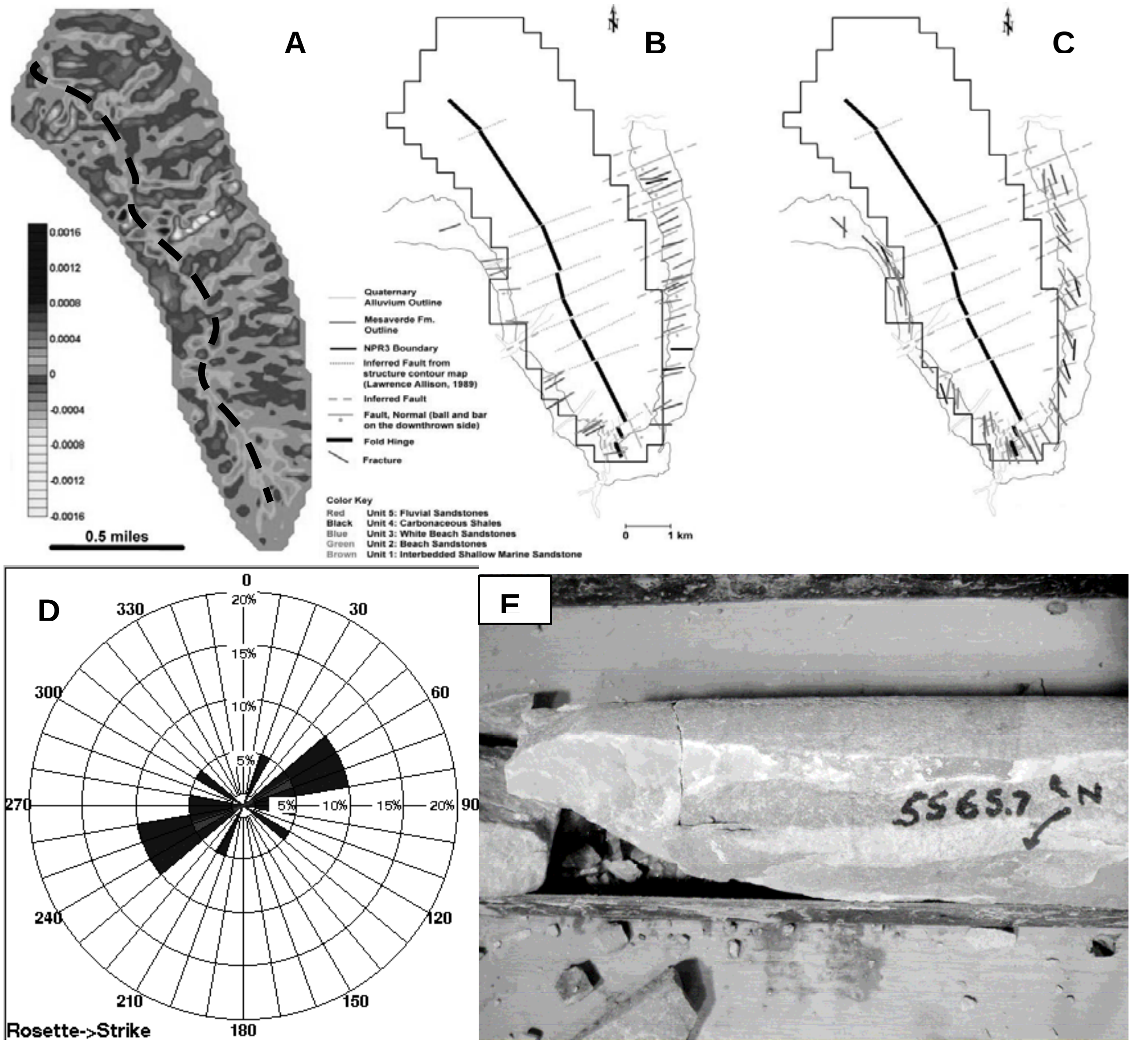

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