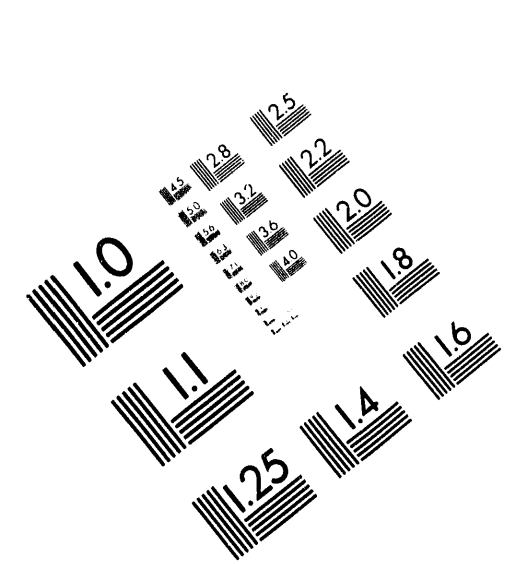

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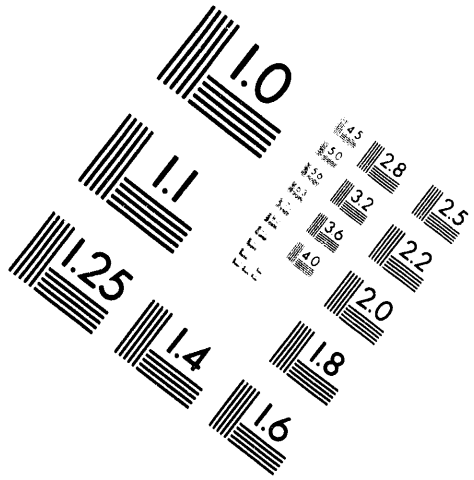

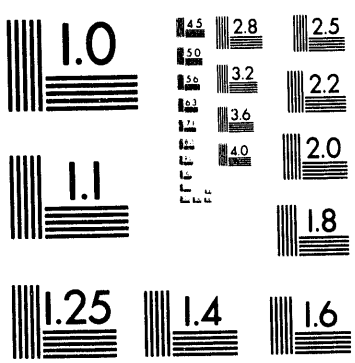

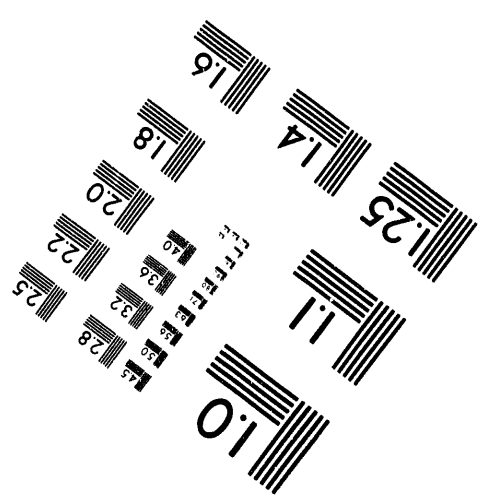

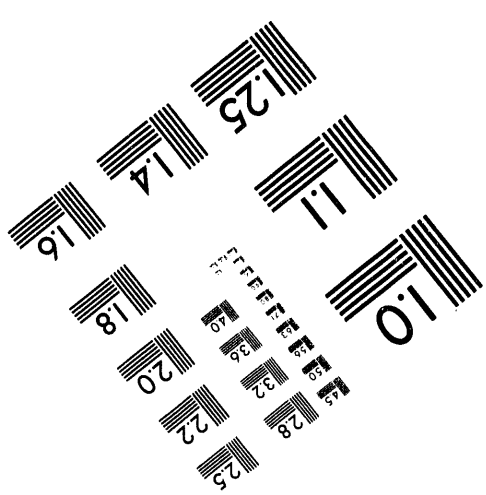

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ANISOTROPY AND SPATIAL VARIATION OF RELATIVE PERMEABILITY AND LITHOLOGIC CHARACTER OF TENSLEEP SANDSTONE RESERVOIRS IN THE BIGHORN AND WIND RIVER BASINS, WYOMING

D.O.E. Contract No. DE-AC22-93BC14897

Contract Starting Date: September 15, 1993
Contract Completion Date: September 14, 1996

D. O. E. Award for the Current Year: $258,359

Third Quarterly Technical Progress Report

Reporting Period: April 1, 1994 -- June 30, 1994

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Department of Energy Contracting Officer: Mr. Eric T. Bell

July 22, 1994

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Objectives

This multidisciplinary study is designed to provide improvements in advanced reservoir characterization techniques. This goal is to be accomplished through: (1) an examination of the spatial variation and anisotropy of relative permeability in the Tensleep Sandstone reservoirs of Wyoming; (2) the placement of that variation and anisotropy into paleogeographic, depositional, and diagenetic frameworks; (3) the development of pore-system imagery techniques for the calculation of relative permeability; and (4) reservoir simulations testing the impact of relative permeability anisotropy and spatial variation on Tensleep Sandstone reservoir enhanced oil recovery.

Concurrent efforts are aimed at understanding the spatial and dynamic alteration in sandstone reservoirs that is caused by rock-fluid interaction during CO_2-enhanced oil recovery processes. The work focuses on quantifying the interrelationship of fluid-rock interaction with lithologic characterization in terms of changes in relative permeability, wettability, and pore structure, and with fluid characterization in terms of changes in chemical composition and fluid properties. This work will establish new criteria for the susceptibility of Tensleep Sandstone reservoirs to formation alteration that results in change in relative permeability and in wellbore scale damage. This task will be accomplished by flow experiments using core material; examination of regional trends in water chemistry; examination of local water chemistry trends at field scale; and chemical modeling of both the experimental and reservoir systems in order to scale up the experiments to field scales.

Progress Summary

The project reached full staffing this quarter. Considerable progress was made on each of the tasks. The building of the subsurface database for Task 1.0 is on schedule and includes information for 1463 well locations. Field work for Task 1.0 began at the end of this quarter. The Tensleep core examination has been delayed until Dr. Crabaugh, the project sedimentologist, has completed the initial field work. Task 2.0 is ahead of schedule and proceeding with testing and calibration of the relative permeability measurement apparatus. The initial regional water chemistry investigation for Task 3.0 was completed. Also, the first CO_2 rock-water interaction experiment was designed this quarter and is scheduled for next quarter.

TASK 1.0 — REGIONAL FRAMEWORKS. This research will associate spatial distributions and anisotropy of relative permeability with the depositional subfacies and zones of diagenetic alteration found within the Tensleep Sandstone. The associations between depositional lithofacies, diagenetic alteration, and pore geometry will strongly link relative permeability with the distinct and measurable dimensions of lithofacies and authigenic mineral facies. Effects of the depositional processes and burial diagenesis will be investigated.

We have completed building the computer database for both basins. This includes 1463 well locations. Over 200 porosity (density and neutron) and gamma ray log traces have been digitized. We project that another 200 traces will be added by summer's end. Core analyses from 70 wells have also been entered into the database. These materials will form the basis for the subsurface mapping that will be the principle work of Task 1.0 during the winter months. The software obtained (PRODUCTION ANALYST) allows us to interactively build cross sections and maps, and add correlations of our internal divisions of the Tensleep sandstones. Burial histories for four key locations in the two basins were contructed. These histories indicate relatively shallow burial for the Tensleep during its early stages. This is an important point to later interpretation of Tensleep Formation water chemistry evolution (Task 3.0).

Dr. Mary Crabaugh, the project eolian sedimentologist, arrived on May 31. Her initial field work commenced in early July. She spent the month of June familiarizing herself with current concepts of Tensleep deposition, stratigraphy, and paleogeography. A number of other workers have identified several correlatable surfaces in the Tensleep. Dr. Crabaugh is charged with interpreting the origin of these surfaces, determining the lithofacies present, and providing lithofacies samples for Tasks 2.0 and 3.0. She will be joined in the field by Ms. Lauren Personette, a UW geology undergraduate student. Core examination has been delayed until Dr. Crabaugh has completed the initial stages of the field work.

TASK 2.0 — RELATIVE PERMEABILITY MEASUREMENTS. The focus of this task is to obtain quantitative laboratory data on the magnitude and variability of relative permeability anisotropy and spatial variation of the dominant reservoir and boundary surface lithologies of the Tensleep Sandstone. Existing data will be collected, compiled, and placed within the regional frameworks constructed in Task 1.0. Laboratory measurements will be performed in the Petroleum Engineering Department at the University of Wyoming. Relative permeability will be measured using the unsteady-state technique. An additional objective of this study is to provide algorithms for calculating relative permeability from quantitative pore imagery data.

The construction of the apparatus has been completed. Testing and calibration is in progress. We have established procedures to be used to measure relative permeability. The laboratory work for measurement of relative permeability is ahead of schedule. We have obtained Tensleep windripple laminated eolian sandstone from the Owl Creek uplift, the structure that separates the Big Horn and Wind River basins. We have also obtained crude oil from the Black Mountain oil field (Texaco). This crude oil has typical Tensleep viscosity and API gravity. The oil will be the principle hydrocarbon used for the experiments. In the laboratory, we have cut cores both parallel and perpendicular to bedding planes and have begun preliminary permeability analysis. The plugs have been flooded with both water and oil. A few modifications to the apparatus have been necessary. Apparatus pressures are high due to relatively low permeability and high oil viscosity (100cps). Flow output is unusually abrupt upon break-through of water. We believe that this is due to some irregularities in the rubber confining sleeve allowing leakage along the sides. Fractional flow in the first test was not smooth, as is required by the J-B-N relative permeability calculation in order to avoid singularities in the solution. Experimental modifications will be made during the next quarter.

The field coring device (a modified chain saw) has been successfully fitted to cut the required 1.5-inch cores.

TASK 3.0, CO2 FLOOD — FORMATION ALTERATION AND WELLBORE DAMAGE. The work of this task is to establish criteria for susceptibility of Tensleep reservoirs to formation alteration resulting in a change in absolute or relative permeability and possible wellbore scale damage during CO_2 enhanced oil recovery. This advanced reservoir characterization technology will be used to optimize recovery efficiency. This task includes: (a) flow experiments on core material to examine the effects of CO_2 flooding on the alteration of the fluid and rock system; (b) examination of regional trends in water chemistry; (c) examination of local water chemistry trends at field scale; and (d) chemical modeling of both the reservoir and experimental systems in order to scale-up the experiments to reservoir conditions.

Chemistry of Tensleep Formation Water

We have compiled 94 water analyses for Tensleep Formation water from both the Wyoming State Geological Survey and publications. The waters which have been included in the study have a charge balance of ± 10%. This necessary criterion eliminates roughly two-thirds of the available analyses. The analyses include data of total dissolved solids (TDS), pH, Na^+, K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, Cl^-, and HCO_3^-. The latitude and longitude were obtained for each well. We will continue to enlarge this water database through acquisition of analyses from industrial sources. Also, we are currently entering Tensleep formation water resistivities into the database. These analyses require additional computer-intelligible location information. This work will be completed in the fourth quarter.

The TDS of the Tensleep formation waters varies from 234 mg/l to 10,994 mg/l, which is much lower than that of sea water (35,000 mg/l). Thus far, we have not found a typical NaCl-type solution. These compositions indicate that the original formation waters were completely flushed out of the formation and that reaction between the rock and the meteoric water that penetrated into the formation produced new water chemistries. The burial histories indicate that the Tensleep experienced relatively shallow burial during its early history. Hence, pre-Laramide flushing and mixing of connate and meteoric water

likely occurred. The current distribution of water chemistry (see below), however, clearly shows a Laramide recharge pattern.

We have found two types of water chemistry in Tensleep Formation water. Water A is rich in Ca^{2+}, Mg^{2+}, SO_4^{2-}, and HCO_3^- and has very low Cl^- content ($X_{Cl} < 0.05$, where X_{Cl} is the mole fraction of chloride). Water B has higher Cl^- and a mole fraction of Cl^- which widely varies ($0.05 < X_{Cl} < 0.67$). Water A chemistry has a good linearity between $[Ca^{2+} + Mg^{2+}]$ and $[SO_4^{2-} + HCO_3^-]$, suggesting that this chemistry is controlled by dissolution /precipitation of anhydrite, gypsum, calcite, and dolomite, as suggested by Mankiewicz and Steidtman (1979). We consider that Water A is the typical formation water chemistry of the Tensleep Formation. This relation between $[Ca^{2+} + Mg^{2+}]$ and $[SO_4^{2-} + HCO_3^-]$ in type B waters is obscure, compared with the clear relation in type A water. The formation water of the Park City Formation, which overlies the Tensleep Formation, is rich in NaCl. Its proximity suugests that the water chemistry of type B water is likely due to mixing with the waters of this formation or the underlying Madison Formation, which also contains NaCl-rich formation waters.

The wells that produced type A waters from the Tensleep that we have obtained thus far are distributed mainly along the northeast side of the Bighorn Basin, whereas type B waters are distributed mainly along the southwest side of the basin. The high-TDS waters of both types are distributed basin-ward of major faults, whereas low-TDS waters are found along the perimeter of the basin, indicating that the basin bounding faults prevent penetration of meteoric water, as shown by Huntoon (1982).

CO_2-Flooding Experiment

We have designed the first experiment of CO_2 flooding at the Petroleum Research Center, Marathon Oil Company, Littleton, Colorado. We will run

experiments at 80°C and 2400 psi (165.5 bars), which are conditions close to those found in the Tensleep Formation in the Bonanza Oil Field in the Bighorn Basin. The pressure vessel will hold up to six core pieces 1.5 inches in diameter and 3 inches in length. We will obtain Tensleep core samples from the core collection of Marathon Oil Company. We will use a magnesium and calcium sulfate solution as a nutrient solution (TDS = 2,726 mg/l), which is a typical type A water chemistry. This solution should be in equilibrium with respect to anhydrite at experimental temperature and pressure. The experimental nutrient solution will be pressurized with CO_2 gas to obtain $P_{CO2} = P_{total}$. Oil will not be used in the first run. The first run has been scheduled to begin September 6.

TASK 4.0 — PROJECT MANAGEMENT AND TECHNICAL TRANSFER. This task incorporates efforts to achieve a high level of success in this interdisciplinary project. This administrative task provides for effective coordination and integration of the project's research tasks. The program manager is responsible for ensuring that the task workers meet on a frequent and regular basis to exchange information and discuss results. The program manager is responsible for the coordination and timely reporting of results to its Industry Advisor/Mentors, the Department of Energy, and the scientific and engineering communities.

The project reached full staffing late in this quarter. An additional DOE reporting requirement, the Project Fact Sheet, was prepared in April. The Industrial Advisor/Mentors were contacted by phone or written correspondence. The entire group has met on occasion to review the project's direction. The Task leaders for Tasks 1.0, 2.0 and 3.0 now have adjoining offices.

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