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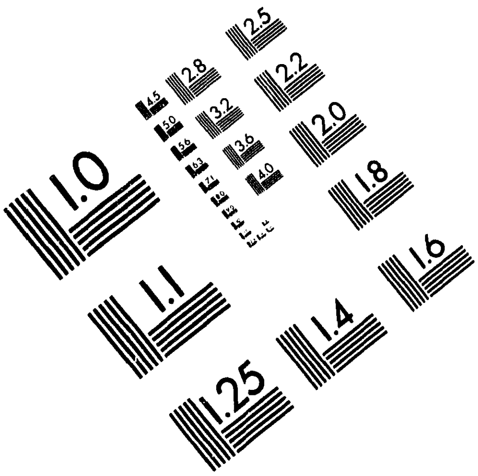

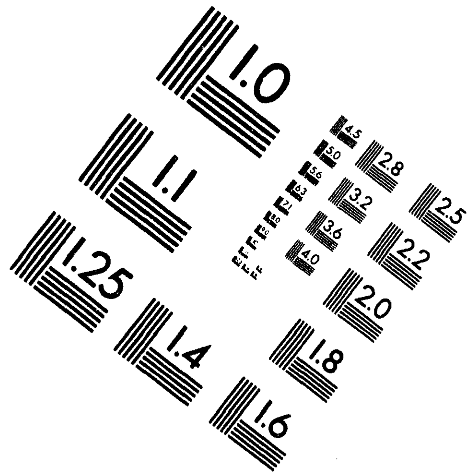

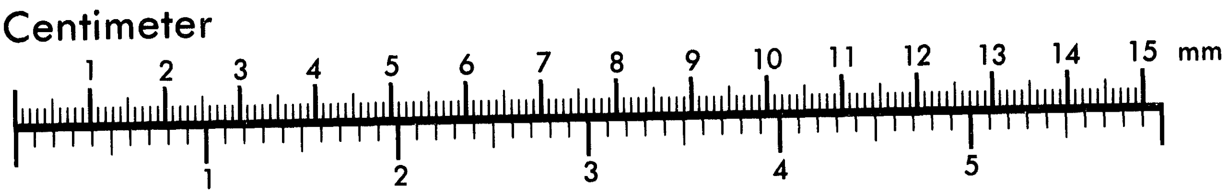

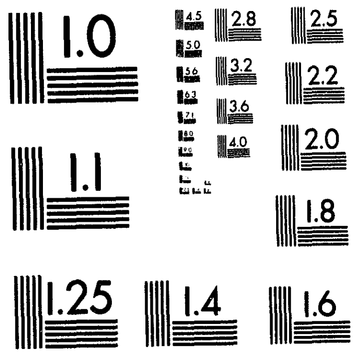

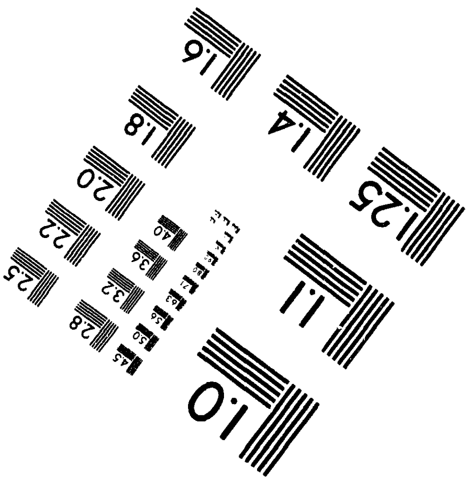

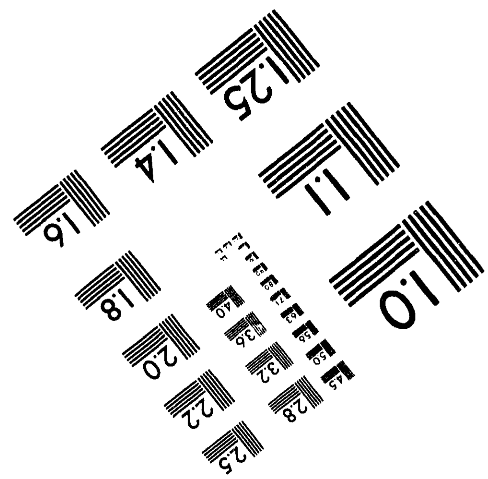

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Summary Annual Report

Geophysical and Transport Properties of Reservoir Rocks

Contract No. DE-AC22-89 BC 14475

University of California at Berkeley
Berkeley, CA 94720

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Principal Investigator:
Neville G.W. Cook

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Objectives

Definition of petrophysical properties, such as porosity, permeability and fluid saturation, on the scale of meters, is the key to planning and control of successful Enhanced Oil Recovery techniques for domestic reservoirs. Macroscopic transport properties in reservoir rocks depend critically upon processes at the pore level involving interactions between the pore topology and the physical and chemical properties of the rock minerals and interstitial fluids. Similar interactions at the pore level determine also the macroscopic electrical and seismic properties of reservoir rocks. The objective of this research is to understand, using analysis and experiment, how fluids in pores affect the geophysical and transport properties of reservoir rocks. The goal is to develop equations relating seismic and electrical properties of rock to the porosity, permeability and fluid saturations so as to invert geophysical images for improved reservoir management.

Summary of Progress

In FY 91 research was carried out in Tasks 2, 3, and 4 as scheduled in the Management Plan for this project. Progress in each task, is discussed below.

Task 2 Fluid permeability and electrical impedance with Wood's Metal.

Porosimetry measurements using Wood's metal have been made on samples of Berea sandstone 2 inches long x 2 inches in diameter. The percolation threshold was detected by measuring electrical resistance across the length of the sample. As soon as percolation was achieved, the sample was quenched in crushed ice to preserve the percolating structure. The first experiments showed that a preferred path of interconnected pores existed near the cylindrical surface of the sample beneath the rubber jacket. A technique for sealing the outer pores with a coating of epoxy resin was developed and tests to obtain intrinsic percolating structures were then performed. A capillary pressure of 0.67 atm (corresponding to a throat diameter of 24 μm is needed to establish a percolating path along the 2 inch length of the Berea sandstone. (For Indiana limestone the corresponding pressure is 1 atm and 16 μm). The percolated samples were next divided into quarters along their axial length. The residual permeability of the final 0.5 inches of the percolated specimen was only 20% of the single phase permeability of the rock even though less than 10% if the pore space was occupied by the non-wetting (immobile) percolated phase.

Task 3. Analysis of pore topology, permeability and impedance.

Techniques for dissolving away the complete mineral phase in specimens as large as 1 inch cube using hydrofluoric and hydrochloric acids were developed. Using specimens of Berea sandstone and Indiana limestone partially saturated with Wood's metal in Task 2, the three dimensional structure of the pore topology was studied by stereo pairs of SEM micrographs. The topology of the sandstone comprises large pores connected by small throats. The topology of the limestone pores comprises ribbon-like clusters.

Cross-sections of pores occupied by wetting and non-wetting phases were obtained from collages of SEM micrographs of polished sections saturated with Wood's metal and epoxy resin. Using the Kozeny-Carmen equation and pore cross-sections resulted in predicted permeabilities at least an order of magnitude larger than measured permeabilities. Further analyses showed that pore cross-sectional shapes were not adequate to explain the difference between measured and predicted permeabilities.

Task 4 Measurements of permeability, electrical and seismic properties.

Extensive measurements of compressional and shear wave velocities and attenuation have been made in specimens of Berea sandstone, Indiana limestone, sintered glass beads and alundum under uniaxial and hydrostatic stresses using a variety of pore fluids. Sintered alundum and glass beads were used because these porous materials have well-bonded grain contacts as verified by stereo SEM micrographs. Compressional and shear wave attenuation in alundum and Berea sandstone saturated with water, n-decane, glycerol and silicone oil was measured as a function of uniaxial and hydrostatic applied stress. All of these fluids have similar density and compressibilities, but differ in viscosity and chemistry as reflected by their surface tension: water (1cP, 72m J/m^2); n-decane (0.92cP, 28m J/m^2); glycerol (1490cP, 64mj/m^2), and silicone oil (913cP, 21mJ/m^2). Using the different fluids it was shown that attenuation in alundum is virtually independent of applied stress but increases with viscosity as predicted by Biot theory for the experimental seismic wave frequencies. Results of tests on Berea sandstone, however, were not consistent with Biot theory. Compressional and shear wave attenuation in the sandstone is very sensitive to the applied stress and depends both on the chemistry and viscosity of the pore fluid. Using water as a pore fluid a series of tests were also performed on Berea sandstone under varying degrees of saturation.

Significant Accomplishments

A new technique, one-dimensional percolation with Wood's metal, provides a very precise means for determining the characteristics of the critical percolating path through a porous medium and preserving that path for subsequent analysis by a variety of techniques.

In conventionally prepared (diamond core drilling) samples jacketed in a rubber sleeve, a spurious, preferred critical pathway exists adjacent to the cylindrical surface. Such pathways may have affected the results of many published permeability and porosimetry measurements.

The critical percolating path accounts for a very significant fraction of the total permeability in the samples tested. Results imply that about 80% of the total permeability derives from critical percolating paths that occupy less than 10% of the pore space.

Velocities and attenuation in sintered alundum and fused glass beads are found to be essentially independent of the nature (uniaxial or hydrostatic) and magnitudes of the applied stresses. They depend only on the density and viscosity of the contained fluid and on the pore topology. The experimental results have been shown to agree well with Biot theory for wave propagation in saturated porous materials.

Compressional and shear wave attenuation in Berea sandstone was found to very sensitive to the stress state as well as the chemistry of the pore fluid. Results were not consistent with Biot theory and show that physical and chemical interactions between the pore fluids and minerals at the grain contacts are important in seismic wave propagation in reservoir rocks.

With water as a pore fluid attenuation in the Berea samples is independent of saturation in the range 4 percent to 100 percent and does not depend upon whether the water is added before or after stress is applied.

Significance for EOR Research Plan

...nces in seismic and electromagnetic imaging at a scale smaller than interwell spa...ng offer the prospect of studying intrinsic variations in reservoir lithology and fluid contents as well as changes brought about by production processes. The inversion of such images to determine reservoir properties such as porosity, as well as fluid content and chemistry, is essential to the application of imaging results to the optimum design and implementation of improved extraction and production processes.

Results from seismic measurements performed so far in this study suggest that even subtle changes in fluid contacts and the in-situ state of effective stress can be detected using geophysical imaging techniques. The experiments using Wood's metal and wax are revealing the topology and transport properties of the pore space in clastic sedimentary rocks. A deeper understanding of these properties is considered to be the key to the recovery of much of the mobile oil left in domestic reservoirs and to the effective management of enhanced oil recovery techniques. The results of Wood's metal percolation tests indicate that most of the permeability of Berea sandstone resides in the critical percolating paths and these paths occupy only a small fraction of the total porosity. This result may have important implications for flooding in terms of override and efficiency as a function of saturation.

Future Research Plans

In Task 2 measurements of fluid permeability and electrical impedance using different partial saturations of hydrocarbon waxes and brines will be completed and the influence of pore deformation at high effective stresses will be measured.

The topology of wetting and non-wetting phases in samples from Task 2 will be digitized in Task 3 to produce three-dimensional computer images of pore networks for quantitative analysis, using topological, network, and effective medium theories.

In Task 4 seismic velocities and attenuation in specimens partially saturated with Wood's metal, sulfur, hydrocarbons and brines from Task 2 will be measured at different effective stresses, so that seismic properties can be correlated with fluid permeability and electrical impedance measurements. Seismic results will be analyzed in the frequency domain and mechanistic theories for attenuation will be developed in Task 5.

Publications

"Measured and theoretical Biot attenuation and velocities for ultrasonic P- and S-waves in sintered glass beads," K.T. Nihei, N.G.W. Cook, and L.R. Myer. Submitted for presentation at 120th Meeting of the Acoustical Society of America, November, 1990.

"Role of fluids on ultrasonic attenuation in porous materials, " K.T. Nihei, P.J. Cook, L.R. Myer and R. Súarez-Rivera. Submitted for presentation at 120th Meeting of the Acoustical Society of America, November 1990.

"Influence of grain contact stresses on P- and S-wave attenuation in partially saturated Berea sandstone," R. Súarez-Rivera, K.T. Nihei and N.G.W. Cook. Submitted for presentation at 120th Meeting of the Acoustical Society of America, November 1990.

"Predicting permeability and electrical conductivity of sedimentary rocks from micro-geometry," E.M. Schlueter, N.G.W. Cook and R.W. Zimmerman. Submitted for presentation at American Geophysical Union Fall Meeting, December 1990.

"The effect of percolating structures on the petrophysical properties of Berea sandstone, D. Agrawal, L. R. Myer and N.G.W. Cook. Submitted for presentation at the 32nd U.S. Rock Mechanics Symposium, June 1991.

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