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

Quarterly Report

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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;
4. reservoir simulations testing the impact of relative permeability anisotropy and spatial variation on Tensleep Sandstone reservoir enhanced oil recovery; and
5. a geochemical investigation of the spatial and dynamic alteration in sandstone reservoirs that is caused by rock-fluid interaction during CO₂ – enhanced oil recovery processes.

SUMMARY OF TECHNICAL PROGRESS

We have completed our analysis of the Tensleep Sandstone and are preparing the final report. Several of the key results of the project are listed below.

Regional Frameworks

Reservoir heterogeneity in terms of barriers and baffles to fluid flow in the Tensleep Sandstone is primarily controlled by the processes that take place during both accumulation and preservation of the eolian system. Accumulation-related small-scale heterogeneity is caused by grain-packing variation associated with stratification types and erosional bounding surfaces within the eolian units. Laterally extensive marine dolomitic units form the large-scale heterogeneities; they result from fluctuations in relative sea level, which cause preservation of the eolian units. The large-scale heterogeneities present in the Upper Tensleep Sandstone are observed and traceable across portions of the Bighorn Basin. These same units are not traceable south into the Wind River Basin to any credible extent. The smaller scale features have lateral maximum extents ranging from 1000's to a few feet.

A hierarchy of flow-units exists within the Tensleep eolian units. These flow-units are defined by erosional bounding surfaces formed by bedform surface processes during accumulation of the eolian sediments. The erosional bounding surfaces commonly separate tightly packed wind-ripple laminae above the surface from more loosely packed wind-ripple and grainflow laminae below. This results in fluid flow being greater parallel to the boundaries than across the boundaries.

Bedform reconstructions utilizing outcrop foreset orientation and outcrop photomosaics indicate that the compound cross-strata of the Tensleep were produced by compound crescentic bedforms migrating to the south-southwest, with superimposed bedforms on some portions of the lee face migrating to the west.

Well-log cross sections were used to correlate six eolian-marine sequences across the Bighorn Basin. Individual sequences tend to thicken to the west, but they show localized variations in thickness related to local subsidence changes. The

Tensleep was placed into a sequence stratigraphic framework such that the erosional bounding surfaces capping the marine dolomitic units are equivalent to sequence boundaries. Correlation to a relative sea-level curve suggests that the sequence boundary and the eolian accumulation formed during the time of falling relative sea level.

Borehole images can be used to identify erosional bounding surfaces in eolian cross-strata and classify them according to the depositional processes that formed them. After structural dip is removed, foreset and bounding surface dip direction and dip orientation data can be used to recreate the configuration of the dunes that formed the Tensleep eolian accumulations. Bedform reconstruction can be used to model the three-dimensional geometry of flow-units enclosed by erosional bounding surfaces. Such models can be used to distribute heterogeneous porosities and permeabilities into reservoir flow models. These models can also be used as input into horizontal drilling and completion designs.

The depth interval of the Tensleep Sandstone interval is relatively small and hence the variation of thermal exposure and therefore the range of extent of diagenesis is small. The variation of diagenesis on spatial variations in relative permeability is confined to the variations of cementation within a given interval and therefore more strongly controlled by either depositional factors (i.e., local operation of preservation and accumulation processes) or related to current exposure. There is some evidence that indicates that absolute (gas) permeability heterogeneity (commonly examined in outcrop analog) is not always a good indicator of two phase permeability in the subsurface.

Relative Permeability Anisotropy and Heterogeneity

Eighty-four samples of subsurface and outcropping eolian sandstone were measured for directional oil-water relative permeability. Included in the sample set were samples of the lamination types dominant in Tensleep reservoirs. The key sedimentary bounding surfaces were also sampled. This study has made explicit measurements of directional variations in relative permeability, that is anisotropy, in Tensleep reservoir sandstones. The measurements show an anisotropy exclusive of variations in gas permeability. The measurements show that in general the vertical oil permeability is lower than the horizontal oil relative permeability. Comparison of companion gas permeabilities and relative permeabilities indicates that gas permeability anisotropy is not always an indicator of oil-water relative permeability. The relative permeability anisotropy is also demonstrated by the differences in the amount of oil produced before water breakthrough. Those cores measured across bounding surfaces and laminations produced a greater fraction of their total oil before water breakthrough. After breakthrough those cores tend to rapidly produce increasing amounts of water. This piston-like displacement across the fabric and baffles within the reservoirs has implications for effective drainage and development.

To maximize piston-like displacement across the bounding surfaces, primary production through horizontal radial flow should produce the greatest flow across these surfaces. The placement of wells with respect to the orientation of the bedforms is key. Areas that are past breakthrough may show improved incremental recovery from horizontal wellbores drilled such that they penetrate the greatest number of second-order bounding surfaces. This directional approach utilizes the better post-breakthrough recovery properties parallel to laminations and bounding

surfaces. These properties are demonstrated in field behavior and in two-phase flow reservoir simulations.

Pore Image Analysis

Expressions were developed to derive oil-water relative permeability from pore image analysis data collected using polished thin sections viewed using a scanning electron microscope (S.E.M.) equipped with a backscattered electron detector. The expressions are derived principally from the Kozeny-Carmen equation.

From this study, water saturation, oil relative permeability and water relative permeability values were predicted and observed to closely follow the measured values. The approach is relatively quick and can be further developed to improve site-specific sensitivity. The approach can easily reduce the cost of relative permeability analysts two-thirds.

CO₂ Coreflood — Formation Alteration and Wellbore Damage

Regional water chemistry variations of the Tensleep, Bighorn Basin, Wyoming shows four formation water chemistry types. These four were analyzed for susceptibility to scale and formation damage. Overall, Tensleep oil fields on the western Bighorn Basin have higher susceptibility to wellbore scale and formation damage as a result of CO₂ flooding. Also risk of wellbore scale increases with higher initial water saturation.

TECHNICAL TRANSFER

Technical transfer of the results of this project has covered a variety of media and venues, including the internet. This has allowed us to reach the largest number of people who can benefit from this DOE sponsored research.

In addition to the formal technical transfer items discussed below, numerous informal contacts have been made with industry representatives. Marathon personnel from both the Cody and Littleton offices have made site visits to our offices and have made numerous phone contacts.

The exhibit booth of the Institute for Energy Research which includes highlights of this research has been another important mode of informal technical transfer. Many people in the petroleum industry have learned of this research through this exhibit booth and from the researchers who are on hand to discuss it. The booth was displayed at IER's open house in 1994 and 1995. It was also on display at the Capitol offices for the 1996 Wyoming legislative session where it was seen by all the legislators, several of whom are in the petroleum industry and all of whom have constituents who are affected by oil revenues. Also, the exhibit booth and the results of this research were shown at the Wyoming Governor's Conference on Energy and Minerals in Casper and at a reservoir characterization conference in Denver sponsored by the Gas Research Institute and the Independent Petroleum Association of Mountain States. Attendance at these events resulted in numerous requests for more information and for copies of our annual reports.

World Wide Web Site

We created our www site (www/ierultra1.uwyo.edu) to take advantage of the technology enabling people to access our research results from their computer. The

site includes our past technical reports and a considerable portion of the data and results of this study. Since May, 1996, when we began collecting this type of data, our web site has been visited over 600 times from locations across the United States as well as abroad.

Publications and Theses

This DOE project has resulted in two masters theses, one in petroleum engineering and one in geology. Both of these masters students have gone on to work in the petroleum industry, one with AGAT Laboratories in Canada and the other with Burlington Northern in Midland, Texas.

In addition to the theses, technology transfer has taken place via petroleum industry publications. Several articles have been published, one is in press, and several have been submitted. Additionally, because much of the results were completed late in the term of the contract, several additional publications are in preparation. These will present the latest results as well as pull together the results of the different tasks. Publications — published, in press, and submitted — are listed below.

Ajdari, I., 1995, Anisotropy of relative permeability within the Tensleep Sandstone: M.S. thesis, University of Wyoming, 106 p.

Carr-Crabaugh, M., and Dunn, T.L., 1996, Reservoir heterogeneity as a function of accumulation and preservation dynamics, Tensleep Sandstone, Bighorn and Wind River Basins, Wyoming *in* M.W. Longman and M.D. Sonnenfeld, eds., Paleozoic systems of the Rocky Mountain region: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), p. 305-320.

Carr-Crabaugh, M., Hurley, N.F., and Carlson, J., 1996, Interpreting eolian reservoir architecture using borehole images: GCS-SEPM Foundation 17th Annual Research Conference on Stratigraphic Analysis, December 8-11, 1996, Houston.

Crabaugh, Mary, and Dunn, Thomas L., 1995, Reservoir heterogeneity as a function of accumulation and preservation dynamics, upper Tensleep Sandstone, Bighorn Basin, Wyoming: (abstract) Program of the Annual Convention of American Association of Petroleum Geologists, p. 18A.

Dunn, Thomas L., Carr, M., Humphreys, J. D., and Iverson, W.P., Relative permeability anisotropy and heterogeneity of the upper Tensleep Sandstone and implications for oil recovery from eolian reservoirs; *in preparation*, to be submitted to American Association of Petroleum Geologists Bulletin.

Dunn, Thomas L. and Humphreys, J. D., Image analysis applications to estimating relative permeability; *in preparation*, to be submitted to American Association of Petroleum Geologists Bulletin.

Humphreys, J. D., 1996, Determination and geologic interpretation of relative permeability anisotropy and heterogeneity in eolian depositional units of the

Tensleep Sandstone, Wyoming: Master of Science Thesis, University of Wyoming, 175 pp.

Iverson, W.P., T.L. Dunn, and I. Ajdari, 1996, Relative permeability anisotropy measurements in Tensleep Sandstone: Society Of Petroleum Engineers, Paper No. SPE 35435; SPE/DOE Tenth Symposium On Improved Oil Recovery.

Shiraki, Ryoji, and Dunn, Thomas L., 1995, Origins of Tensleep formation water chemistry and the prediction of scale formation during CO₂ treatments, Bighorn Basin, Wyoming: (abstract) Program of the Annual Convention of American Association of Petroleum Geologists, p. 88A.

Shiraki, R., and Dunn, T. L., Experimental study on CO₂ core-flooding using dolomite- and anhydrite-cemented Tensleep sandstone from the Bighorn Basin, Wyoming: *submitted to* American Association of Petroleum Geologists 1997 Annual Convention.

Shiraki, R., and Dunn, T. L., Experimental study on water-rock interactions during CO₂ flooding in Tensleep sandstone reservoirs, northern Wyoming, USA: *in preparation* to be submitted to Applied Geochemistry.

Shiraki, R., and Dunn, T. L., Experimental study on crude oil-water-rock interactions during CO₂ flooding in Tensleep sandstone reservoirs, northern Wyoming, USA: implications for carbonate scale formation: *in preparation* to be submitted to Applied Geochemistry.

Presentations

Presentations of the research results have been made at national and local meetings. These have included both oral presentations and poster displays. Presentations have also been made to individual oil companies. Additional presentations are planned for later in 1996 and in 1997. All of these presentations are listed below.

Dunn, Thomas L., John D. Humphreys, and Iverson, W. P., 1997, (submitted), Relative permeability anisotropy and heterogeneity of the upper Tensleep Sandstone and implications for oil recovery from eolian reservoirs: American Association of Petroleum Geologists Annual Meeting, April, Houston, TX.

Humphreys, J.D., and Dunn, T.L., 1996, Geologic interpretation of relative permeability anisotropy in eolian sandstones, Tensleep Sandstone, Wyoming: Reservoir Characterization Symposium, Denver, CO, Sept. 13, 1996, sponsored by the Rocky Mountain Association of Geologists and the Denver Geophysical Society.

Carr, Mary, 1996, Reservoir heterogeneity as a function of accumulation and preservation dynamics, upper Tensleep Sandstone, Bighorn Basin, Wyoming: Rocky Mountain Section of Society of Sedimentary Geologists (SEPM), Luncheon, Denver, CO.

- Carr-Crabaugh, M., 1995, Tensleep reservoir architecture: Presentation to Marathon Oil Co., July, Cody, Wyoming.
- Carr-Crabaugh, M., 1995, Tensleep Sandstone reservoir architecture seen in outcrop in the Bighorn Basin, Wyoming: Field Trip for Marathon Oil Co. personnel from Cody, Wyoming office.
- Crabaugh, Mary, and Dunn, Thomas L., 1995, Reservoir heterogeneity as a function of accumulation and preservation dynamics, upper Tensleep Sandstone, Bighorn Basin, Wyoming: Poster Presentation at the American Association of Petroleum Geologists Annual Convention, March 5-8, Houston.
- Shiraki, Ryoji, and Dunn, Thomas L., 1995, Origins of Tensleep formation water chemistry and the prediction of scale formation during CO₂ treatments, Bighorn Basin, Wyoming: Poster Presentation at the American Association of Petroleum Geologists Annual Convention, March 5-8, Houston.