TITLE: MULTIDISCIPLINARY IMAGING OF ROCK PROPERTIES IN CARBONATE RESERVOIRS FOR FLOW-UNIT TARGETING

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Abstract

Our analysis and imaging of reservoir properties at the Fullerton Clear Fork field (Figure 1) is in its final stages. Major accomplishments during the past 6 months include: (1) characterization of facies and cyclicity in cores, (2) correlation of cycles and sequences using core-calibrated wireline logs, (3) calculation and modeling of wireline porosity, (4) analysis of new cores for conventional and special core analysis data, (5) construction of full-field reservoir model, and (6) revision of 3D seismic inversion of reservoir porosity and permeability.

One activity has been eliminated from the originally proposed tasks. Task 3 (Characterization and Modeling of Rock Mechanics and Fractures) has been deleted because we have determined that fractures are not significant contributing in the reservoir under study.

A second project extension has been asked for to extend the project until 7/31/04. Remaining project activities are: (1) interpretation and synthesis of fieldwide data, (2) preparation of 3D virtual reality demonstrations of reservoir model and attributes, (3) transfer of working data sets to the operator for reservoir implementation and decision-making, and (4) preparation and distribution of final reports.
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Introduction

Project staff has continued to make excellent progress toward goals and objectives of the project. This report describes the work accomplished on the project during months 25 through 30 of the project, a comprehensive and multi-disciplinary characterization of the Clear Fork reservoir at Fullerton field in West Texas (Fig. 1).

Figure 1. Regional map of the Permian Basin showing location of reservoir study and analogous outcrops.
Executive Summary

The project is moving into its final stages. We have completed most of the field-wide data collection activities at Fullerton Clear Fork field (Fig. 1) and are now concentrating on interpretation and synthesis. Specific progress has been made in the following areas of the study: (1) characterization of facies and cyclicity in cores, (2) correlation of cycles and sequences using core-calibrated wireline logs, (3) calculation and modeling of wireline porosity, (4) analysis of new cores for conventional and special core analysis data, (5) construction of full-field reservoir model, and (6) revision of 3D seismic inversion of reservoir porosity and permeability.

Examination and re-examination of core facies and cyclicity continues as a basis for calibrating wireline logs for purposes of establishing field-wide correlations of reservoir framework. More than 14,000 ft of core have now been studied. These studies reveal that Clear Fork (upper part of reservoir) sequences and cycles are persistent over the entire field area: a relationship consistent with the interpreted platform-top setting of this unit. This continuity has made it possible to construct a high-resolution stratigraphic framework for this section of the reservoir over the entire field. By contrast, cyclicity and facies continuity are very poorly developed in the Wichita (lower part of the reservoir section). This is due to the dominantly peritidal nature of the unit. We have, however, identified a marine flooding surface within the Wichita that constrains reservoir correlations.

Using core-based calibrations of wireline logs we have now picked more than 30,000 stratigraphic tops in more than 750 well logs in the field. Wireline picks are based on core-defined relationships between facies and cyclicity using gamma ray and porosity logs. The stratigraphic picks have been used to construct the reservoir framework for a full-field model.
Basic calculation of wireline log porosity has been completed for the 750 wells in the field that have useable porosity log suites. We are undertaking further work to normalize all porosity logs to create a more realistic porosity data set for the field.

We have constructed a preliminary full-field model of the reservoir incorporating the cycle-based stratigraphic framework and calculated porosity data for 750 wells. Work is continuing to fine-tune the architecture and porosity modeling. Ultimately this model will be used to calculate original resource volume.

Refinement of the 3D seismic and wireline log inversion model of porosity continues. The model now displays a very close match between calculated wireline log porosity and 3D seismic velocity-based porosity calculations. The model provides superior control on the interwell and extrawell distribution of porosity within the reservoir. Work is underway to calculate permeability and oil saturation from the model.

Work is also underway to build a virtual reality model of the reservoir in order to better image reservoir attributes. This model will facilitate understanding and interpretation the 3D distribution of reservoir properties and their control on flow.

The project will end on July 31. Multiple presentations and technology transfer activities have already been scheduled in July for the operator of the field, ExxonMobil.

**Experimental**

210 new plug samples from the FCU 7630 core were collected and submitted for conventional core analysis of porosity and permeability. Thin sections were also prepared from each plug for characterization of pore types and rock fabric. The results of the analyses
and companion descriptions of rock fabrics from thin sections are being used to improve and extend our knowledge of the distribution of rock fabrics and properties in the reservoir.
Figure 2. Map of field showing location of study areas, cores, and 3-D seismic data.
Three additional samples were collected and submitted for laboratory analysis of formation factor, resistivity index, air-oil capillary pressure, and high pressure mercury injection capillary pressure. These samples were especially selected to examine probably moldic pore systems in the reservoir. Data will be used to update and modify previously reported saturation and rock fabric relationships.

**Results and Discussion**

Work in the past six months has focused on 1) characterization of facies and cyclicity in cores, (2) correlation of cycles and sequences using core-calibrated wireline logs, (3) calculation and modeling of wireline porosity, (4) analysis of new cores for conventional and special core analysis data, (5) construction of full-field reservoir model, and (6) revision of 3D seismic inversion of reservoir porosity and permeability. Specific progress is discussed below following the tasks laid out in the original proposal and work plan.

**Subtask 1.1 Describe Facies and Cyclicity in Cores.**

Examination and re-examination of core facies and cyclicity continues as a basis for calibrating wireline logs for purposes of establishing field-wide correlations of reservoir framework. More than 14,000 ft of core have now been studied. These studies reveal that Clear Fork (upper part of reservoir) sequences and cycles are persistent over the entire field area: a relationship consistent with the interpreted platform-top setting of this unit. This continuity has made it possible to construct a high-resolution stratigraphic framework for this section of the reservoir over the entire field. By contrast, cyclicity and facies continuity are very poorly developed in the Wichita (lower part of the reservoir section). This is due to the
dominantly peritidal nature of this unit. We have, however, identified a marine flooding
surface within the Wichita that constrains reservoir correlations. This model is supported by
3D seismic data from the Fullerton field area (Fig. 4) and from other 3D data volumes in the
Permian Basin.

Figure 3. Sequence stratigraphic model of the Clear Fork reservoir at Fullerton field.
Subtask 1.2 Describe Facies and Cyclicity in Outcrops.

We have completed all outcrop characterization work and have used the results to help constrain the depositional model used to construct the reservoir model. No additional work was done during the past 6 months.
Subtask 1.3 Develop Wireline Correlation Framework.

Using core-based calibrations of wireline logs we have now picked approximately 45,000 stratigraphic tops in more than 780 well logs in the field (an area of more than 45 square miles).

Wireline picks are based on core-defined relationships between facies and cyclicity using gamma ray and porosity logs. The stratigraphic picks have been used to construct the reservoir framework for a full-field model. Correlations consist of 6 interpreted cycles in Leonardian composite sequence L3 (Tubb), 27 cycles in L2 (Lower Clear Fork), and 10 porosity-based horizons as well as 2 distinct flooding events in Leonardian composite sequence L1 (Wichita). Cycles and horizons in the reservoir interval were divided into a typically high-porosity top and low-porosity base for the purposes of flow simulation in two study areas, adding 24 additional picks to 265 wells. When creating surfaces for the 3-D porosity model, we discovered that parts of the field (extreme western and eastern edges) typically have poorer wireline log suites and therefore did not meet our initial criteria for correlation. However, well control was needed in these areas for the model surfaces. Thus, wireline picks were made in a row of wells (94) along the edges of the field regardless of log quality to provide this surface control.

With these picks in place, we have generated isopach and porosity-height maps of key reservoir intervals, including L2.1, L2.2, and L2.3 in the Lower Clear Fork, as well as various divisions of the peritidal portion of L1 (Wichita). Structure maps have also been created for the surfaces bounding these units.
Core descriptions have been shifted by matching core analysis porosity and wireline porosity and then loaded into the Landmark OpenWorks database as a lithology column and can be displayed alongside wireline logs and picks.

Subtask 2.1 Measure Petrophysical Properties in Core.

After initial review of the first 30 samples selected for special core analysis was completed, an additional three samples were chosen to better cover the range of moldic porosity observed in the reservoir. These samples were analyzed for electrical properties and high pressure mercury injection capillary pressure measurements. Currently we are assessing the results of this data in the context of developing an improved capillary pressure model for the Clear Fork formation and to better understand the effects of patchy occlusion of pore space by anhydrite and moldic porosity on the electrical properties. The initial results suggest that the these lithologic situations do not affect the electrical properties as originally anticipated, so more detailed work is currently underway.

Subtask 2.2 Define and Characterize Rock Fabrics

All available thin sections at Fullerton Field, including 210 new thin sections with matching core analysis cut from the FCU 7630 core, have now been described to characterize rock fabrics and assign petrophysical classes. A total of 1,719 thin sections from 21 wells have been described during this project. Apparent rock fabric numbers were calculated for 46 wells with core analysis and dolostone/limestone mineralogy changes assessed using log data (PE and/or neutron and density porosity) from 108 wells. Together, this information enabled us to define rock fabric parameters by stratigraphic interval over the entire field. The extents
of stratigraphic intervals of limestone were mapped and matrix corrections made to porosity wireline logs to generate a corrected total porosity curves for 724 wells. Changes in petrophysical class throughout the reservoir interval were mapped by stratigraphic unit and extent. Rock fabric number (RFN) transforms associated with each petrophysical class were then assigned to the appropriate intervals in wells with modern (CNL or SNP) porosity logs and permeability and saturation calculated.

Map patterns of changes in petrophysical classes by sequence are as follows:

- Where penetrated, the Abo, or subtidal portion of composite sequence 1 (L1),
contains dominantly petrophysical class 1 dolostone fabrics. We have used a
RFN 1 transform to calculate permeability and saturation in this interval.

- The Wichita, or peritidal portion of Leonardian composite sequence 1 (L1),
contains dominantly petrophysical class 3 dolostone and some class 3
limestone fabrics, with a few thin and generally non-correlative class 2
dolostone intervals. A RFN 3 transform was used throughout the field to
calculate permeability and saturation in this interval.

- Lower Clear Fork Leonardian high-frequency sequence 2.1 (L2.1), consists of
class 1 or 2 dolostones and class 2 limestones overlain by class 3 dolostones.
Whereas class 3 dolostones characterize the two latest and dominantly
peritidal cycles in this high-frequency sequence throughout the entire field and
a RFN 3 transform was used to calculate permeability and saturation, the
underlying subtidal section varies by region. Class 2 limestones are largely
preserved in the eastern and southern parts of the field. In the west-central part
of the field, the section has been dolomitized into large crystalline dolostones
and medium crystalline dolostones with poikilotopic anhydrite, which are best fit by a RFN 1 transform. In the northwestern part of the field, the section has been dolomitized into medium crystalline dolostones, which are best fit by a RFN 2 transform. Although fine scale alterations of rock fabrics were observed where we resampled for foot-by-foot thin sections (FCU 7630 and 5927), we would require many more sets of foot-by-foot samples to map these subtle fabric variations throughout the field.

- Lower Clear Fork Leonardian high-frequency sequence 2.2 (L2.2) contains petrophysical class 1 dolostones throughout the main body of the field, with the exception of areas of class 2 limestone in the northwestern part of the simulation area and in the southern part of the field. We looked specifically at these two areas of limestone and found RFN 2.5 and RFN 2 transforms to be appropriate for the northern and southern areas of limestone, respectively.

- Lower Clear Fork Leonardian high-frequency sequence 2.3 (L2.3) contains primarily very low porosity class 3 fabrics in most areas and is therefore considered non-reservoir. We investigated an indication of some higher apparent rock fabric numbers calculated from the FCU 7630 core with foot-by-foot thin sections and found that these comprise a very small part of the interval and are not likely present elsewhere in the field. Thus, L2.3 was not considered part of the reservoir and calculations were not performed.
Subtask 2.3 Collect relative-permeability and capillary-pressure data.

Three additional samples have been submitted for capillary pressure measurements, bringing the total of special core analysis samples submitted to 37. Measurements of relative permeability are being delayed until further reservoir characterization is completed.

Subtask 2.4 Calibrate Wireline Logs for Rock Fabric Identification.

Investigation and evaluation continues with regard to using resistivity-based porosity to differentiate between interparticle and moldic porosity types. This involves calibration issues primarily associated with the borehole environment, invasion. Processing of approximately 300 wells indicates that some form of self-normalization can be used to better resolve this issue. This research is continuing.

Subtask 3.1 Collect rock-mechanics data (subcritical crack indices).

This task has been deleted.

Subtask 3.2 Model fracture growth

No significant fractures have been observed to date. This task has been deleted.

Subtask 4.1 Construct 3-D Seismic Attribute Model of Reservoir Porosity.

Our work on poststack seismic data is nearly finished. This work reveals and depicts rich information about reservoir stratigraphy, sedimentology, and physical properties. Our approach has been to take a systematic approach to pursue better seismic interpretation. First, we worked on basic data reconditioning within seismic frequency range (5-70 Hz in this
study) to improve seismic data interpretability. Two key techniques were applied. A simple seismic phase rotation (to 90°) reconditions seismic data for impedance representation, roughly linking seismic amplitude directly to log lithology and porosity. High-frequency enhancement raises the dominant frequency of 3-D seismic data from 30 to 50 Hz, significantly improving seismic resolution.

However, there is a limit to improvements in seismic data interpretability possible from basic data reconditioning. The 90°-phasing does not eliminate the wavelet effect. To remove wavelet sidelobes for truer representation of geology we must perform a seismic inversion. On the other hand, although the high-frequency enhancement can help push the resolution limit to the high-frequency end of the spectrum, the resolution is still not enough for reservoir flow model construction. It is obvious in these rocks that the only source of high-resolution information beyond seismic resolution is well data. Inversion without use of constraining well data will not provide reservoir details beyond seismic resolution. To solve this problem, we developed a more advanced data reconditioning method called progressive inversion. With this approach, more accurate and log-resolution (2 ft) seismic mapping of reservoir parameters can be achieved.

Our tentative conclusions from this work at this point are as follows.

1. Poststack seismic data are commonly not in optimal form and require reconditioning before they can be used for stratigraphic analysis and reservoir characterization.

2. Basic data conditioning applies do-it-yourself poststack processing tools to improve data interpretability and resolution. A 90°-phasing adjusts seismic traces to resemble impedance logs; a high-frequency enhancing enables interpreters to identify more and thinner geologic units (100-ft level).
3. Further improvement in reservoir interpretation and modeling requires involvement of geologists in progressive seismic inversion by providing a geologic model and quality-checking seismic picking of high-resolution geologic boundaries. Progressive inversion promises to seamlessly integrate geologic knowledge and seismic data for detailed impedance modeling up to wireline log resolution.

Subtask 4.2. Integrate 3-D data with rock-fabric and cycle-stratigraphic data.

To demonstrate the value and limit of our progressive seismic inversion research, nine wells were removed from the 66-well data base to recreate the seven-horizon initial acoustic impedance (AI) model. A new inversion was then done following exactly the same procedure and parameter setup. Results are displayed in Figure 5.
There are two major observations:

1. Seismic data provide missing geologic information between and beyond well control. Figure 5a depicts an area of the original well log porosity model. Note that when well 2 was removed from the model significant changes in the porosity result (decreased porosity at A and increased porosity at B; see Fig 5b). By contrast, the 3D inversion model (Fig. 5d) restores the missing porosity at A and the low porosity zone at B. Even with a missing well, the inversion produces results that are similar to the original wireline log model.
(using all available well control, Fig. 5a) and the inversion model made using all well control (Fig. 5c). In other words, our inversion approach produces an accurate model of the reservoir even where well control is reduced.

2. High-resolution details in the inversion are imperfect. The seismic signal is low frequency in nature, with a resolution no better than a quarter wavelength (approximately 20 m (7 ft) in this case). The high-resolution layering (1 ft in the initial model and 2 ft in the inversion) is defined by well AI logs within stratigraphic framework between and beyond wells. Seismic inversion adjusts AI distribution without changing the thickness architecture. Unfortunately, in this study, only the simplest mapping was conducted at the high-resolution scale: thin-bed thickness is proportional to interval thickness between horizons; AI distribution in each bed is predicted by inverse square distance rule. As the result, the error in thin-bed thickness and AI mapping is not trivial, leading to an imperfect AI estimation. As a result, inversions with or without using the missing wells show somewhat different details near the well location (Figure 5). Some isolated thin beds are totally unrepresented without the missing wells. To further improve the inversion, effort has to be made to develop more advanced mapping algorithms beyond the proportional layering and inverse square distance rule.

Subtask 4.3. Distribute reservoir properties through interwell space.

We have constructed a 3D reservoir model for the entire field using 35 cycle tops and wireline log data from 730 wells (those with good quality data). Cycle tops were mapped based on well picks guided by the conceptual geological model, well log ties, and seismic data. Horizons in Lower Clear Fork and Wichita were mapped mainly based on core-based
wireline log picks; those in Abo were mapped based on a conceptual model of the clinoformal geometries of the prograding Abo platform margin.

Table 1. Horizons used in 3D geological models

<table>
<thead>
<tr>
<th>Zone</th>
<th>Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Clear Fork</td>
<td>2270</td>
</tr>
<tr>
<td>2.2 (Zone 1)</td>
<td>2260</td>
</tr>
<tr>
<td></td>
<td>2250</td>
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<tr>
<td></td>
<td>2240</td>
</tr>
<tr>
<td></td>
<td>2230</td>
</tr>
<tr>
<td></td>
<td>2220</td>
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<tr>
<td></td>
<td>2210</td>
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<td></td>
<td>2200</td>
</tr>
<tr>
<td>Lower Clear Fork</td>
<td>2150</td>
</tr>
<tr>
<td>2.1 (Zone 2)</td>
<td>2140</td>
</tr>
<tr>
<td></td>
<td>2130</td>
</tr>
<tr>
<td></td>
<td>2120</td>
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<tr>
<td></td>
<td>2110</td>
</tr>
<tr>
<td></td>
<td>2105</td>
</tr>
<tr>
<td>Upper Wichita</td>
<td>W1</td>
</tr>
<tr>
<td></td>
<td>W2</td>
</tr>
<tr>
<td></td>
<td>W3</td>
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<td></td>
<td>W4</td>
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<tr>
<td></td>
<td>W5</td>
</tr>
<tr>
<td>Lower Wichita</td>
<td>W8</td>
</tr>
<tr>
<td></td>
<td>W9</td>
</tr>
<tr>
<td></td>
<td>W10</td>
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<tr>
<td></td>
<td>W11</td>
</tr>
<tr>
<td></td>
<td>W12</td>
</tr>
</tbody>
</table>
Two 3D-model software packages (RMS and GOCAD) were used to build the full field geological model. Petrophysical properties of porosity, permeability and initial water saturation were derived from wireline log data for 730 selected wells. These data were converted from the standard LAS format into RMS well format to load into both packages. The 3D models are composed of cells 150 ft in x and y directions. The total number of cells in the model is about 3.7 million with 222 columns, 471 rows and 35 layers. The reservoir architecture built in the 3D model (Fig. 6) shows the prograding wedges in the Abo (blue color layers). Porosity distribution in Fig. 7 suggests that this reservoir is highly heterogeneous in both lateral and vertical directions.
Table 2. Dimensions of 3D geological models

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Cell length (ft)</th>
<th>Number of Cells</th>
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</thead>
<tbody>
<tr>
<td>X</td>
<td>150</td>
<td>222</td>
</tr>
<tr>
<td>Y</td>
<td>150</td>
<td>471</td>
</tr>
<tr>
<td>Z</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3,659,670</td>
</tr>
</tbody>
</table>

Figure 6 Reservoir architecture of Fullerton full-field 3D geological model showing the prograding wedges in the lower Abo.
Figure 7. Porosity distribution in selected cycle layers at Fullerton Clear Fork field. Layers 5 and 7 are in HFS L2.2 (Lower Clear Fork); Layers 14 and 16 are in HFS L2.1 (Lower Clear Fork); Layer 18 and 20 are in the upper and lower Wichita respectively.

**Operator Contact and Technology Transfer**

The Bureau continues to meet regularly with ExxonMobil, the reservoir operator, to discuss results and plan future activities. We met with the ExxonMobil reservoir team in November to discuss progress on the project. At that meeting we worked out optimum ways to transfer data bases and graphics data that will assure maximum use of the study by the
operator. It is currently planned that we will deliver the database from the project to ExxonMobil in June. As soon as the data are loaded and operational at their offices, the Bureau project staff will travel to Houston to introduce the data and demonstrate its use to the ExxonMobil reservoir team. A more formal, company-wide presentation of the results of the study will be presented to ExxonMobil later in the year.

The 14 well locations defined based on Bureau analysis of the field’s infill potential are scheduled to be drilled in late summer 2004.

**Remaining Work**

Remaining activities to be conducted on the project include (1) completion of 3D seismic inversion studies and comparison with wireline log based reservoir model, (2) construction of 3D virtual reality model to aid in visualizing model design and reservoir flow, (3) preparation of 3D imaging sequences for technology transfer, (4) final updating of full-field reservoir model and calculation of oil saturation models, (5) calculation of remaining resource volumes, and (6) preparation of final reports and presentations.

**Project Schedule Changes**

Although we have continued to make good progress on all aspects of the study, some elements of the project will require more time to complete than the current project completion date will allow. Specifically, we need more time to complete the following research activities: (1) construction and interpretation of a virtual reality model for the reservoir, (2) completion of 3D seismic porosity and permeability inversion models, (3) construction of geostatistical models of porosity distribution. All of these activities are key contributions to the project and to DOE’s stated objectives to create better methods of
imaging reservoir properties. We purposely delayed undertaking these research activities until all supporting data and interpretations were completed. We have now completed these supporting studies and are now ready to undertake the final elements of the project. However, in order to do so, we need an extension to the current project completion date. Accordingly, we have requested that the project completion date be changed to 7/31/04.