INTEGRATED OUTCROP AND SUBSURFACE STUDIES OF THE
INTERWELL ENVIRONMENT OF CARBONATE RESERVOIRS:
CLEAR FORK (LEONARADIAN AGE) RESERVOIRS, WEST TEXAS
AND NEW MEXICO

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Integrated Outcrop and Subsurface Studies of the Interwell Environment of Carbonate Reservoirs: Clear Fork (Leonaradian Age) Reservoirs, West Texas and New Mexico

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Abstract
The analysis of facies geometries in the Apache Canyon Clear Fork outcrop has been completed. In general, the facies and cycles are continuous on the scale of miles in the transgressive systems tracts. Cycle thicknesses are 5 to 10 ft. Cycle dimensions in the inner ramp and ramp crest are variable but are normally less than 2,000 ft long and 10 to 20 ft thick. Cycle thicknesses in the outer-ramp and tidal-flat facies range from 5 to 10 ft, and outer ramp cycles are highly continuous, whereas tidal-flat cycles are discontinuous on the scale of about 2,000 ft.

A preliminary reservoir model of the middle Clear Fork reservoir has been constructed for a one-mile square area in the South Wasson Clear Fork field. Seven silt-based high-frequency cycles (HFC) and 15 carbonate HFC's have been defined and surfaces mapped in 38 wells. The HFC's are thought to be upward-shallowing, mud-dominated to grain-dominated cycles with the grain-dominated fabrics being more porous and permeable than the mud-dominated fabrics. The mud-dominated dolostone has medium-sized dolomite crystals and belongs to petrophysical class 2, as does the grain-dominated dolopackstone. However, the porosity and permeability values plot in the petrophysical class 1 field because of the patchy distribution of porosity caused by the large volume of poikilotopic anhydrite. Therefore, a single porosity-permeability transform can be used to characterize the vertical permeability profile at each well. The HFC surfaces and the vertical permeability profiles have been input into Stratamodel, and the resulting permeability model is layered in a manner that is consistent with the Apache Canyon Clear Fork outcrop.
Results and Discussion

We have completed the first year of this project and are reporting significant progress. This report is concentrated on work done within Task 1, Outcrop Analog Tasks, and Task 2, Subsurface Applications Tasks.

Task 1a. Construct Model of Outcrop Stratigraphic Framework

Characterization of cycle and facies architecture on lower Clear Fork and lowermost upper Clear Fork equivalent outcrops in Apache Canyon of Sierra Diablo is complete (fig. 1). The focus of detailed study in Apache Canyon has been the upper Clear Fork section because this interval contains the productive interval in South Wasson field, the primary subsurface study area. As reported previously, parts of three high-frequency sequences (HFS), each 60 to 100 ft thick, are present on the south wall of Apache Canyon (fig. 2). HFS's display an upward-deepening or backstepping pattern associated with longer-term sea level rise. Each HFS is composed of upward-shallowing cycles whose thickness, facies composition, and continuity vary within and between HFS's.

Outer ramp cycles and related transgressive ramp cycles display the greatest cycle continuity and have similar cycle thicknesses (table 1). This is expected because transgressive facies tracts mark landward stepping of outer ramp deposits onto the platform. Cycles deposited during maximum flooding of HFS 3.1 on a low-accommodation transgressive ramp average 6 to 8 ft and are characterized by burrowed, skeletal-rich bases and well sorted, skeletal-poor, peloid packstone to grain-dominated packstone tops (fig. 3). Cycle tops are commonly burrowed and boundaries are diffuse making precise cycle-top delineation difficult. These cycles display extremely good continuity and can be traced the length of the outcrop, more than 6,000 ft (table 1). Facies contrasts are subtle in these cycles, however, owing to low energy, making cycle contacts gradational. The analogous maximum flooding cycles in the higher accommodation transgressive leg of HFS 3.2 and those in the outer ramp display much sharper cycle boundaries because of the contrast between basal fusulinid-rich wackestones and higher energy cycle-top peloid/ooid grain-dominated packstones in these successions (fig. 4).
Table 1. Cycle and facies tract continuity; upper Clear Fork, Sierra Diablo Mountains.

<table>
<thead>
<tr>
<th>Facies tract</th>
<th>Facies tract length</th>
<th>Cycle continuity</th>
<th>Cycle thickness</th>
<th>Cycle boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low accommodation transgressive ramp</td>
<td>Thousands of feet (&gt;6,000)</td>
<td>Length of facies tract</td>
<td>5 – 10 ft (2 – 3 m)</td>
<td>Subtle</td>
</tr>
<tr>
<td>High accommodation transgressive ramp</td>
<td>Thousands of feet (&gt;6,000)</td>
<td>Length of facies tract</td>
<td>10 ft (3 m)</td>
<td>Sharp</td>
</tr>
<tr>
<td>Outer ramp</td>
<td>Thousands of feet (2,000 +)</td>
<td>Length of facies tract</td>
<td>5 – 10 ft (2 – 3 m)</td>
<td>Sharp</td>
</tr>
<tr>
<td>Inner ramp</td>
<td>Thousands of feet (3,000 +)</td>
<td>Variable (&lt; 2000 ft)</td>
<td>10 – 20 ft (3 – 6 m)</td>
<td>Variable</td>
</tr>
<tr>
<td>Tidal flat</td>
<td>Thousands of feet (5,000 +)</td>
<td>Variable (&lt; 2000 ft)</td>
<td>Variable: 5 – 10 ft (2 – 3 m)</td>
<td>Variable</td>
</tr>
<tr>
<td>Ramp crest</td>
<td>Narrow (&lt;2,000 ft)</td>
<td>Variable</td>
<td>Variable: 10 – 20 ft (3 – 6 m)</td>
<td>Variable</td>
</tr>
</tbody>
</table>

Ramp crest cycles are composed of basal peloidal wackestone and packstone and are capped by crinoid-bearing ooid/peloid grain-dominated packstone and grainstone (fig. 4). As with other cycle types, continuity is limited to the dimensions of the facies tract. Because the ramp crest is narrow, cycle continuity is relatively short (2,000 ft). Ramp crest cycles average 10 ft (3 m) thick but are commonly amalgamated into thicker cycle bundles of 20 to 30 ft (7 to 10 m). Facies contrast is moderate, but because of amalgamation, cycle boundaries are not always readily definable (fig. 4).

Although the inner ramp extends for many miles, cycle continuity is highly variable because of the low energy conditions that prevail and the resulting low but variable contrast among facies. For the most part, cyclicity in this tract is weakly defined to absent. The tidal flat facies tract also displays long dimensions but like the inner ramp cycle continuity is relatively low and highly variable because of the dominance of autocyclic processes. Cycle contacts are locally very sharp, but because facies stacking patterns vary greatly over short distances, cycle boundaries are difficult to trace laterally.
Because each HFS is composed of facies tracts (inner ramp, tidal flat, ramp crest, outer ramp) that step first landward during transgression and then basinward during regression, and because facies tracts have distinct styles of cyclicity and cycle continuity, recognition of both HFS and facies tract positions is of considerable importance in establishing reservoir heterogeneity.

**Task 1b. Construct Model of Fine-Scale Petrophysical Heterogeneity**

Additional outcrop data are being evaluated.

**Task 1c. Construct Model of Fracture Porosity and Permeability**

Fracture data have been collected from the Apache Canyon outcrop and is being analyzed.

**Task 2b. Gather Subsurface Data**

Fracture data collected from thin sections of core material are being analyzed.

**Task 2c. Construct Subsurface Reservoir Model**

A preliminary subsurface reservoir model of the middle Clear Fork reservoir has been constructed for the one mile square area in the South Wasson Clear Fork field (fig. 5). The middle Clear Fork is the lower portion of the upper Clear Fork and is defined as the interval from the top of the Tubb sandstone to the top of the middle Clear Fork reservoir. The top of the middle Clear Fork reservoir is defined by the change from low water saturation to high water saturation in the porous zones, which corresponds to the top of the Leonardian sequence 4 as described below (fig. 6). The interval from the top of the middle Clear Fork to the Glorieta Formation will be referred to as the uppermost Clear Fork to distinguish it from the upper Clear Fork.

A sequence stratigraphic framework based on geologic descriptions of nine cores and guided by the sequence stratigraphic framework developed at Apache Canyon has been constructed for the upper Clear Fork (fig. 7). Unfortunately, the Clear Fork section exposed in Apache Canyon represents only the lower Clear Fork, Tubb, and basal part of
the upper Clear Fork in the subsurface, which is below the middle Clear Fork reservoir at South Wasson field. Nevertheless, the outcrop observations provide important guidelines for understanding the sequence and cycle stratigraphy in South Wasson.

Four sequences have been defined on the basis of facies succession and seismic interpretation (fig. 7). Leonardian 3 (L3) extends from the base of the Tubb Formation to the base of the silty interval located at the top of the middle Clear Fork. Leonardian 4 (L4) includes most of the silty interval, and the top of L4 approximates the top of the middle Clear Fork as defined above. Leonardian 5 (L5) extends from the silty interval to the base of the Glorieta. Leonardian 6 (L6) extends from L5 to the top of the Glorieta. Unfortunately, the Clear Fork section exposed in Apache Canyon represents only the basal part of the upper Clear Fork in the subsurface, which is below the reservoir at South Wasson field. Nevertheless, the outcrop observations described above provide important guidelines for understanding the sequence and cycle stratigraphy in South Wasson as well as in other productive Clear Fork fields in the Permian Basin.

High-frequency cycles (HFC) found in the middle Clear Fork are typically subtidal. Two groups of HFC's are present; (1) silt based HFC's grading upward into mud-dominated fabrics and capped by grain-dominated fabrics and (2) carbonate HFC's grading upward from mud-dominated to grain-dominated fabrics. The silt-based HFC's are found in the upper 150 ft of the middle Clear Fork and are labeled A through G. The remainder of the reservoir interval (down to the producing oil-water contact of ~3300 subsea) is composed of upward-shallowing carbonate subtidal HFC's that are labeled 1 through 15.

The silt beds are readily apparent from gamma-ray response, water saturation, and by overlaying sonic and porosity logs (fig. 8). Correlation between wells is relatively straightforward despite lateral changes in silt content. Identifying tops of carbonate HFC's is more difficult because the Clear Fork generally contains large amounts of diagenetic uranium. The gamma-ray log responds to gamma rays emitted from thorium, potassium, and uranium. Thorium and potassium are concentrated in insoluble residue material (clays, rock fragments, silt, etc.). The volume of insoluble material often correlates with depositional energy, which can be related to the volume of lime mud in the sediment and thus to HFC's. The gamma-ray activity from the uranium masks the
depositional signature, however, making it nearly impossible to use the gamma-ray log to identify HFC's.

Cross plots of Archie water saturation values and total porosity have been used to identify rock fabrics and to pick HFC tops (Lucia and others, 1995). Saturation/porosity plots were constructed for the middle Clear Fork and compared with rock-fabric descriptions from core material. The results suggest that a distinction can be made between grain- and mud-dominated fabrics (fig. 9) using saturation/porosity plots. Further examination, however, suggests that the distinction is based primarily on porosity, grain-dominated packstones having higher porosity than mud-dominated fabrics. This observation was tested using detailed thin-section descriptions and core porosity data. The results indicate that grain-dominated dolostones are more porous than mud-dominated dolostones (fig. 10). Dolowackestones have an average porosity of 4.5 percent and make up 70 percent of the samples with less than 5 percent porosity. Mud-dominated dolopackstones have an average porosity of 7 percent, and grain-dominated dolopackstones an average porosity of 9 percent. Together they make up 70 percent of the samples with more than 5 percent porosity. The grain-dominated packstone fabric makes up 70 percent of the samples with more than 10 percent porosity.

These observations suggest that vertical porosity profiles can be used to define the mud-dominated and grain-dominated portions of subtidal carbonate HFC's in the middle Clear Fork reservoir. This conclusion is supported by a comparison of the vertical porosity profile from wireline logs with subtidal carbonate HFC's from core description (fig. 11). The comparison shows a vertical increase in porosity within the HFCs with the capping grain-dominated fabrics usually having the highest porosity values. Grain-dominated packstones defined by saturation/porosity cross plots are closely correlated to porosity. However, the porous intervals in the lower interval of HFC's 4 and 5 are correctly identified as mud-dominated by the saturation/porosity cross plot method. Therefore, the saturation/porosity method is sometimes useful for identifying porous mud-dominated fabrics.

The high-frequency cycles were identified in uncored wells using the porosity log and guided by saturation/porosity cross-plot analysis. It is assumed that the mud-dominated lower part of the HFC will have low porosity and the grain-dominated
packstone upper part will have high porosity. This assumption is modified only when the saturation-porosity cross plot suggests a high porosity mud-dominated fabric. It is also assumed that rapid vertical changes in porosity reflect small scale variability and are not spatially correlated (Senger and others, 1993). These rapid changes are interpreted to be near-random porosity variations on the scale of feet and not porous dolomite beds.

Each HFC is divided into two flow layers, a lower mud-dominated flow layer and an upper grain-dominated flow layer. This strategy is used in order to maintain the high porosity character of the grain-dominated fabrics and the low porosity character of the mud-dominated fabrics when the reservoir model is converted into a flow simulation model.

A segment of the resulting correlation is shown in figure 12. Well 7531 is a cored well, and the HFC tops and core description are shown in figure 11. There is always considerable judgment exercised in picking the tops of the HFC's. In well 7538 the vertical increase in porosity within each HFC is apparent except for HFC 2, in which the basal mud-dominated fabric is very thin or nonexistent. In well 7531 there is no grain-dominated cap indicated to HFC 7 by porosity or log analysis most likely because it is cemented. The HFC top is extended through this interval from neighboring wells. Because there is little porosity in this interval the location of the cycle top makes little difference in the petrophysical model. The mud-dominated base of HFC 6 thickens greatly in well 8542, and the correctness of this correlation must be judged by examination of nearby wells.

In general, average HFC thickness does not change greatly. Overall the average thickness of both the silt-based and carbonate HFC’s is 28 ft. The silt-based HFCs range in average thickness from 16 to 40 ft, whereas the carbonate HFC’s range from 26 to 33 ft. These thicknesses are larger than those described from the Apache Canyon outcrop as presented in this report (see task 1a). The middle Clear Fork reservoir is interpreted as a ramp-crest and adjacent inner ramp deposit. Outcrop cycles from these facies tracts are variable and range from 10 to 20 ft in thickness.

Converting the porosity model to permeability was a simple task, but the relationships between rock fabric and petrophysical properties are unique and suggest
new research directions. The porosity-permeability cross plot for the middle Clear Fork reservoir is well constrained (fig. 13) and is characterized by the following transform.

\[ k = (7.917 \times 10^7) \times (\phi^{6.3655}) \]

Total porosity is used because thin-section descriptions indicate that separate-vug porosity is minimal. A reasonable agreement between core permeability and log-estimated permeability is obtained using this transform except where core and log porosity do not match and where the porosity intervals are very thin (fig. 14). Another possible explanation is that microfractures are present where core permeability is higher than calculated permeability. Evaluation of this possibility is part of task 2b, and preliminary results were presented in the March semi-annual report.

The porosity-permeability cross plot is confined to the petrophysical class 1 field (Lucia, 1995), whereas the rock fabrics are predominately class 2 grain-dominated dolopackstones and medium crystalline mud-dominated dolostones. This discrepancy is related to the uneven distribution of porosity on the scale of the permeability plug. Rock-fabric petrophysical classes are based on the assumption that the pore size is relatively uniform within the core sample used to measure the petrophysical properties. Thin-section examination of the Clear Fork samples shows large volumes of anhydrite. The porosity and permeability values for these samples would plot within the class 2 petrophysical field if this anhydrite were pore filling and evenly spaced throughout the sample. However, the anhydrite has a poikilotopic texture and is scattered throughout the sample. The porosity is reduced to near zero where it is present, but between the patches of anhydrite the pore size and porosity have not been reduced (fig. 15).

The relationship between pore-throat size, porosity, and permeability for sandstone has been described by Pittman (1992) and can be applied to carbonate rocks having little or no vuggy porosity. When Pittman’s relationship is compared with the rock-fabric petrophysical fields described by Lucia (1995) it is clear that as pore-throat size of a rock fabric is reduced, porosity and permeability are reduced following the trend described by the petrophysical class fields. However, in the middle Clear Fork, porosity is reduced through patchy anhydrite replacement and cementation without changing the
pore-throat size. Therefore, the permeability is reduced following the trend of equal pore-throat sizes moving from class 2 to class 1 (fig. 15). This trend has been substantiated using pore-throat sizes calculated from capillary pressure data.

An example of the resulting permeability model is presented in figure 16. Only HFC's 1, 2, and 3 are presented in a north-south cross section. Flow layers labeled “a” are interpreted to be grain-dominated flow layers, and layers labeled “b” are mud-dominated dolostones. Flow layers 1b and 3b are uniformly tight and form flow barriers. Flow layer 2b has discontinuous permeability. The continuity of the permeability increases from discontinuous in 3a, to gradually changing from south to north in 2a, and to relatively continuous in 1a. This type of heterogeneity is typical of the seven silt-based HFC's and the 15 carbonate HFC's described from the middle Clear Fork reservoir.

Conclusions

(1) The project is progressing at an acceptable pace, and no problems have been encountered.

(2) Facies dimension and continuity have been described from the outcrop and show a high degree of continuity on the 1,000-ft scale and small amounts of thickness variation. This result is consistent with other outcrop observations that we have made and supports our overall conclusion that lateral changes in subtidal cycles are very gradual on an interwell scale in carbonate ramp reservoirs of West Texas.

(3) High-frequency cycles (HFC) in the middle Clear Fork reservoir can be characterized as basal mud-dominated dolostones overlain by grain-dominated dolostones, and these fabrics can be identified from porosity curves and guided by a rock-fabric, water saturation, porosity relationship. A single porosity-permeability transform characteristic of petrophysical class 1 is justified on the basis of uneven porosity distribution at the scale of core samples. The continuous layers of dense mud-dominated dolostone at the base of most HFC's are consistent with the cycle continuity described from the Apache Canyon outcrop.
References


Figure 1. Clear Fork sequence stratigraphic architecture at Apache Canyon, Sierra Diablo Mountains, West Texas.
Figure 2. Upper Clear Fork facies architecture and cycle geometry at Apache Canyon, Sierra Diablo Mountains, West Texas.
Clear Fork of Apache Canyon, Sierra Diablo Mountains, West Texas

Figure 3. Low-accommodation styles of cyclicity in high-frequency sequence 3.1, upper Upward-shallowing cycle.
Figure 4. High-accommodation styles of cyclicity in high-frequency sequence 3.2, upper Clear Fork of Apache Canyon, Sierra Diablo Mountains, West Texas.
Figure 5. South Wasson field map showing location of reservoir model and structure top of the Tubb Formation.
Figure 6. Water saturation vs. depth plot for a portion of the upper Clear Fork showing stratigraphic terminology used in this report. Notice the increase in water saturation above the middle Clear Fork top.
Figure 7. Upper Clear Fork sequence stratigraphic framework for the South Wasson Clear Fork field.
Figure 8. Depth plot of the upper part of the middle Clear Fork showing silty beds defined by overlying sonic and porosity logs and by high water saturation values.
Figure 9. Cross plot of porosity and water saturation for a portion of the middle Clear Fork in well SWCF 7531 showing a grain-dominated packstone field and the location of grain-dominated packstones in a depth plot of porosity and water saturation.
Figure 10. Porosity histograms for three rock fabrics showing the increase in porosity from dolowackestone to grain-dominated dolopackstone.
The rock-fabric description is based on core descriptions as well as core descriptions from adjacent wells. The rock-fabric description is shown on the left side of this diagram is based on core descriptions from adjacent wells. The fabric is derived from the log and shows highest porosity values corresponding to the intervals of grain-dominated packstone. The log-based values are shown in the middle of the diagram. The fabric from logs shows the mud-dominated packstone. The mud-dominated packstone is shown in the middle of the diagram.
Figure 12. An illustration showing a portion of the high-frequency cycle (HFC) correlation. The HFCs are divided into two flow layers: a lower grain-dominated flow layer and an upper grain-dominated flow layer. Most of the HFCs show an upward increase in porosity.
Figure 13. Porosity-permeability transform for the middle Clear Fork reservoir.
Figure 14. Comparison of log porosity and permeability values with core data from well 7531.
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Figure 16. Permeability cross section of a portion of the reservoir model showing high-frequency cycles and flow layers.