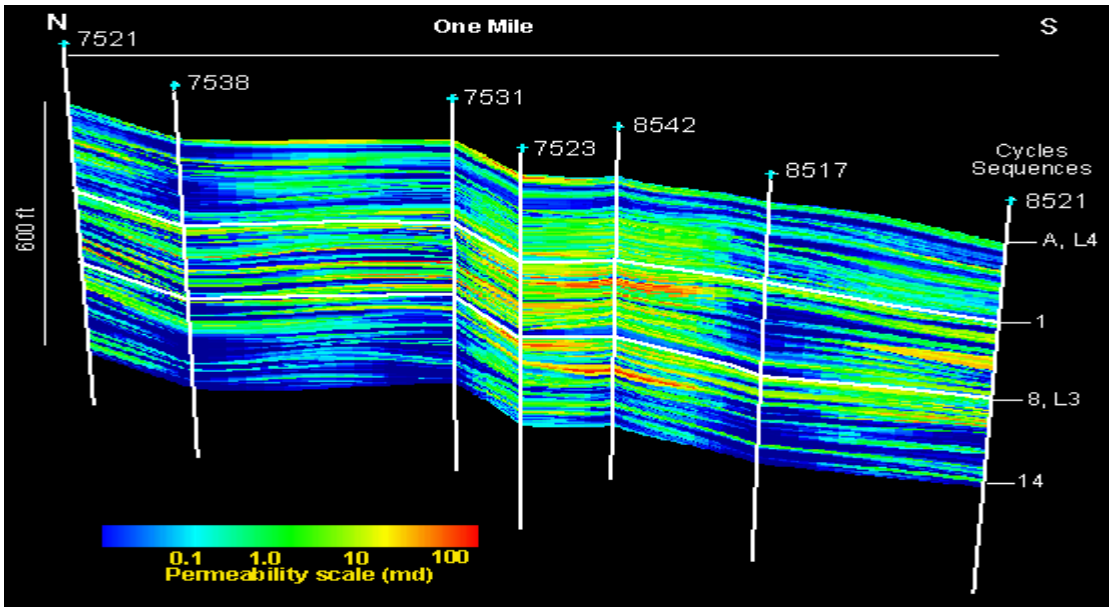
15105 University of Texas at Austin
Integrated Outcrop & Subsurface Studies of the Interwell Environment of Carbonate Reservoirs: Clear Fork (Leonardian Age) Reservoirs, West Texas & New Mexico

Success Story Summary



The Permian Clear Fork reservoirs of the Permian Basin in West Texas and New Mexico are estimated to contain 6.5 billion barrels of remaining oil. The recovery efficiency of these complex sets of carbonate reservoirs is generally very low (around 8-15%) due to the presence of a wide variety of interwell heterogeneities, impact of fractures with different types of porefillings, etc. In this project, the Bureau of Economic Geology at the University of Texas at Austin, through a consortium of 14 major and independent oil companies, is using outcrop and subsurface geologic and petrophysical data for a robust modeling of the 3D reservoir environment. To develop a reservoir model for a 1 square mile area of the middle and lower Clear Fork reservoirs, a detailed stratigraphic framework and high frequency cycle (HFC) architecture is first developed from subsurface core data in South Wasson field, guided by detailed outcrop studies at Apache Canyon of the equivalent formation and 3D seismic data. Each HFC is composed of an upper more porous grain-dominated fabric and a lower less porous mud-dominated fabric. The carbonate rocks were then divided into three rock-fabric classes based on thin section descriptions and wireline logs. A unique relationship between rock-fabric and pore-size distribution allowed a single porosity-permeability transform for each class. After identification of the rock-fabrics and cycles from core descriptions, these were mapped throughout the reservoir using wireline logs. The permeabilities computed from rock-fabric data had excellent agreement with those obtained from core data. The rock-fabric flow layers and permeability profiles defined the reservoir model. Twenty-two high frequency cycles were correlated between 38 wells in the 1-square-mile study area. Porosity, permeability and water saturation values were calculated at each well and the values interpolated between wells. The layered nature of the reservoir and considerable lateral heterogeneity can be seen in the cross-section of permeability distributions shown above. An 1,800 ft transact of 1 inch diameter samples were collected from one cycle at the Apache Canyon outcrop and the transact sampled with 5 ft spacing. Permeability, porosity, and grain density were measured and the spatial statistics analyzed geostatistically. A detailed stochastic model of an ideal HFC constructed with the above data shows considerable lateral variability. From outcrop measurements, a power law relationship was defined between fracture aperture and length and the information integrated in the Clear Fork reservoir model. However, most

of the fractures in the subsurface were filled with dolomite and anhydrite, and the timing of their generation relative to fracture formation is a key to predicting fracture permeability. The technology for identification and mapping of high and low permeable flow layers, their petrophysical properties and other small-scale heterogeneities developed in this project will considerably help in enhancing production from these complex set of reservoirs. Even if a tenth of the remaining oil in Clear Fork reservoirs could be recovered by the application of the new technology developed in this project, then it would add 650 MMBLS to the national oil reserves. Addition of such a reserve will generate $1,462 and $448 million in royalty and taxes respectively and will add ~1623 new jobs across all sectors of the Texas economy.

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Integrated Outcrop and Subsurface Studies of the Interwell Environment of Carbonate Reservoirs: Clear Fork (Leonardian Age) Reservoirs, West Texas and New Mexico/ Fundamental Geoscience Award

Problem: The Permian Clear Fork reservoirs of the Permian Basin, West Texas and New Mexico, are estimated to contain 6.5 billion barrels of remaining oil. This complex set of reservoirs is still poorly understood in terms of fine-scale interwell heterogeneities and the impact of natural fractures on fluid flow and recovery. The effect on fluid flow of high and low permeability zones and modeling of touching-vug pore systems are other major issues in carbonate reservoir characterization. For enhancing production from these reservoirs there is an urgent need for development of conceptual models of interwell heterogeneity for these reservoirs using integrated stratigraphic, structural, petrophysical, and engineering disciplines.

Project Objective: The mission objective of the Bureau of Economic Geology (BEG), the University of Texas at Austin (UT) is to use outcrop and subsurface geologic and petrophysical data from carbonate reservoir strata as the basis for developing new and integrated methodologies for better understanding and describing the 3D reservoir environment. The Bureau has been active for over 12 years in developing integrated geologic and engineering models of carbonate reservoirs in the Permian Basin of West Texas and New Mexico. Much of this work has been focused on the younger Grayburg and San Andres fields of the Permian Basin. The current research is designed to test models developed in the earlier studies and to develop new engineering scale-up tools and new fracture models for these reservoirs.

Project Costs: The research in this project is being carried out by the Reservoir Characterization Research Laboratory (RCRL) for carbonate studies which is an industrial research consortium run by the Bureau of Economic Geology (BEG), The University of Texas at Austin (UT). The total cost of the project is $ 898,000, out of which $ 718,000 is funded by the DOE and the rest is funded from non-DOE sources. The RCRL has maintained a membership of between 13 and 18 companies per year in the research consortium and the 2000 sponsors of the program are as follows:

1. Altura Energy (now OXY Permian)
2. Amerada Hess

3. Aramco
4. BP-Amoco
5. Chevron
6. Elf Aquitaine
7. Exxon Mobile
8. Kinder Morgan
9. Marathon
10. Pan Canadian
11. Petroleum Development Oman
12. Shell EP Technology and Research
13. Texaco
14. Total-Fina

Technology Change: This project focused on constructing a reservoir model of a one-mile^2 area of the middle and lower Clear Fork reservoirs (see figure below) of the South Wasson Clear Fork field in the Permian basin of West Texas and New Mexico. The RCRL has been involved for several years in developing sequence stratigraphic models and has concentrated on rock fabric research for developing petrophysical properties of oil and gas reservoirs. RCRL has realized that the adequacy of the various methods to produce geologically realistic reservoir models depends upon the degree to which the sequence stratigraphic framework and rock-fabric distribution have been conditioned by appropriate geological models, outcrop analogs, 3-D seismic data, and petrophysical data. The result of these work are summarized in Appendix-A.

Technology Transfer Method:

- The RCRL program has run continuously since 1987 and has produced more than 30 outside and BEG publications on carbonate reservoir characterization, sequence stratigraphy, petrophysics, geostatistics, and petroleum engineering. RCRL provides research results to sponsor companies through annual review meetings, CD's, preprints of publications, short courses on geologic and engineering aspects of carbonate research, and a mentoring program working hands-on with industry staff and data sets.
- RCRL results are posted on a password-protected website (www.beg.utexas.edu/indassoc/rcrl/index.htm) under a general heading, such as " South Wasson Clear Fork (Permian) reservoir studies"
- Research results are presented annually to the sponsors of the RCRL (Reservoir Characterization Research Laboratory for Carbonate Studies). Sponsors include fourteen companies, at present, including Amerada Hess, Altura (now Oxy), BP-Amoco, Chevron, Exxon-Mobil, Marathon, PennzEnergy, and Texaco.
- Although there are no publications resulting from RCRL's collaborative efforts with Altua (now Oxy Permian) to characterize the South Wasson Clear Fork reservoir, the model they are using to evaluate the CO_2 flood is based on the results of research conducted by RCRL.

Technology Implementation: The technologies developed in this project will be implemented with the help of various research publications, CD'S, short courses on

geologic and engineering aspects of carbonate reservoirs. Mentoring programs that allows hands on interaction with industry staff will also facilitate implementation of the new technologies.

***End Users*:** The main users of the technologies developed in this project will be the oil and gas companies, independent explorationists, and researchers engaged in the exploration of carbonate reservoirs in the Permian and other basins within the U.S. and abroad. The 14 oil and gas companies in the RCRL consortium (see list of companies under project cost) are expected to be the first ones who will take advantage of this research.

Impacts: The performance period of the project is from October 1998 through September 2001 and till the time of writing, this project is about 80% complete.
The successful development of a reservoir model for the prolific carbonate Clear Fork reservoirs of the Permian basin should help to recover significant amount of oil from these reservoirs and should be very useful to all operators engaged in the exploitation of these reservoirs. The following technologies developed in this project should have general applications in other carbonate reservoirs besides the Clear Fork:

Effective Integration of Outcrop and Subsurface data for carbonate Reservoir model Development
Integration of outcrop and subsurface data for the development of a high-resolution reservoir model of the complex Clear Fork carbonate reservoirs. The reservoir model has successfully identified and mapped small-scale interwell heterogeneities that have a strong impact on producibility from such reservoirs.

Application of Rock-fabric Method for Accurate Determination of Permeability and Thin Flow Layers
The highly effective rock-fabric method of analysis will allow accurate determination of permeability, high-frequency cycles and flow layers which is crucial in modeling the highly stratified reservoir such as the Clear Fork. The new technology should have significant impact in characterizing these types of reservoirs.

Development of Fracture Characterization Technology
A fractal relationship between fracture aperture and length has been defined based upon measurements from the Apache Mountain Outcrop. Development of the fracture characterization technologies should be particularly useful because of identification of fractures and fracture-filling material could significantly impact upon the production performance of most carbonate reservoirs.

Modeling of Coupled Matrix and Fracture Flow
An approach for modeling coupled matrix and fracture flow using nonneighbor connections in a traditional finite difference simulator has been tested and found to be feasible. Accuracies within 10% of an analytical solution for a test problem were obtained.

Construction of a Stochastic Model of an Ideal High-Frequency Cycle
Outcrop permeability, porosity and grain density were analyzed geostatistically and the information used to construct a detailed stochastic model an ideal high frequency cycle. The model illustrated the lateral heterogeneity that can b expected within a high-frequency cycle.

Additions to Reserves: Significant oil and gas reserves are expected to occur in fractured carbonate rocks (Economics and the 1995 National Assessment of U.S. Oil and Gas Resources, USGS Open-File Report 95-75-M) in what the USGS defines as undiscovered, technically recoverable resources in conterminous U.S. oil and gas fields. Such undiscovered reserves are likely to be found in several domestic basins such as the Permian Basin in West Texas and the Rocky Mountain basins, the Williston Basin, the Cottonwood Creek and the Oklahoma City fields of Oklahoma, etc. A significant part of the estimated 91 BBO and liquid natural gas in the undiscovered but technologically recoverable reserves are expected to be found in carbonate reservoirs. The geological heterogeneities present in the Clear Fork carbonate reservoirs should be present in the some of the undiscovered carbonate reservoirs also, and technologies developed in this project should find very useful applications in exploiting these reservoirs. The Permian Clear Fork reservoirs of the Permian basin of West Texas and New Mexico are estimated to contain 6.5 billion barrels of remaining oil. Even if the new technologies help to ultimately recover a tenth of this resource, i.e. 650 million barrels of oil, then the total royalty and tax incomes from this additional production will be 1462 and 448 million dollars, respectively. This will pay for the DOE investment in this project many times over. Successful development and application of the technology to other basins within the country and abroad and to other undiscovered reserves discussed above will result in the recovery of significantly larger amounts of oil and natural gas. Such significant additions to national reserves will generate billions of dollars in royalty and tax incomes respectively, not counting the other benefits such incomes will generate on different sectors of the national economy.

Environmental: Successful application of this technology will help to reduce surface imprint through efficient management of the reservoir, effective placement of wells (thereby reducing number of wells needed for reservoir drainage), reliable forecasting of possible production problems and implementation of appropriate remedial measures for efficient exploitation of the stratified carbonate petroleum reservoirs.

Time & Cost Savings: Improved characterization of carbonate reservoirs will result in considerable savings in time and cost to oil an gas explorationists through better placement of wells to drain the reservoirs, reduced number of wells drilled etc.

Slows abandonment of marginal fields: Abandonment of marginal fields may slow down by the application of the new technologies because new areas may be developed that show promise of enhanced oil production that was not possible thus far in these highly heterogeneous reservoirs.

Economic Impact & Job Creation: Even if a tenth of the income generated from sale of oil and gas resources is ploughed back into the oil drilling and production sector of the economy then it will have ripple effect in the economy by creating new earnings and generating new jobs in different sectors of the economy. To estimate these indirect benefits, the Regional Input-Output Modeling System (RIMS II) economic multipliers developed by the Bureau of Economic Analysis within the Department of Commerce can be utilized. In this report they have adopted a set of multipliers from the "Calculated Oil and Gas Industry Multipliers" published in Marginal Oil and Gas: Fuel for Economic Growth, 1997 Edition, from the Interstate Oil and Gas Compact Commission (IOGCC). These multipliers have been used to approximately calculate the indirect economic benefits in the state of Texas (figures for New Mexico should be comparable) as a result of investment of 1/10 of the income generated from oil and gas production in this state.

Estimate of Indirect Economic Benefits Using Final Demand Multipliers

In the State of Texas

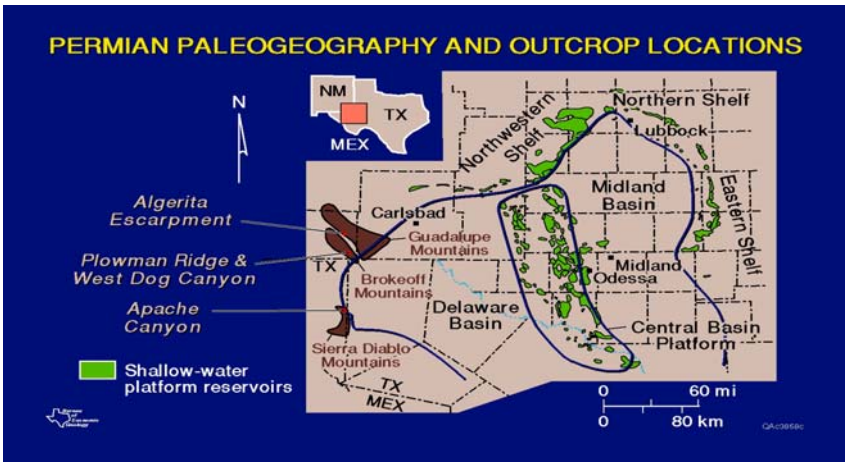
Total Investment	=	$191 million
Addition to Texas Economy	=	$302 million
Creation of Earnings in Texas	=	$41.0 million
Total No. of Jobs created in all sectors of economy in Texas	=	1,623

Appendix-A

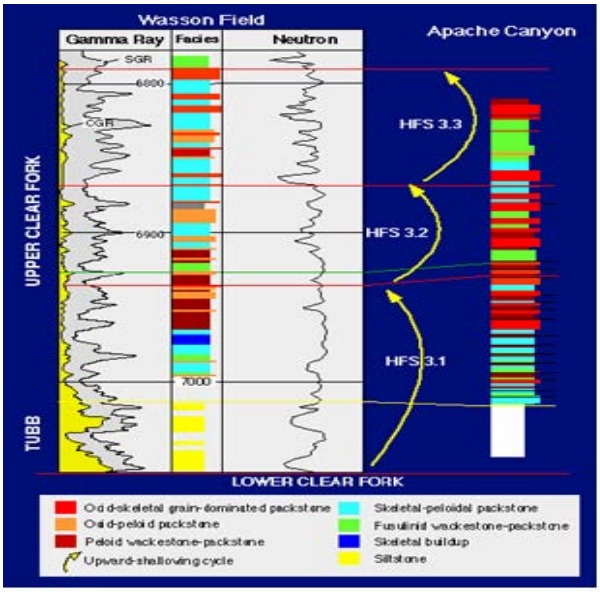
Stratigraphic Framework

Cycle and Facies Architecture

The first step in the construction of the reservoir model of the producing lower and middle Clear Fork reservoirs is the construction of a stratigraphic framework from subsurface core data from the South Wasson field, guided by detailed outcrop studies performed at the Apache Canyon of Sierra Diablo mountain range (see map below for location).



Comparison of outcrop and subsurface data has revealed more detailed information on reservoir architecture. This is illustrated in the following figure that shows 1-D facies stacking and cyclicity in Apache Canyon outcrop and South Wasson field core. Characterization of facies and cycle architecture on lower Clear Fork and lowermost upper Clear Fork equivalent outcrop is complete. The work revealed two high-frequency transgressive-regressive sequences (HFS) in the lower Clear Fork composite depositional sequence and three HFS in the middle Clear Fork Composite depositional sequence.

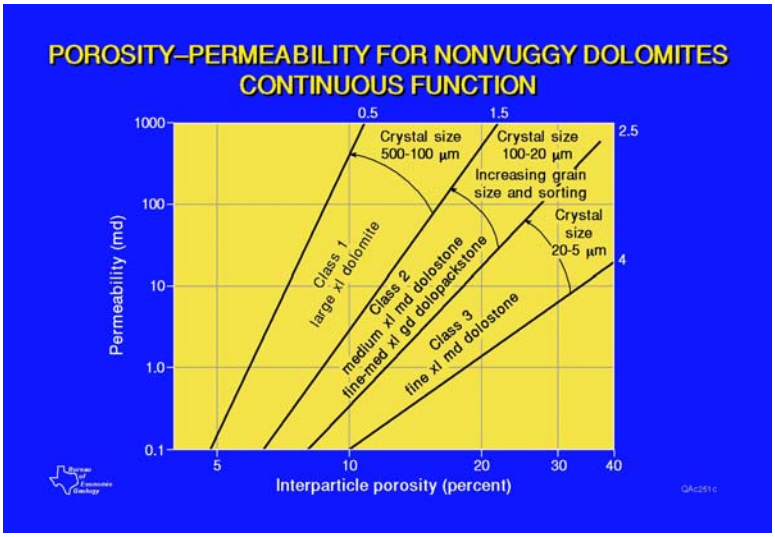


<u>Rock-fabric facies model development</u>

Rock-fabric permeability relationships

High frequency cycle & rock-fabric framework

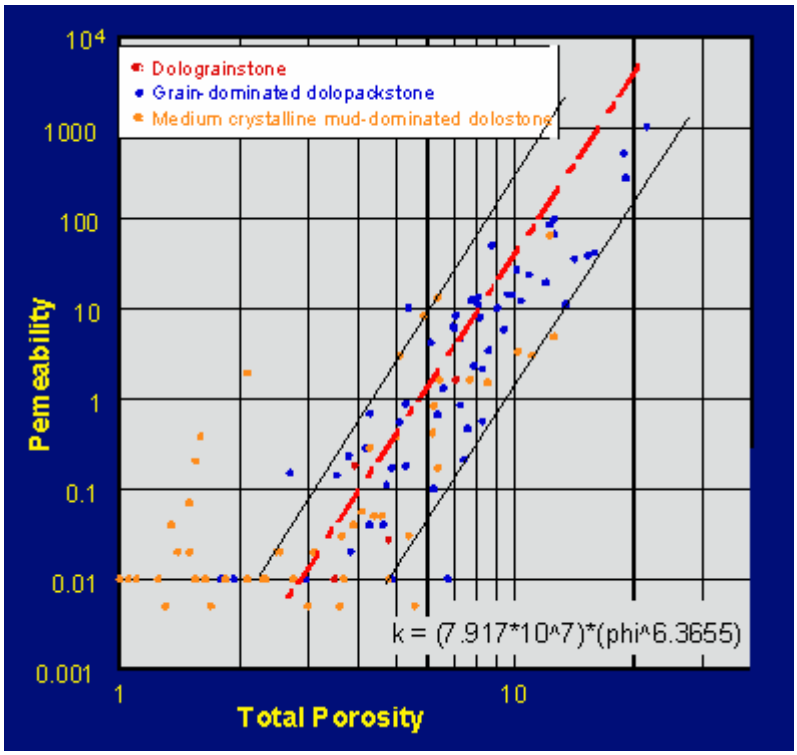
RCRL's past work has established the fundamental link between rock fabric facies and petrophysical properties for most carbonate reservoirs. The link is highly significant in reservoir modeling since it recognizes the importance of accurately distributing the

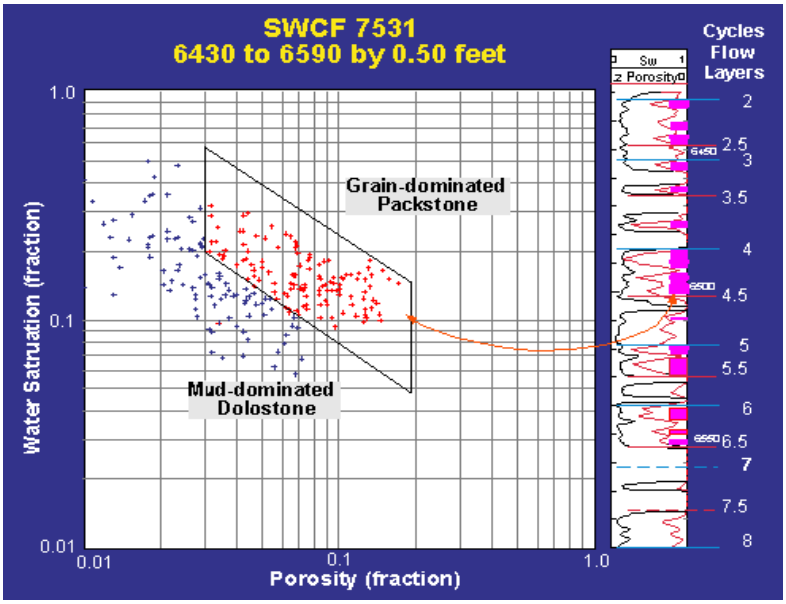


rock-fabric facies at the high-frequency cycle scale in modeling petrophysical properties away from the well bore.

The carbonate rock fabric has been divided into three classes on the basis of the petrophysical properties based upon the grain and mud-dominated character of the carbonate rocks, the crystal size, etc. A rock-fabric model is useful in developing porosity-permeability transforms for different rock-fabric classes. This model is also needed to aid in grouping values into flow layers for purposes of averaging data in developing a detailed reservoir model.

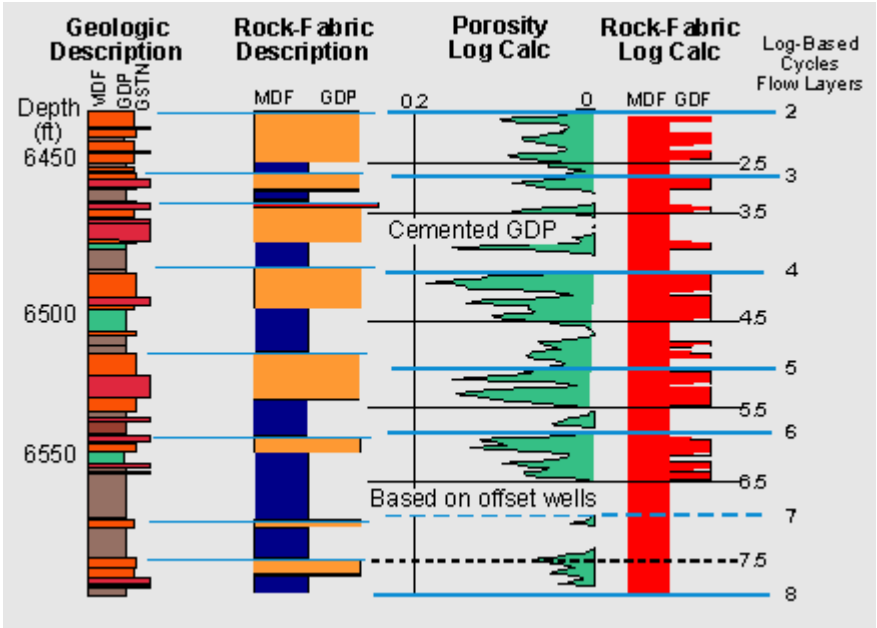
Identification of rock-fabrics, cycles and sequences is based upon core description and then these were mapped throughout the reservoir using wireline logs. Cross-plots of Archie water saturation values and total porosity have also been used to identify rock-fabrics and to pick high frequency cycle (HFC) tops. A dividing line between the two fabrics was defined and used to distinguish between the two fabrics in uncored wells.

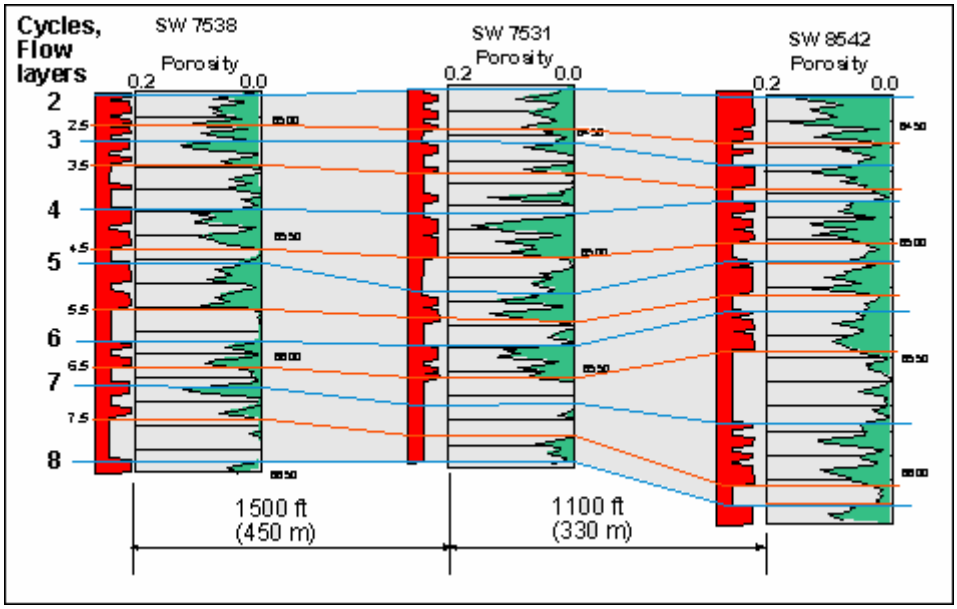




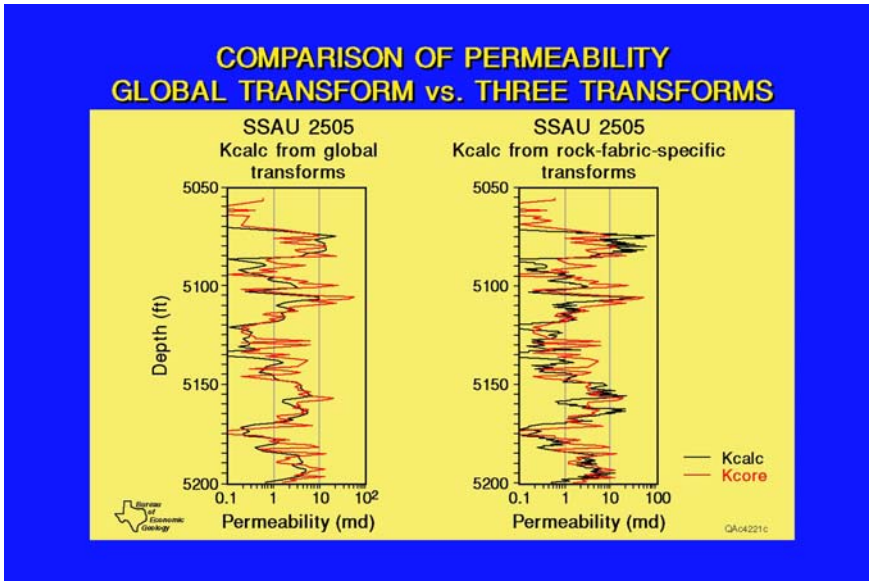
There are two basic rock fabrics in middle Clear Fork reservoir: grain dominated dolopackstone and medium crystalline mud-dominated dolostone. Porosity frequency plots for medium crystalline dolowackestone, medium crystalline mud-dominated dolopackstone, and grain-dominated dolopackstone have been used to test the suggestion that porosity can be used to discriminate between rock fabrics.

A segment of the resulting correlation is shown below. Cycle tops are located at the top of the grain-dominated dolopackstone beds, and each cycle is divided into two rock fabric flow layers, an upper grain-dominated packstone layer and a lower mud-dominated dolostone layer. Petrophysical properties within each flow layer was averaged and interpolated between wells for reservoir model construction





The rock-fabric method was used to calculate permeability from wireline logs. For each rock fabric class a separate porosity-permeability transform provided accurate permeability values for that class. A global porosity-permeability transform for nonvuggy carbonates is derived from the transforms constructed for the three rock-fabric classes using multivariate analysis. Close agreement is indicated between core measured and calculated permeability values for Seminole San Andres Unit well shown below. In this well three rock-fabric specific porosity-permeability transforms were used which resulted in the permeability depth plot shown on the right compared to the core data. The permeability depth plot using the global transform is shown on the left.



Stochastic modeling of an ideal HFC

A 1800 ft transact of 1-inch diameter samples was collected from one cycle of the Apache Canyon outcrop. The transact was sampled with 5 ft spacing and porosity, permeability and grain density were measured and the spatial statistics analyzed geostatistically. This information was used to construct a detailed stochastic model of an ideal HFC. The model illustrates the lateral heterogeneity that can be expected within one HFC.

Fracture Investigations

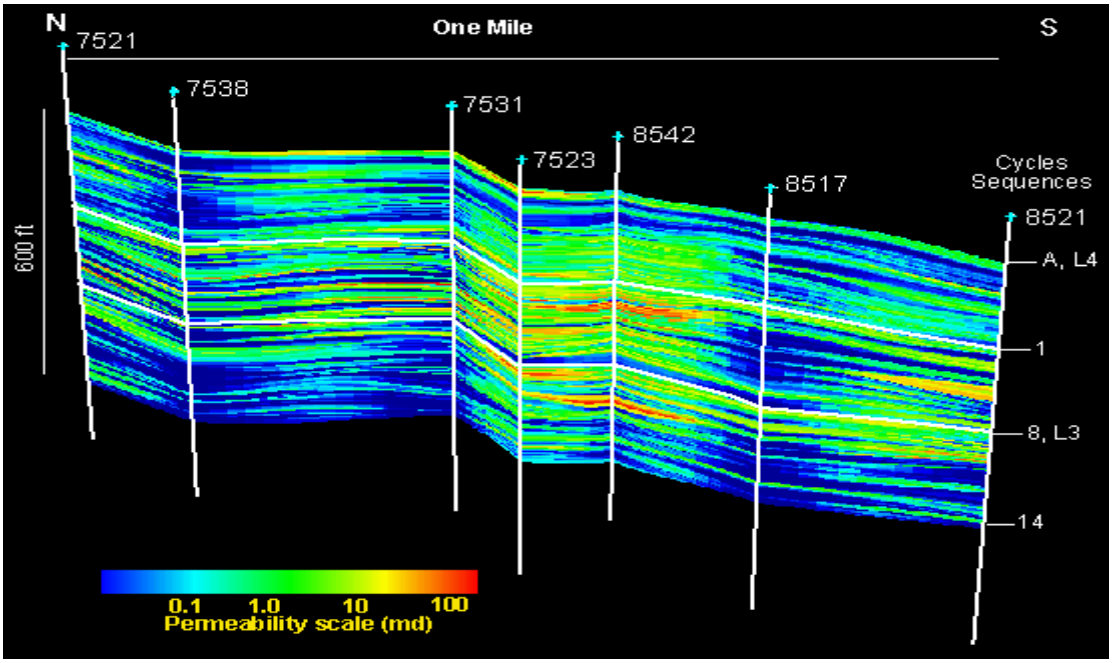
A major goal of this project is to evaluate the impact of fracture porosity on the performance of South Clear Fork reservoir. The outcrop at Apache Canyon contains numerous fractures and information on fracture spacing and aperture values were obtained from four scan lines. A power law relationship between fracture aperture and length has been defined. Such a relationship would permit fracture length estimates to be made from aperture measurements in boreholes (where fracture lengths cannot be determined directly because they exceed borehole diameters). However, many of the fractures in the subsurface are filled with dolomites and anhydrites and the timing of the dolomite and anhydrite formation relative to fracture formation is a key issue in any efforts to predict fracture permeability in SWCF reservoirs. The research on this subject is in progress.

Integration of fracture porosity and permeability into reservoir model

Subcritical crack (SSC) index have been measured on representative rock samples and crack-growth simulator has been used to model potential fracture geometries in the reservoir. The next step is the estimation of effective permeabilities of different fracture patterns obtained from crack-growth simulator.

Development of the comprehensive reservoir model

Petrophysical properties are averaged within each flow layer and interpolated between wells for construction of the subsurface reservoir model of the Clear Fork Reservoir for the one-mile square area in the South Wasson Clear Fork field. A robust 3-D permeability model has been constructed using the calculated permeability profiles, high-frequency cycles and the flow layers. Twenty-two high-frequency cycles have been correlated between 38 wells in the study area.



For each well, porosity, permeability and water saturation have been calculated using the relationships discussed above, and the values interpolated between wells. The figure above shows the permeability distribution that clearly illustrates the highly stratified nature of the reservoir. Areas of high and low permeability distributions are also present indicating the presence of fine-scale interwell heterogeneities.