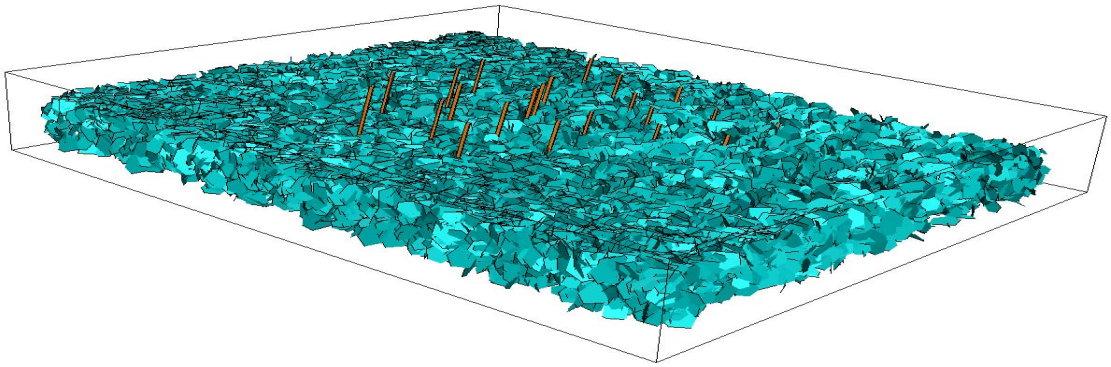
# 15101 Golder & Associates
# Discrete Feature Approach for Heterogeneous Reservoir Production Enhancement/Fundamental Geoscience Award
# Success Story Summary



**Discrete Feature Network (DFN) model of Yates field, Texas obtained from analysis of multiple scale geological, geophysical and reservoir data**

In heterogeneous reservoirs where discrete features such as fractures, faults and discontinuous sand distribution play a significant role in permeability, the ultimate recovery can be as low as 10% of the estimated oil-in-place (OIP). The unrecovered oil in such reservoirs constitutes a significant potential resource for the mature petroleum industry in the United States. In conventional reservoir engineering, simplifying assumptions are made, based on a “layer cake” continuum concept that fails when discrete features control flow at the well scale, or networks of discrete features control flow at the interwell scale. In this project, the Golder Associates team developed and demonstrated the use of discrete feature network (DFN) models as the key tool for integrating geological, geophysical and engineering data from a wide range of scales to improve reservoir development and increase oil production efficiency. The key issues addressed by the new technology are: placement of injection and production wells that could determine production efficiency, development of enhanced completion connection between well completion and the discrete reservoir flow network and development in gel treatment to effectively seal the fractures and improve reservoir sweep efficiency.

The usefulness of DFN approach in IOR applications was demonstrated in four producing fields by first developing DFN models of discrete features in the reservoirs from reservoir data and then extrapolating the features using a combination of geological and geostatistical methods. Preliminary data indicate that the application of DFN approach to surfactant injection in Yates field resulted in enhanced oil production of 36,300 barrels and the gel treatment in South Oregon field yielded 10 BOPD from each well.

The DFN technology is directly applicable to a large percentage of the secondary and tertiary oil recovery projects currently underway in the United States, and could be of significant value in the design of future oil recovery projects. The new approach should

be applicable to a wide range of heterogeneous reservoirs, the most important of which are the fractured carbonate reservoirs that account for 20% of total oil production within the United States and abroad. On a conservative estimate, the successful application of this approach should help to add at least 182 million barrels of oil and 1.77 TCF of natural gas to the national reserves. Development of these resources should generate 288 and 941 million dollars in tax and royalty incomes and create 1082 new jobs in all sectors of the national economy.

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## Discrete Feature Approach for Heterogeneous Reservoir Production Enhancement/Fundamental Geoscience Award

***Problem***: In reservoirs where discontinuous features such as faults and discontinuous sands play a significant role in reservoir permeability, the ultimate recovery can be less than 10% of the estimated oil-in-place (OIP). The remaining oil is technically or economically unrecoverable. The unrecovered oil constitutes a significant potential resource for the mature petroleum industry in the United States.

Golder Associates' project team has proposed to use the concept of discrete feature network (DFN) modeling for integrating geological, geophysical, and engineering data to improve reservoir development and increase oil production efficiency. The discrete feature network approach is based on the premise that discrete features such as fractures, faults, alluvial or solution features, permeable beds or bedding contacts etc. provide the primary hydraulic flow paths and connections, and that accurate representation of flow path geometry is a key to reservoir engineering. In contrast to this, in conventional reservoir engineering, simplifying assumptions are made based on a "layer cake" continuum concepts which fails when discrete features control flow at the well scale, or networks of discrete features control flow at the interwell scale and tract scale. The continuum approach requires an "upscaling" to extrapolate continuum properties between scales, while ignoring both the single well discrete features and the tract scale discrete feature networks.

Optimization of oil production and recovery requires very detailed understanding of processes in the injection or production intervals. At this scale, individual discrete features can play a very significant role, as can the discrete feature networks that extend away from the wells. However individual features and networks must be averaged away in the conventional continuum approach. This makes it difficult to apply continuum approaches to directly address EOR techniques at the decision making scale of the individual well installation.

In contrast, the Discrete Feature Network (DFN) model approach can directly and explicitly include key features at the well completions, interwell, and tract scales within the same model. As a result, the DFN approach has the potential to directly address the

issues of well completion geometry to improve reservoir production and recovery. In this project, the Golder Associates' project has developed and demonstrated the integration of geological, geophysical, and engineering data from a wide range of scale into a comprehensive model that can be used directly to improve production efficiency.

***Project Objectives:*** The objectives of research in this project are to develop and demonstrate practical technologies for improvement of production efficiency in heterogeneous reservoirs through integration of diverse data at a range of scales. The Discrete Fracture Network (DFN) approach has been adopted to directly address key issues (see DFN chart below) which control oil production:

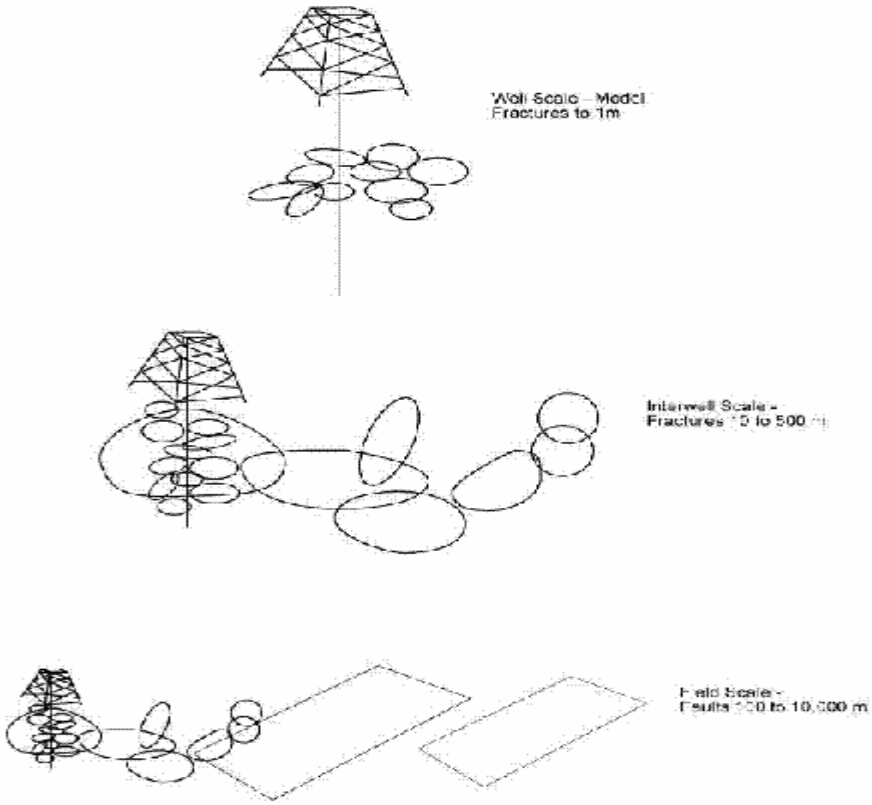



Figure 3-57 Multiscale Modeling with Discrete Fracture Networks

- Strategic completion Placement. The placement of injection and production of wells in a heterogeneous reservoir can have a key role in determining production efficiency and ultimate recovery. For example, fracture networks delivering water to the well need to be avoided in production wells, while fractures that are part of the extensive fracture networks feeding oil to the well need to be intersected.
- Enhanced Completion Connection. In reservoirs of highly varying flow capacity there is often a need to improve the connection between the well completion and the discrete reservoir flow network by experimenting with several of the stimulating techniques that hold promise. These techniques can be applied most effectively with an understanding of the discrete feature network flow characteristics of the reservoir.

- Strategic Completion Connection Reduction-Gel Treatment. Gel treatment provides a method for effectively sealing the fractures and discrete feature networks that are feeding water to production wells. The key issue for gel treatment is the identification of well intervals that contains the fractures or discrete features that would benefit from the gel treatment and the DFN approach was used to identify these intervals.

As an example of the application of the DFN modeling, in the South Oregon Basin field in the Big Horn Basin of Wyoming, the producing Phosphoria formation has significant heterogeneity in reservoir permeability due to a combination of moderate matrix permeability, larger scale fractures with good permeability and local smaller scale fractures that often result in poor fracture permeability. Because of the significant heterogeneity in reservoir permeability, current production suffers from very high (>95%) water cuts, while the oil saturation remains high (up to 80%).

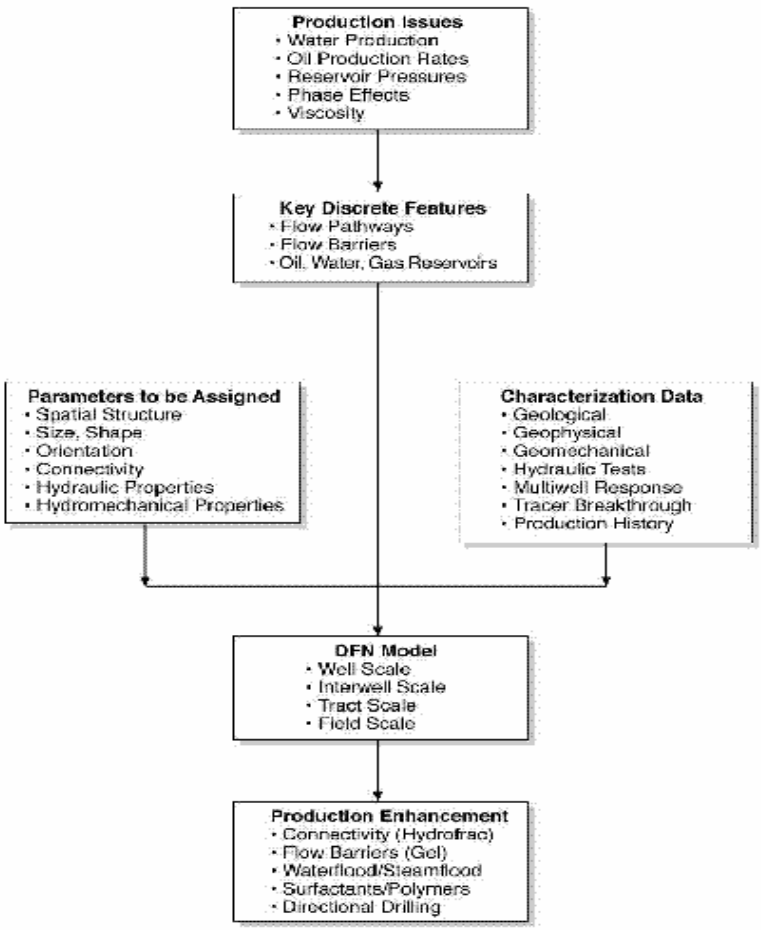



Figure 2-1: DFN Approach for Reservoir Characterization and Engineering

***Project Costs:*** The total estimated costs for the project is $ 1,039,000 out of which DOE's share is $ 739,000 and the rest is funded from non-DOE sources. The

project team consists of a balanced mix of academic, industry and petroleum company personnel. Many of the project members with key management or technical roles are recognized pioneers in the relevant technical areas of importance to the project. The team members of the project consisted of:

Golder Associates Inc. (GOLDER)
The Massachusetts Institute of Technology (MIT)
Marathon Oil Company (MOC)

***Technology Change:*** The important technological changes brought about in this project are developments of discrete feature network (DFN) models of four heterogeneous and fractured reservoirs and then conducting explicit modeling of flow in these reservoirs. The significant technological advances made in this project in the development of discrete fracture network modeling approach for heterogeneous oil reservoirs include:

- the first large scale, fracture network multiphase DFN flow simulations (Oregon Basin)
- direct DFN simulation of gel injection to realistic fracture networks (Oregon Basin, Stoney Point)
- three dimensional, heterogeneous, geo-cellular based DFN modeling for strategic completion (Yates)
- neural network algorithm development for fracture set identification
- fractal, analytical, and numerical solutions for calculation of fracture size distributions from geological and geophysical trace data
- a discrete fracture network approach for conditioning of fractured reservoir connectivity based on tracer tests

***Technology Transfer Method:*** A WWW server (http://heteroil.golder.com) has been established and maintained for this project to provide public access to research advances as they occur and to ensure that research results from this project will be available rapidly and easily to industry, government, and academic users in a timely manner. The WWW server is being continuously updated to contain:

- codes and algorithm for derivation of DFN parameters from heterogeneous reservoir characterization data
- heterogeneous reservoir site characterization database
- DFN model development procedures
- DFN models for project study sites
- DFN model evaluation and application for improved reservoir production efficiency
- papers, reports, and presentations developed within the scope of the project

A list of reports and publications from this project is in Appendix-A.

***Technology Implementation:*** The various techniques developed in this project were applied to generate DFN models of four reservoirs in the study area. The general procedure for developing a DFN model has been discussed in the literature (see

Appendix-A). The DFN technology is then implemented for flow prediction in two fields as briefly discussed below.

*DFN application in South Oregon Field*

The DFN modeling and gel simulations were attempted in the fractured South Oregon Basin. The objective of this study was to determine if by blocking the fractures that connect the injectors with the producers, the water cut in the producers could be reduced and the matrix reservoir pressure could be increased so that there is better sweep of the oil to the producers. First the DFN reservoir model of the fractured South Oregon Basin was created from a detailed analysis of the lineaments at different scales from analysis of seismic, FMI log and outcrop data.

Table 3-57: South Oregon Basin DFN Model

| Set | Orientation Distribution Pole (Trend, Plunge) Fisher Dispersion κ | Length Lognormal Distribution (Mean, Std. Dev) | Intensity $P_{32}$ ($m^2/m^3$) | Permeability (Darcy) |
|---|---|---|---|---|
| East-West | (2.8, 0) κ=30 | 3, 1.15 | 0.02 | 20 Darcy |
| East-South East | (40,0) κ=30 | 20, 10 | 0.035 | 20 Darcy |
| North-South | (260.9,0) κ=30 | 3, 1.5 | 0.03 | 20 Darcy |
| NE-SW | (316.2,0) κ=30 | 20, 10 | 0.11 | 20 Darcy |
| Bedding (Matrix) | (110,25) κ=10 | 20, 10 | 0.1 | 20 Darcy |

The table above presents a summary of the DFN model implemented including fractures and bedding plane elements. The three dimensional DFN representation of the South Oregon Basin is shown below. The fractures and matrix distributions are clearly indicated in this figure.

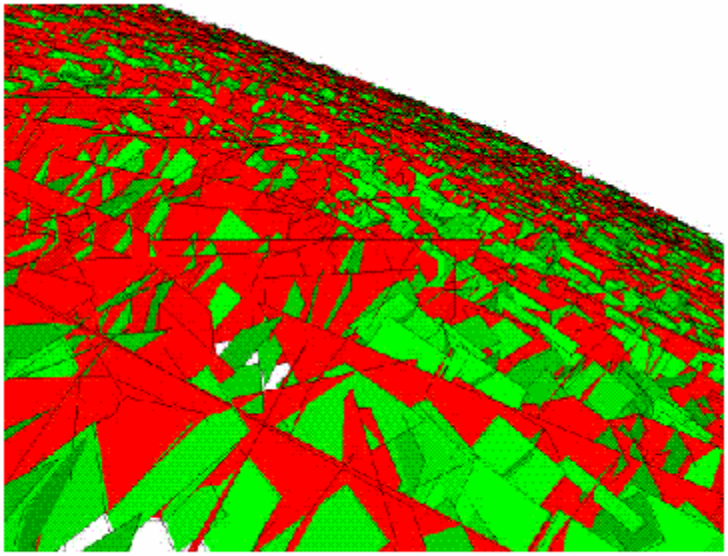


Figure 3-163: Fractures and Matrix Close up for South Oregon Basin Simulation

The effectiveness of waterflooding could be seriously limited in this type of reservoirs if the fractures provide a short circuit for the injected water between the injected and the producing well. Gel treatment aims to improve reservoir pressure maintenance and oil sweep efficiency by blocking the fractures in the vicinity of the injectors. The strategy for simulating the gel treatment is to first simulate the water injection/oil production pair including the effects of the fracture network. As the water injection increases, a pressure break-through occurs allowing water to travel directly from the injection well to the producer. The sweep efficiency is consequently low, and the pressure maintenance ineffective.

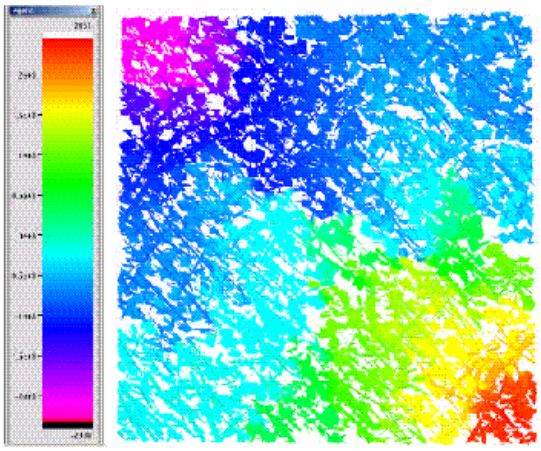


Figure 3-166: South Oregon Basin simulation pre gel. Time = 1 Hour

Now the results of simulation in which the fractures connected to the injection well are blocked by gel injection is shown below. This figure represents the post effective gel treatment case when the fracture transmissivity is reduced to .02 Darcy. The fractures no longer provide short circuit pathways, such that the water injection is able to produce an

increase in the pressure in a consistent and evenly dispersed area. This provides an efficient sweep, driving oil out of the matrix and towards the producing well.

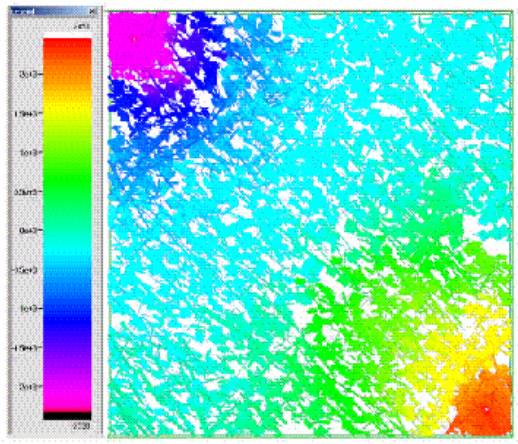


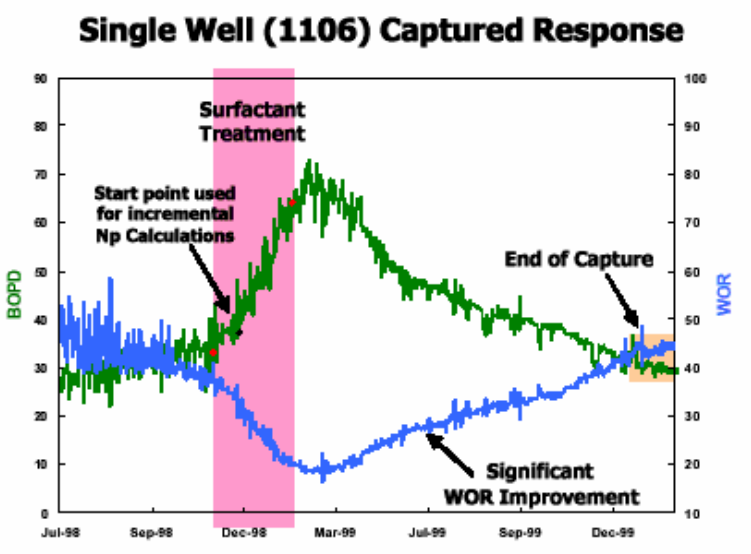
Figure 3-169: South Oregon Basin simulation after gel treatment reduces fracture permeability 3 orders of magnitude

Marathon Oil Company has carried out gel treatments targeting discrete fractures in the South Oregon Basin, consistent with the recommendations based on DFN modeling. These gel treatments have facilitated water injection that maintained formation pressure at 400 psig. Oil production at the wells affected by water injection totals approximately 10 BPD per well. Water extraction is currently about 1000 BWPD. Reduction in water production due to gel injection is difficult to measure accurately. In 75-85% of the gel injections, Marathon does no report an immediate decrease in water production at the offset producers following an injection well gel treatment. Theoretically, we would expect a significant decrease in water production if fracture networks were well plugged with gel. Marathon has however reported that in the project study site, gel injections have resulted in an increase in oil production or a shallowing of the oil decline rate. This indicates that these treatments have been at least partially successful. The observed increase in oil production may be due to improved sweep efficiency or to a change in the vertical profile of injection accessing a different area of the reservoir.

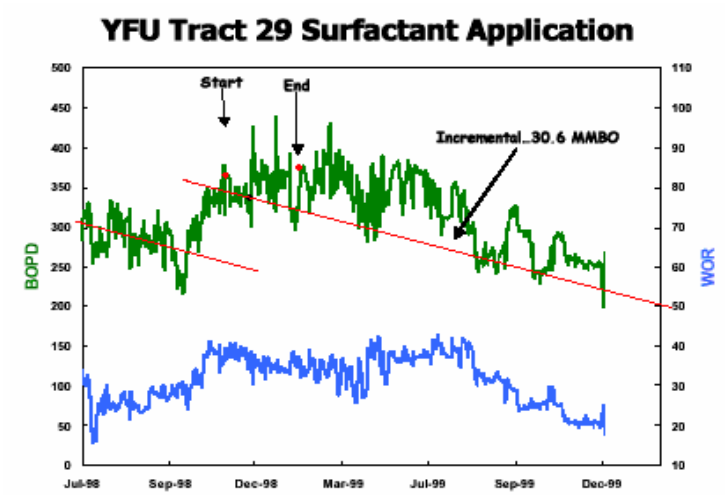
*DFN application in Yates Field*

The DFN approach was tested in the Yates Field, Texas through strategic completion/ deepening of 8 wells by Marathon Oil Company. All the recompleted wells had been previously shut-in due to unfavorable production behavior and they are located in areas having the most favorable characteristics for improved reservoir connection as evaluated from DFN modeling. The post-to-pre-recompletion ratios of daily fluid production were computed for all the recompleted wells. The overall results of recompletion was an increase in the ratio by a factor of 414.8, thereby indicating that the improved fluid production is due to better connectivity as predicted by DFN modeling. It should be noted, however that the net daily gain in oil production from the 8 wells totaled only 27 barrels and as a result the well completions may be considered moderately successful in a technical sense, but not economic. This clearly demonstrates the need for comprehensive integration of DFN analysis of water production with strategic completion analysis developed for Yates Field.

In addition to well completions, a surfactant injection test was conducted in the Yates Field in well YU 2935 and a number of surrounding wells were then monitored for production response. Well YU 1106, which is located most favorably from DFN modeling, exhibited the most marked response to the treatment. This indicated both lateral connectivity through the fracture system, as well as probable effective treatment of the matrix, due to small block size, i.e. high surface area of the fracture/matrix interfaces. The result of this surfactant test was incremental recovery of about 30.6 thousand barrels of oil (see figure below). This represents both a technical success and a promising economic outlook.




**Efficacy of Surfactant Treatment on YU 1106**




**Efficacy of Surfactant Treatment on Tract 29, Yates Field**

Although detailed DFN analysis was also carried out in the North Oregon Basin Field, Wyoming, Marathon Oil Company has not yet conducted gel treatments in this field based on this analysis. Similarly detailed DFN analysis conducted in support of IOR on

the Stoney Point Field, Michigan also could not be evaluated from field data due to a change in the ownership of the field during this project.

***End Users:*** The potential end users of the new DFN technology will be the large number of major and independent oil and gas producers who have heterogeneous oil and gas reservoirs with large variations in permeability. An effective DFN technology will find applications throughout the productive life of an oil field, from the primary recovery to waterflooding and then to any IOR applications that the reservoir may be subjected to.

***Impacts:*** A successful DFN technology will have considerable impact on the oil and gas industry by providing an effective technology to exploit heterogeneous clastic and fractured carbonate reservoirs in basins around the world. The discrete feature network technologies developed within this project are directly applicable to a large percentage of the secondary and tertiary oil recovery projects currently underway in the United States, and can be of significant value to the design of future oil recovery projects.

In order to have some idea about the size of the reserves that the new technology can impact, we refer to Halbouty et al. (1970) who in a survey of 266 giant oil and gas fields with recoverable reserves of 500 million barrels or greater concluded that 44% of the reservoirs produce entirely or substantially from carbonate reservoirs. A review of the statistics suggest that these carbonate reservoirs contain about 61% of the recoverable oil in giant fields. If giant fields contain some 85% of the (Fitzgerald, 1980) of the world's recoverable petroleum reserves, statistics for the giant fields should heavily influence those for all petroleum fields. If one assumes a direct relationship for the entire range of volumetric productivity, then carbonate reservoirs should contain about 60% of the recoverable oil supply of the world. A significant part of this production will be from fractured carbonate reservoirs. From present overall production statistics (Aguilera, 1995) at least a fifth of the total oil and gas reserves are likely to be found in fractured carbonate rocks.

***Addition to reserves:*** Significant oil and gas reserves are expected to occur in fractured carbonate and diagenetically altered clastic 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 <u>undiscovered</u>, <u>technically recoverable</u> resources in conterminous U.S. oil and gas fields. Such undiscovered reserves are likely to be found in several domestic basins in Alaska, the Permian Basin in West Texas and the Rocky Mountain basins, the Williston Basin, the Cottonwood Creek, the Oklahoma City fields of Oklahoma and the Appalachian Basin etc. A significant part of the estimated 91 BBO and liquid natural gas liquids and 885 TCF of natural gas in the undiscovered but technologically recoverable reserves are expected to be found in fractured carbonate reservoirs. Even if a fifth (from present overall production statistics) of the reserves in this category are found in fractured carbonate rocks, then at least 18.2 BBO and 177 TCF of gas will be found in this category of <u>undiscovered but technically recoverable</u> reserves. If the technologies developed in this project help to recover at least a hundredth of the reserves in fractured carbonates, then 0.182 BBO and 1.77 TCF of natural gas will be added to the national reserves in part, through the application of new technologies

developed in this project. 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. Development of such resources will generate billions of dollars in royalty and tax incomes, 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 the number of wells needed for reservoir drainage), reliable forecasting of possible production problems and implementation of appropriate remedial measures for efficient exploitation of the fractured carbonate and heterogeneous clastic petroleum reservoirs.

***Time & Cost Savings:*** By avoiding unnecessary wells in draining highly heterogeneous fractured carbonates and diagenetically altered clastic and carbonate reservoirs and through better placement of wells, the new technology should result in time and cost savings.

***Slows abandonment of marginal fields:*** Abandonment of marginal fields would be slowed by the application of the new technologies because new areas may be developed that show promise of enhanced oil production by identifying favorable areas in a fractured or heterogeneous reservoir that was not possible thus far with existing technology.

***Tax & Royalty Incomes:*** Sale of oil and gas resources developed from application of technologies discussed in this project (0.182 BBO and 1.77 TCF of natural gas) will generate tax and royalty incomes of 288 and 941 million dollars, respectively (at tax and royalty rates of 4.6% and 15%, respectively). Investment of even a fraction of this income will have a ripple effect on the national economy as shown below.

***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 (multipliers are the averages for all the states) as a result of investment of 1/10 of the income generated from oil and gas production in various states.

**Estimate of Indirect Economic Benefits Using Final Demand Multipliers**

| | | |
|---|---|---|
| Total Sale price of Oil @ $15/ barrel) | = | $ 2.73 Billions |
| Total Sale price of Gas @ $2.0/ 1000 cu. ft) | = | $ 3.54 Billions |
| Total income from Taxes @ 4.6% | = | $ 288 Millions |
| Total income from Royalties @ 15% | = | $ 941 Millions |
| Total Investment(1/10 of Income) | = | $ 123 Millions |
| Addition to National Economy | = | $ 182 Millions |
| Creation of Earnings in U.S | = | $ 23.1 Millions |
| Total No. of Jobs created across all sectors of national economy | = | 1,082 |

## Appendix-A

The following reports have been submitted from this project:

| | |
|---|---|
| First Progress Report | Jan 15, 1999 |
| Second Progress Report | July 15, 1999 |
| Third Progress Report | Feb 15, 2000 |
| Fourth Progress Report | July 15, 2000 |
| Fifth Progress Report | Feb 15, 2001 |
| Final Report | Sept 30, 2001 |

The following publications and presentations resulted from this project:

Chen, H., L.R. Lucas, L.A.D. Nogaret, H.D. Yang, and D.E. Kenyon, 2000. Laboratory Monitoring of Surfactant Imbibition Using Computerized Tomography, SPE 59006, presented at the Twelfth SPE/DOE Symposium on Improved Oil Recovery, IOR Technology For The New Millennium 3-5 April 2000, Tulsa, Oklahoma, USA.

Dershowitz, W., E. Wadleigh, G. Lee, and T. Eiben, 1998. Discrete Fracture Network Approach for Thermally Assisted Gravity Segregation Enhanced Oil Recovery. Presented at ISRM '99, Paris.

Dershowitz, W., T. Cladouhos, P. LaPointe, and W. Wadleigh (1999) Discrete Feature Network Methods for IOR in Heterogeneous Reservoirs. 1999 DOE Oil and Gas Conference, Technology Options for Producer Survival. Dallas, June 28-30, 1999.

Dershowitz, W., Th. Eiben SPE, and T W. Doe, 1999. Size, Shape, and Spatial Pattern of Conductive Fractures in Heterogeneous and Fractured Reservoirs. Society of Petroleum Engineers Inc. Paper SPE 56516 presented at the 1999 SPE Annual Technical Conference and Exhibition, Houston, Texas, 3-6 October 1999.

La Pointe, P.,1999. Predicting Hydrology of Fractured Rock Masses from Geology: Techniques, Successes and Failures from Recent Case Histories. International Symposium on the Dynamics of Fluids in Fractured Rocks: Concepts and Recent Advances. 10-12 February, 1999. Berkeley, CA. (Invited Presentation)

LaPointe, P., R. Parney, T. Cladouhos, W. Dershowitz, B. Curran and Eugene Wadleigh, 2000. Discrete Feature Approach for Heterogeneous Reservoir Production Enhancement: (1) South Oregon Basin Field, Wyoming (2) Yates Field, Texas, presented at DOE NPTO Contractor Review Meeting, 26-29 June 2000, Denver, Colorado

Parney, R., T. Cladouhos, P. La Pointe, W. Dershowitz, B. Curran, 2000. Fracture and Production Data Integration Using Discrete Fracture Network Models for Carbonate Reservoir Management, South Oregon Basin Field, Wyoming, SPE 60306. Presented at the 2000 Rocky Mountain Section SPE Meeting, Denver, Colorado.

Snell, J., E. Wadleigh, and J. Tilden, 2000. Fracture Characterization a Key Factor in Yates Steam Pilot Design and Implementation, SPE 59060, presented at the Twelfth SPE/DOE Symposium on Improved Oil Recovery, IOR Technology For The New Millennium 3-5 April 2000, Tulsa, Oklahoma, USA .

Yang, H. and E. Wadleigh, 2000. Dilute Surfactant IOR Design Improvement for Massive, Fractured Carbonate Applications, SPE 59009, presented at the Twelfth SPE/DOE Symposium on Improved Oil Recovery, IOR Technology For The New Millennium 3-5 April 2000, Tulsa, Oklahoma, USA.