Permeability field derived from inversion of water-cut data in the highly heterogeneous North Robertson Unit, West Texas

Prediction of fluid production based on static reservoir models often fails to match the observed field production history. For reliable future performance predictions, it is imperative that the reservoir models adequately reproduce the past performance history of the reservoir and for this, it is necessary to condition the static model with dynamic reservoir data, such as transient pressure, tracer response and multiphase production history. Integration of dynamic data can be particularly effective in identifying preferential flow paths or barriers to flow that can adversely impact sweep efficiency. Identification of the location and distribution of these barriers is critical to the success of the secondary and tertiary recovery efforts.

Integration of production data in conventional finite-difference simulators is computationally infeasible for the large number of simulations involved and has never been done in a fine-scale reservoir model consisting of millions of grid blocks. Lawrence Berkeley National Laboratory and Texas A & M University have, for the first time, adopted a very flexible and efficient approach to merge different data types (production, seismic, well log) by developing a very general and computationally efficient 3D streamline simulator for modeling multiphase flow through fine-scale reservoir models. Besides being cost-effective, the streamline based flow simulator is computationally efficient in rapid inversion of dynamic production data by using an analogy between the streamlines and ray tracing in seismology. This allows application of efficient inversion technology from seismic for integration of production data. The algorithm developed has reduced the time required to invert tracer data for 3D reservoir structure in an entire field by about 10-1000 times. The feasibility of the approach developed has been demonstrated in field applications in the carbonate reservoirs at the North Robertson Unit and the Goldsmith San Andres Unit in West Texas.

The new reservoir characterization technology will lead to efficient management of a wide variety of oil and gas reservoirs by identifying bypassed oil/gas for targeting infill drilling, extending life of wells by reducing early water breakthrough and reducing water cycling and enhancing sweep efficiency. Enhanced production of even 1/2% of oil and gas from already discovered reserves by this technology will result in additional production of 400 MMBLS of oil and 26 Tcf of natural gas. This production will generate 17 billion dollars of income for the Federal government in the form of taxes and royalties and will create 9,000 new jobs in various sectors.
High-Resolution Reservoir Characterization Using Seismic, Well, and Dynamic Data

**Problem:** While static reservoir information derived from geologic, well and seismic data will help to develop the basic reservoir model; such a model may often result in fluid flow predictions that do not match the observed field production history. For accurate prediction of future production, it is imperative that such models adequately reproduce the past performance history. For the reservoir model to accurately reproduce the past performance it has to be conditioned to dynamic data, such as transient pressure, tracer responses and multiphase production history.

Recent advances in 3D seismic and other technologies have made it possible to generate very fine scale reservoir models that may consist of several hundred thousand to millions of grid blocks. Since permeability cannot be directly estimated from seismic data, it is important to integrate production data to obtain information on the flow characteristics of the reservoir. Dynamic data such as transient pressure response, tracer or production history can be particularly effective in identifying preferential flow paths or barriers to flow that can adversely impact sweep efficiency. Integration of production data through inverse modeling is computationally very intensive and is beyond the scope of conventional finite-difference simulators. Therefore, the integration of dynamic data into high-resolution fine scale reservoir models with conventional finite-difference simulators remains an outstanding challenge. A new and efficient approach is needed to merge different types of data, viz. production, seismic, well log, etc. for developing an effective reservoir characterization model that can explain the fluid flow characteristics of the reservoir.

**Project Objective:** The objectives of this project are to develop a systematic procedure for petroleum reservoir characterization that integrates seismic, well and dynamic data (chiefly production data such as water-cut, but also including transient pressure test or tracer test data) for a realistic description of fluid movement in the reservoir and to demonstrate the approach in field applications. The key elements of the project are the development of a very general and computationally efficient 3D streamline simulator for modeling multiphase flow through fine-scale reservoir models, rapid inversion of dynamic production data by using an analogy between seismic rays and the streamlines and integration of 3D seismic with well data using a robust, statistical technique. The resultant product will be a computer package for integrated reservoir characterization that incorporates 3D seismic, well and dynamic data. Besides its use as a forward model, an important objective of research will be to take advantage of the ability of the streamline modeling method to compute reservoir parameter sensitivities to production response and these sensitivities form an essential component of production data integration procedure.

**Project Cost:** The total estimated cost for the project is $682,000, out of which DOE’s share is $362,000. The non-DOE share of $320,000 was obtained from a consortium of oil and gas and service companies. Each member of the consortium (made up of Tomoseis, Chevron, Exxon-Mobil, Landmark, RC2, BP-Amoco, Total-Fina, Statoil, Phillips, JNOC, Schlumberger and EcoPetrol) has contributed $25,000 to the conduct of research in this project.
Technology Change: A number of conceptual and technological innovations were introduced in this project and some of the important ones are described below:

- The development of the comprehensive streamline simulator package for detailed characterization of reservoirs that can integrate production data (such as multiphase flow, pressure and tracer), with seismic, well log etc. Integration of production data requires a large number of reservoir simulations and is computationally infeasible with conventional, finite-difference simulators. Therefore there was urgent need for development of the new streamline simulator that can very effectively integrate the different data types.

- Fast and efficient inversion of dynamic production data like multiphase flow, pressure, and tracer to obtain information on flow characteristics of the reservoir is an important technological breakthrough achieved in this project. An innovative approach was to develop the inversion of production data in a manner analogous to seismic data. Since the streamline transport equation can be cast in the form of the Eikonal equation, the governing equation for travel time tomography, the efficient inversion techniques from geophysical imaging could be applied to the inversion of the production data also. This is the first time such production data has been integrated directly into fine-scale reservoir models consisting of > 30,000 grid blocks without any artificial reduction of parameter space. More significantly, this has been accomplished with reasonable computational efforts (less than 3 hours of c.p.u time and is estimated to be 10-1000 times faster than the conventional simulator).

- Coupling of production history and seismic information using a geostatistical approach and joint inversion of production and seismic data. The important aspects of the geostatistical approach are the uses of non-parametric regression to correlate seismic attributes with formation properties at the wells, generation of conditional realizations of formation properties in the interwell region using seismic attributes and conditioning formation properties using production history. The important joint inversions performed were, construction of a geological model using well log and seismic data, construction of interwell saturation changes using time-lapse seismic data, cross-checking saturation distribution with production data using streamline simulation.

The applications of the new approaches were first illustrated by several examples on synthetic data involving integration of tracer and water-cut responses into two and three-dimensional reservoir models for derivation of the permeability fields.
The above figure shows the results of pressure inversion on synthetic data to obtain permeability distribution in the field. The synthetic model is on the left and is a spatially correlated random permeability field and contains a 300% variation in permeability. On average, permeabilities are lower to the west and higher to the east. The injection and the observation wells are indicated by stars. The permeability resulting from inversion of arrival times of the pressure head values from the injection well to the observation wells are shown on the right. The close agreement between the synthetic model and the derived permeability field distribution is a testimony to the accuracy of the inversion technology developed.

Integration of tracer and water responses into a fine scale, high-resolution reservoir model consisting of grid dimensions of 50x25x25 or a total of 31250 cells was accomplished in less than 3 hours using a Silicon Graphics and is estimated to be 10-1000 times faster than in the conventional simulator. On comparison of the inverted permeability model with the reference model, it was observed that the inverted model reproduces most of the features of the reference permeability model.

**Technology Transfer Method:** An important vehicle for transfer of technology in this project will be through the various members of the consortium who actively participated in the development of the new technology. The consortium was made up of the following major and independent oil and gas and service companies: Tomoseis, Chevron, Exxon-Mobil, Landmark, RC2, BP-Amoco, Total-Fina, Statoil, Phillips, JNOC, Schlumberger. Presentations and publications (see list attached) at leading technical society meetings were another important means for dissemination of information and transfer of technology to the interested parties and the public at large. Results of research presented, particularly at several meetings of the Society of Petroleum Engineers, generated a good deal of interest.

**Research Wins Prestigious Ferguson awards**
- Based on research conducted in this project Mr. Seongsik Yoon was awarded the Cedric K. Ferguson medal (given to young scientists under age 33) for the best peer-approved technical paper of the Society of Petroleum Engineers during 1999. The
paper is titled "Integrating Dynamic Data Into High-Resolution Models Using Streamline-Based Analytic Sensitivity Coefficients". The coauthors and principal investigators of this project, Mr. Don Vasco and Mr. Akhil Datta-gupta were awarded the Ferguson certificates.

- This significant award recognizes the potential application of technology developed in this project to improve reservoir characterization and enhance oil and gas production from heterogeneous reservoirs.

**Presentations and Publications**


**Technology Implementation:** The result of the research conducted in this project will be a three-dimensional reservoir simulator package for characterizing petroleum reservoirs and the new technology will be implemented with this computer package. The technology for characterizing petroleum reservoirs developed were first applied to several synthetic data sets and then validated in the following field demonstration projects:

- A carbonate field at the North Robertson Unit in the Permian Basin of West Texas
- A second carbonate field at the Goldsmith San Andres Unit of West Texas
- A sandstone reservoir Unit at the Stratton Field in south Texas
- Two fields in the Middle East by Industry Partner

![North Robinson Field](image)
As part of the continuing effort to integrate dynamic data, the researchers in this project have also developed a very efficient transient pressure imaging technique. In this approach the pressure inversion is decoupled into an arrival time inversion and an amplitude inversion. This technique has been applied for inverting pressure variations in two interference tests from Conoco’s Borehole test facility. The inversion algorithm has also been applied to a set of crosswell pressure data. The pressure variations induced by 3 source intervals recorded by 12 transducers were used to image permeability variations between two wells. The results closely agree with 3D seismic data and also confirmed from cores from a deviated well taken in this area. A technique to compute relative permeability parameters using water-cut histories was also developed.

**End Users:** A consortium of oil and gas and service companies actively participated in the conduct of research performed in this project. This consortium was made up of Tomoseis, Chevron, Exxon-Mobil, Landmark, RC2, BP-Amoco, Total-Fina, Statoil, Phillips, JNOC, Schlumberger and EcoPetrol.

**Impacts:** The project is about 75% complete and the full impact of the project is expected to be felt only after all the tasks are completed. Due to the flexibility, cost-effectiveness and computational efficiency of the new technology developed in this project for high-resolution reservoir characterization, it will have far reaching impacts in the management of oil and gas reservoirs. It will lead to better pattern balancing, reduced water cycling and enhanced sweep efficiency of the reservoir. Probably the most important contribution from this high-resolution investigation will be the ability to identify bypassed oil and gas saturated zones for infill drilling. Other benefits will accrue in the form of extending the life of wells by reducing early breakthroughs and improving the turn-around time for data integration.

**Cost effectiveness:** Conditioning reservoir models with dynamic data could be computationally prohibitive with the conventional finite-difference simulator, and has never been done for fine scale reservoir descriptions consisting of several million grid cells. An important advantage of the streamline simulator and also the algorithm developed for inversion of production data is a drastic reduction in the computation time. Streamline simulation can be 10-1,000 times faster then the conventional simulators and should significantly reduce data processing costs.
Future Work: A proposal has been put forward for an extension of this research that emphasizes joint inversion of seismic and production data for high resolution estimates of permeability. A number of field applications for validation of inversion results have been planned. Industry partners in the consortium will furnish field data and financial contribution to the project and would participate in field application and validation of results and eventually in commercialization of the new technology.

Reserves Additions: The project is nearly 75% complete. Once all the field demonstrations of the relevant technologies have been completed, an effective tool will be available for characterizing heterogeneous reservoirs such as the carbonate reservoirs in the Permian basin or the fractured sandstone reservoirs in the Gulf Coast and other basins. Because of the various heterogeneities and insufficient information on the flow properties of these heterogeneous reservoirs, hydrocarbon recovery from such reservoirs is usually very small. Improved characterization of such reservoirs will result in enhanced recoveries of oil and gas through various waterflood and IOR operations. These reserves will generate additional taxes and royalties for the Federal government.

Economic Benefits: Significant economic impact is expected to accrue from the new technology through efficient management of low permeability, heterogeneous reservoirs. Maximum benefit would result from judicious placement of wells, enhanced recovery operations, etc. Even ½ % enhanced production of oil and gas from already discovered reserves will result in enhanced production of 400 million barrels of oil and 26 Tcf of natural gas. The enhanced production of oil and gas will generate incomes of 7 and 10 billion dollars in taxes and royalties, respectively for the Federal government.

Job creation: To estimate these indirect benefits, the Bureau of Economic Analysis within the Department of Commerce has developed a system of multipliers to approximately estimate the effect of investment in the oil industry to all other sectors of the economy. Using an average multiplier of 1.4776 for all the oil and gas producing states in the country, it is estimated that even if 10% of the income from oil and gas production is ploughed back into the economy, it will add about 2.5 billion dollars to the overall economy of the country and will have the potential to ultimately create 15,000 new jobs across all sectors of the economy.

Environmental Safety: A streamline-based inversion approach for partitioning tracer response to estimate spatial distribution of NAPL (Non-Aqueous Phase Liquid) has been developed. It is now well recognized that the presence of NAPLs poses a significant impediment to aquifer restoration. In order for any remediation technique to be successful, it is essential that the NAPL distribution should be properly characterized. The results of tracer data inversion technology from this project will have very useful application in characterizing reservoirs for distribution of contaminants. The method was applied to map NAPL saturation distribution at the Lost Hill air force base by partitioning tracer data. A cut-away view of the Lost Hill NAPL saturation distribution is shown below. It has also been demonstrated that the new approach is faster by about three orders of magnitude.
Improved reservoir characterization and more accurate mapping of flow properties in the reservoir will result in lesser number of wells needed to drain the reservoir and hence will reduce surface imprint.