

CONF- 970692--1

RECEIVED

MAY 05 1997

OSTI

SPE 38284



Integrated Reservoir Management for the Long Term - The Carpinteria Offshore Field

E.M. Whitney, SPE, Los Alamos National Laboratory, M.R. Brickey, Minerals Management Service, S.E. Coombs, Coombs & Associates, C.A. Duda and V.K. Duda, California State Lands Commission

This paper was prepared for presentation at the 1997 SPE Western Regional Meeting held in Long Beach, California, 25-27 June 1997.

This paper was selected for presentation by an SPE Program Committee following review of information contained in an abstract submitted by the author(s). Contents of the paper, as presented, have not been reviewed by the Society of Petroleum Engineers and are subject to correction by the author(s). The material, as presented, does not necessarily reflect any position of the Society of Petroleum Engineers, its officers, or members. Papers presented at SPE meetings are subject to publication review by Editorial Committees of the Society of Petroleum Engineers. Electronic reproduction, distribution, or storage of any part of this paper for commercial purposes without the written consent of the Society of Petroleum Engineers is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of where and by whom the paper was presented. Write Librarian, SPE, P.O. Box 833836, Richardson, TX 75083-3836, U.S.A., fax 01-972-952-9435.

Abstract

The Carpinteria Offshore Field, Santa Barbara, California, has produced more than 100 million barrels of oil to date. This mature field has continued operations in an economically and politically challenging environment that finally resulted in the abandonment of the field's California State leases by the lease holder. The abandoned leases, together with adjoining federal leases are now operated by an independent producer. Los Alamos National Laboratory has joined with that independent operator, Pacific Operators Offshore, and with the State Lands Commission of California and the Minerals Management Service, in a unique collaborative effort to redevelop the mature field. This project is a part of a larger umbrella project, the Advanced Reservoir Management Project (ARM), that is designed to demonstrate the worth of advanced computational tools and state of the art methods for independent oil and gas producers. The Carpinteria Reservoir Redevelopment project takes a long-term view of reservoir management - as a result, our management plan includes a continuing investment in time and technology in order to better understand the reservoir. In particular, we have completed an extensive reservoir characterization and geological modeling effort that has created a self-consistent model, satisfying geophysical, geological, and engineering data constraints. We have begun the engineering-intensive flow simulation phase of the project using the current geological description of the reservoir, and are confident that our careful efforts in geological modeling will result in a reasonable reservoir flow model.

Dynamic documents exist that are used by participants to stay abreast of developments on the project. These WWW pages may be viewed at

<http://ees.lanl.gov/EES5/arm/pool> Other sites of interest, that describe the nature of the agencies and companies involved in the project are at
<http://ees.lanl.gov/EES5/>,
<http://www.mms.gov/omm/pacific/index.html>,
<http://www.slc.ca.gov>, and
<http://www.pacops.com>.

Introduction

The Carpinteria Offshore Field (Santa Barbara, California, Figure 1) was discovered in 1964, and has been developed over three decades with deviated drilling from five platforms. The field has produced more than 100 million barrels of oil to date. This mature field is analogous to other nearby offshore fields, and efforts to redevelop it therefore have great implications for those fields.

The three mile coastal waters boundary between Federal and State leases cuts through the Carpinteria field, so that of the five leases on the field, three belong to the State, and two are Federal. Over the years, various companies have operated the leases, a situation that has resulted in a disjointed production strategy for the reservoir as a whole.

29 productive intervals have been identified and mapped in the Carpinteria reservoir, and production from these intervals has been comingled to a large degree on individual leases throughout the history of the field. In recent years, increased water cuts and sand production from unconsolidated strata, accompanied by lower production, reduced the profitability of the field, and contributed to a decision by the operator to abandon the California State leases. Two of the abandoned State leases, together with the adjoining federal lease are now operated by an independent producer, Pacific Operators Offshore, Inc. (POOL).

In the course of abandonment by the previous operator in 1996, all wells on the two production platforms in the State leases were plugged and abandoned, and the platforms were removed. The State leases are thus unreachable by drilling, except from platforms in Federal leases. Plans for redeveloping the reservoir include options for high angle

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

ln

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

extended reach drilling, to recover oil from various parts of the reservoir, including the otherwise inaccessible State leases.

In 1993, when POOI acquired the leases, the conceptual model of the field was confusing. This confusion was the result of multiple interpretations of geological and engineering data by a variety of operators. No field wide reservoir interpretation was available to POOI that integrated geological, geophysical, engineering (well test), and production data.

POOI recognized that to understand such a complex geological environment, advanced modeling and visualization technologies would be required, that would permit the building of a coherent model of the reservoir sands, and would permit that model to be viewed in three dimensions. This model would be viewed and manipulated to reveal its surfaces, volumes, and its distribution of rock and fluid properties.

The long-term reservoir management plans for the Carpinteria Field will make use of reservoir simulation as a guide for production operations in the field. In order to conduct meaningful reservoir simulation studies, and thereby meet the needs of the operator and the management plan, a credible reservoir model was needed. The construction of this model is the subject of this paper.

The Advanced Reservoir Management Project

These advanced technologies were offered to independent oil and gas producers by DOE, as part of the Advanced Reservoir Management Project (ARM) at Los Alamos National Laboratory (LANL). POOI recognized this opportunity, and joined in a Cooperative Research and Development Agreement (CRADA) with LANL. POOI also sought the participation of the royalty owners in the field, the California State Lands Commission (CSLC) and the Minerals Management Service (MMS) of the Department of Interior. These agencies joined POOI and LANL to form the Carpinteria Offshore Field Redevelopment Project.

The Carpinteria project is the first collaboration of its kind, of which the authors are aware. It brings together Federal and State agencies, an industry partner, and a national laboratory, in a combined effort to understand, and thereby guide the redevelopment and management of a mature offshore field. Additionally, the participants retained the consulting services of other organizations, to fill out the technical competency of the team - Coombs and Associates, for petrophysical and well log analysis, R.G. Heck and Associates, for specialized geological interpretations, and the University of Houston, for reservoir flow simulation.

The impetus for collaboration on the Carpinteria Project varies among organizations - POOI is interested in increased revenues from improved production. California State Lands Commission and the Minerals Management Service are interested in continuing royalty revenues from the Carpinteria field, and in understanding the implications that

redevelopment has for the many other similar offshore fields. Los Alamos National Laboratory and the Department of Energy are committed to supporting domestic independent oil and gas producers as they improve reservoir management practices by applying available technology.
(<http://ees.lanl.gov/EES5/arm>)

The Virtual Enterprise

The Carpinteria project depends on the "virtual enterprise" model to tap the resources of its many participants. Simply stated, the virtual enterprise is the combination of efforts of individuals and companies that join together to accomplish a common goal. The individuals and companies that work together in the virtual enterprise may be, as in the case of the Carpinteria project, geographically dispersed, yet interact in a common workplace every day. This common workplace is the union of computers and networks at each of the remote locations where the individuals and companies reside.

The importance of the virtual enterprise to independent oil and gas producers cannot be overstated. It enables any independent producer to enlist widely dispersed technical resources and expertise, to solve a specific problem, inexpensively, and in a well-coordinated way. It provides the independent producer access to technical resources equivalent to those in a major oil company. Recent successes with virtual enterprise teams have helped other independent operators solve complex problems. (1,2)

The management of this enterprise is in the case of the Carpinteria project, distributed among the various participants. But it need not be so. An independent producing company may develop and centrally manage a virtual enterprise with known and trusted subcontractors and consultants. The foundation for such an enterprise is the company's association with these consultants; networked computers make available the common "virtual office" where they can work together (Figure 2).

In the case of the Carpinteria project, no one of the participants has the expertise and equipment to carry out a project of this scale alone - each has unique resources that benefit the overall project. The project depends on a coordination of these widely distributed resources. The situation is complicated by the fact that management too, is dispersed among the organizations. The project management has therefore depended on conference-call meetings, email, electronic file transfers, and the WWW to create this coordination of resources, to direct the project, to monitor progress, and to receive feedback.

Project Planning and Preparations

There are four main segments in the reservoir management scheme for the Carpinteria Reservoir - Geological modeling, geostatistical modeling, engineering modeling, and project integration. The task diagram shows various subtasks within

these main segments (Figure 3). Early in the life of the project, a consensus was reached by the various participants' management about commitment of resources to the project.

Data Review and Analysis

An initial review of available data revealed multiple well log traces from slightly more than 200 wells, cross sections and geological maps from previous studies of the reservoir, comments on the depositional history of the field, engineering and production data (Figure 4).

Geological Modeling

Well log analysis

Coombs and Associates obtained hard copies of all well logs, digitized the several thousand traces, and formatted this large data set in a series of standard format files. The vectorized forms of the well log traces were then transformed into reservoir property logs (porosity, permeability, and water saturation) for the 200 wells. All of this raw data and calculated information, and additional information on reservoir description and performance, is part of a distributed database that is being compiled by MMS and CSLC, to be archived in commercially available databases for later use.

Well Logs Correlation

Initial well correlations were made from the paper SP and GR logs, and paper cross sections were generated to guide preliminary rough correlating work. The initial correlations were refined on visually intuitive multiple-well log display panels in a computer-aided design (CAD) package. The data for these CAD displays were generated with script files in a commercially available spreadsheet program. The script extracts SP and GR picks from the database where they are stored, and writes these data to files for display by the CAD package. This method was used to create display panels that showed as many as twenty digitized correlation logs at a time. More importantly, the display panels were projected on a computer monitor, where it was possible to alter the scale, position, or color of any trace, which significantly reduced the time required to make and to QC the correlations. Iterations of selecting marker picks, entering the picks in the database, and visually reviewing the results in display panels proved invaluable in ensuring the quality of the resulting data set.

All well directional surveys were used to compute true vertical depth logs and true stratigraphic thickness logs were prepared by integrating dipmeter and dip from contour maps. These corrected logs allow well log traces to be correlated without the distorting effects of well deviation or structural dip.

The x, y, and z locations of all picks in all wells were calculated from directional surveys and measured depth logs. Well marker picks were then mapped in a commercial mapping package over the areal extent of the Carpinteria Field. The resulting 31 maps were imported into a 3D visualization package, and examined for errors. This QC step proved invaluable for understanding the limitations of the

mapping, and for identifying data errors. It also highlighted the need to better define stratigraphic volumes, by mapping well marker picks of sand bottoms. Accordingly, the same process of correlating and QC (with CAD displays) was repeated for bottoms of productive intervals, and the same mapping and 3D visualization QC effort was again employed to assure that all surfaces honored all available data.

Database Generation

As mentioned previously, geological and engineering data are stored in three different commercial databases. Commercial software was chosen for the project to guarantee availability, flexibility, and long term support for the database products in our reservoir management software suite. The first database serves as a repository for digitized well log traces. The second is an industry oriented database solution, and serves to house production and completion information, as well as fluid property tables and other engineering data. The third contains marker picks, and directional survey data. There has been a continuing process of database archival and QC of reservoir information; errors and omissions are corrected in the database and new data are added. In this way, the most recent data are always available for the construction of successive reservoir model generations.

Oil-Water Contacts

The Carpinteria field has multiple oil-water contacts. For the most part, individual lithologically defined zones appear to be hydraulically isolated from others. This complicates the calculation of oil in place volumetrics.

It was first thought that oil water contacts would be identified from distributions of saturation in a 3D geological model. However, it became evident that saturation was not a simple function of depth below sea level, but that water contacts in correlated layers occurred at successively greater depths to the east.

This unforeseen variation in saturations indicated that oil water contacts might be tilted in the field, and it was decided that a careful determination of oil water contacts would be needed in all wells. These contacts in individual wells were picked from calculated water saturation logs. However, these calculated logs did not exist for many of the wells in the eastern (State leases) portion of the field. Oil water contacts there were picked from SP, GR, and resistivity logs. These picks were compared with those from calculated logs for consistency.

These new picks confirmed that the oil water contacts are not horizontal, but incline approximately five degrees down plunge to the east on lease P-0166, and about two degrees to the east in the State leases on the field. With this interpretation in mind, the picks were mapped and gridded in three dimensions, and the resulting surfaces were conservatively extrapolated to their intersection with tops of stratigraphic units (Figure 5).

A careful examination of the intersections of these extrapolations with structural surfaces and a visual review of the distribution of wells that are fully oil or water saturated led to editing and remapping of the oil-water contact surfaces. This remapping ensured that not only are all oil water contact picks honored, but also that the intersection of the oil water contact surface and top of stratigraphy (correlated surface) honors the saturation state of wells in a given zone.

Structural and Fault Mapping

It is recognized that faulting in the field plays an important role in the static distribution of fluids, and in flow behavior of the reservoir. It has been a goal of the project to capture important faulting effects not only in the interpretive geological model, but in the engineering flow model as well. The Hobson thrust fault has been identified in previous work and its faulting interpretation was supported by missing section and repeated section analysis in well logs. Although other significant anomalies in contour maps were identified in early work on the project, no further evidence of any other faults existed at the time, and so the first several generations of the geological model included only the Hobson fault.

Previous geological studies included many interpreted faults that explained multiple well to well production anomalies, but which had not been detected by well penetrations. These production anomalies are currently interpreted to be the result of a tilted oil water contact. This interpretation rests on three lines of reasoning. First, the careful process of picking oil water contacts in all wells has shown such a tilted interface. Second, if there were many small faults, it is unlikely that they would remain undetected in the over 200 wells have been drilled in the field. Third, nearby reservoirs, that are tectonically related to the Carpinteria field, have not been shown to exhibit such faulting.

R.G. Heck and Associates has been retained to study other significant faults in the field, and has recently described several faults consistent with anomalies in structure maps, five of which explain large offsets in the oil water contacts that are apparently unrelated to the overall tilted trend. Evidence for these few faults is found in missing and repeated section intervals in true stratigraphic thickness logs from Coombs and Associates. The latest geological model, which is the basis for the reservoir flow modeling, includes six of these faults.

Framework Grid Construction and Attribute Distribution
A 3D gridded structural framework has been constructed that is the basis for computational modeling of both static and dynamic phenomena. The grids for this 3D geological framework are required to be orthogonal in the x and y directions, and each must be locked to the same x, y points. However, all nodes are permitted to vary vertically, and in this way, 3D surfaces are created that follow stratigraphic boundaries.

The 3D-grid volume was constructed of the 29 tops and bottoms of pay zone intervals, i.e. the 58 bounding surface grids are from the structural mapping work of the CSLC and MMS. In addition, oil-water contact surfaces for each of the zones were incorporated in the model. Because zone top and zone bottom surfaces guide the correlation of properties between wells, the process of matching well marker picks to these surfaces at the wells is extremely important; this was the motivation for repeated QC and remapping.

Each stratigraphic model unit, between a top and a bottom grid, is mathematically subdivided into grid cell layers that are used to project bedding patterns within that zone. The process of vertically subdividing units results in a highly refined grid; several million cells are required to capture heterogeneity in the many layers of the many zones in the reservoir.

The calculated coordinates (x, y, true vertical depth) for the paths of all wells are incorporated into the framework grid, and all intersections of well paths and grid cells are calculated internally. Reservoir properties, calculated from wireline log traces, are tied directly to the well path at the resolution of the well log data.

These reservoir attributes are then distributed throughout the volume of the 3D model. We used an inverse distance squared weighting for the interpolation of all properties, during this first phase of model construction. We recognize the weaknesses of this deterministic approach, and plan to remedy this problem by applying spatial statistical methods of distribution in an improved model.

Volumetrics Calculations

Calculation of original oil in place was conducted on the model. Only saturation of mobile oil in individual zones was included in the calculation. The model volumetric calculations were compared with standard engineering/production calculations conducted by POOI. Together, these volumetric calculations contributed to a recent decision to proceed with redevelopment of the field.

Visual Data QC

The two geological modeling software packages used on this project, and many similar packages that are available commercially, permit displays of three dimensional data sets to be zoomed, scaled, and dynamically viewed from any direction. Such software also permits the creation of 2D exhibits, that ultimately leads to a reduction in the time and effort associated with mapping and cross section generation. Many helpful displays of the model were created (arbitrary vertical cross sections, stratigraphic sections, 3D property volumes, etc.) We found this sophisticated display capability to be extremely useful in reviewing contoured data, visualizing intersections between structural surfaces, recognizing thickness changes between multiple surfaces, and visualizing the relationship between fault planes, surfaces, and deviated well traces.

Grid Upscaling and Reservoir Simulator Initialization

A meeting was held upon completion of the first completely populated model of the field, and geology, engineering, and operational concerns for modeling were addressed. A key point of discussion was the extent to which this geological model might be upscaled for flow simulation studies. On the one hand, computing speeds required that the flow model be limited in size. On the other hand, preserving the 3D heterogeneity of the geological model is certainly important if we are to closely mimic flow behavior in the flow model.

An initial coarsening of the grid that preserved lithologic variability was still too large for flow simulation. A second grid upscaling resulted in a smaller grid, but resulted in averaged units that were deemed lithologically and hydraulically different. A decision was made to first proceed with another upscaled grid that merged cells of similar porosity, and to later address upscaling issues again as a part of planned spatial statistical studies.

The geological model was exported for flow simulation, imported into a commercial reservoir flow simulation package, and initialized. This process was supported by an integrated geomodeling/reservoir simulation software platform, which helped us avoid the complexities of data reformatting that often accompany any data export/import operations.

A gridding module within this integrated environment permitted upscaling, based on various averaging schemes. The current upscaled model was generated by vertically averaging together regions of similar porosity. The areal resolution of the model was not changed, and resulted in a grid that has more than one well intersecting some of the grid blocks. This was not deemed an insurmountable problem, and lumped production will be used for those grid cells with more than a single well.

The history-matching phase of the reservoir simulation studies has not yet begun, as it has been decided that a new generation of the geological model should first be exported. This new generation model will include five faults that are thought to be important in governing flow behavior in the reservoir.

Geostatistical Modeling

To date, the geological modeling work has depended on deterministic interpolation schemes to fill the volume of the model's 3D-grid structure. There is a weakness in this approach: by making the assumption that properties may be interpolated from well to well, we have overlooked important information about the way in which the data varies from well to well.

An improvement would be to employ some similarity-dissimilarity analysis that quantifies correlation lengths

between wells, and that reproduces in the final model the statistical character of our sample data.

The most intuitive way to employ this analysis is to examine lateral continuity in a single stratigraphic unit. We do this naturally when we visually correlate features between well log traces. When a feature appears in one log, and not in another, we must decide how far to correlate the feature between the logs. Although this exercise is subjective, we have effectively determined a correlation length for the given attribute. However, we would probably not expect to use the same correlation in any other direction. Instead, we would search for another well log in the new direction, and again examine the similarity-dissimilarity between those two logs. Extending this methodology to a large, spatially distributed data set, we would like to examine the correlation between each well and every other well in the collection. This is an extremely time consuming exercise, and one that is difficult to do rigorously.

A preliminary study was made of spatial correlations of attributes in the reservoir data. The purpose of the study was to determine whether sufficient lateral continuity exists in individual units to make geostatistical estimation and simulation approaches worthwhile. The "F" zone was chosen as the region of interest for this study.

Empirical variograms of the calculated properties data suggest fairly good correlation over distances of at least 500 feet in the "F" zone. In this first analysis, the empirical variograms show spikes at small lags that might be eliminated in a more careful outliers analysis. At a depth of 3000 feet, the distance between wells exceeds 500 feet for only about 10% of the wells. Thus within the field, at least in the depth range of 2500 to 4000 feet, there will usually be data within 200 or 300 feet of any point that we wish to estimate. Given this density of data, the empirical variograms suggest that improvements in the distribution of properties between wells can be expected if geostatistical methods for estimation and simulation are used.

Conclusions

Integrated reservoir management approaches have already provided a valid option for redeveloping the complex Carpinteria field, (geomodeling and well planning) and will yield more benefits as fluid movement in the reservoir is studied.

Geological/engineering reservoir modeling pays off in the long term, as it enables the operator to evaluate alternate development scenarios, but it requires an up-front investment. This investment may be managed as a virtual enterprise, making world class expertise available to independent operators.

The use of geological modeling tools requires extensive data preparation and QC, as the tools do not observe, define, or

correct data errors. However, these tools ultimately offer a valuable visual approach to data QC and understanding.

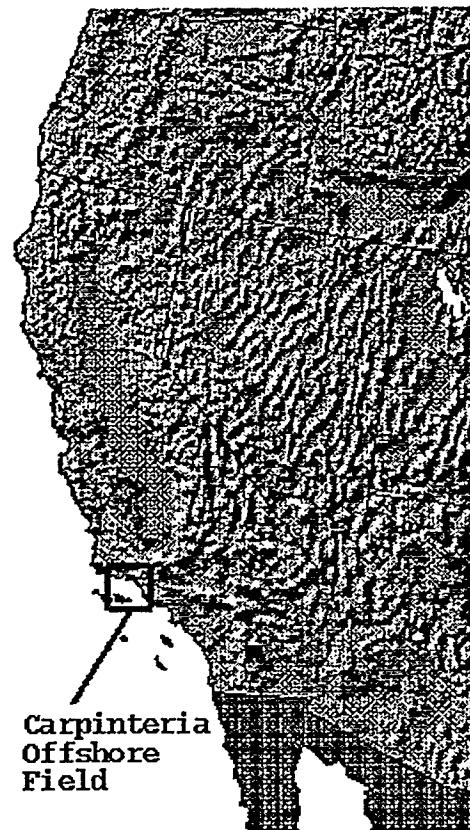
Closely integrated geological and engineering modeling leads to a self-consistent reservoir model that honors all available data, including interpretive data, and more closely approximates reality, making it useful as a predictive tool. Well planning and design in an alternating water-oil stratigraphy environment is greatly enhanced by the use of a visual geomodeling environment. It is especially helpful in avoiding interference between wellbores, and in steering to significant accumulations of hydrocarbons.

A preliminary scoping study has motivated the application of geostatistical methods to describe the distribution of reservoir properties in the model.

Flow simulation modeling depends on such a model, and will help guide the long-term management of this mature reservoir.

Figures

Figure 1. The Carpinteria Offshore Field is located near Santa Barbara, California, and is divided into California State and Federal leases by the three-mile coastal water limit.



Acknowledgements:

The authors wish to acknowledge the following federal and state agencies that have funded this work: U.S. Department of Energy, the Minerals Management Service of the U.S. Department of Interior, and the California State Lands Commission. The authors also wish to acknowledge the contributions of R.G. Heck and Associates in developing the faulting interpretations for the Carpinteria Field.

References:

1. Murphy, M.B., Stubbs, B.A., Uszynski, B.J., Martin, F.D., Kendall, R.P., Whitney, E.M., Hardage, B.A., and Weiss, W.W., "Advanced Oil Recovery Technologies for Improved Recovery from Slope Basin Clastic Reservoirs, Nash Draw Brushy Canyon Pool, Eddy County, NM", First Annual Report to the U.S. DOE, DOE Cooperative Agreement No. DE-FC-95BC14941, October, 1996.
2. Voskanian, M.M., Kendall, R.P., Whitney, E.M., Coombs, S., Paul, R.G., and Ershaghi, I., "A Simulation-Based Reservoir Management Program", SPE Paper #35703, SPE Western Regional Meeting, Anchorage, AK, May 22-24, 1996.

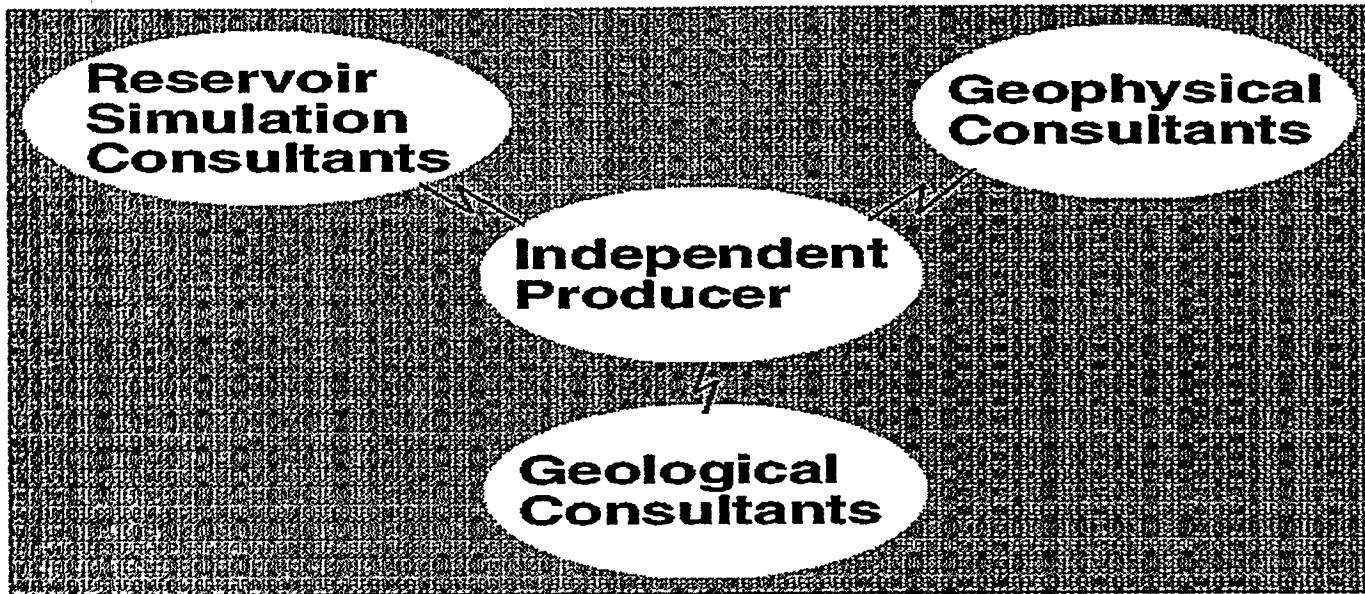
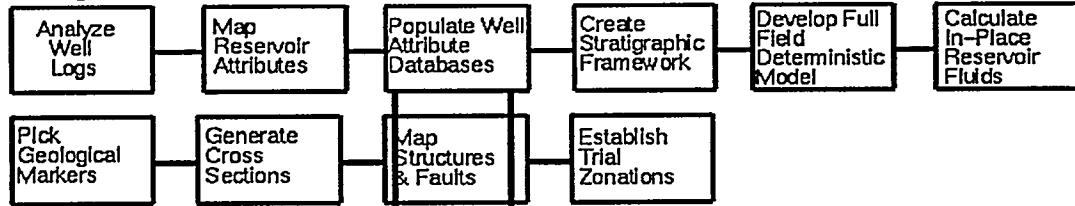


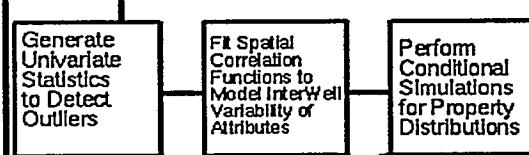
Figure 2. The virtual enterprise provides a small independent producer access to the technical resources that have previously been available only to major oil companies.

Carpinteria Reservoir Re-Development Project Integrated Task Diagram

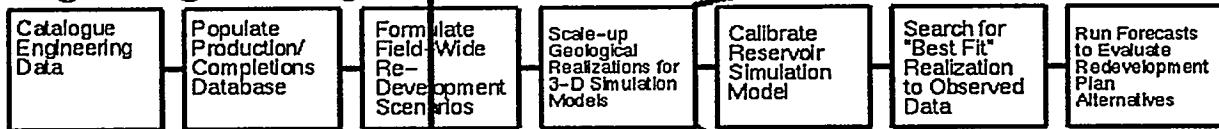
Geological Modeling



Geostatistical Modeling



Engineering Modeling



Project Integration



Figure 3. Integrated outline for Carpinteria Project. The many tasks are distributed among the project participants.

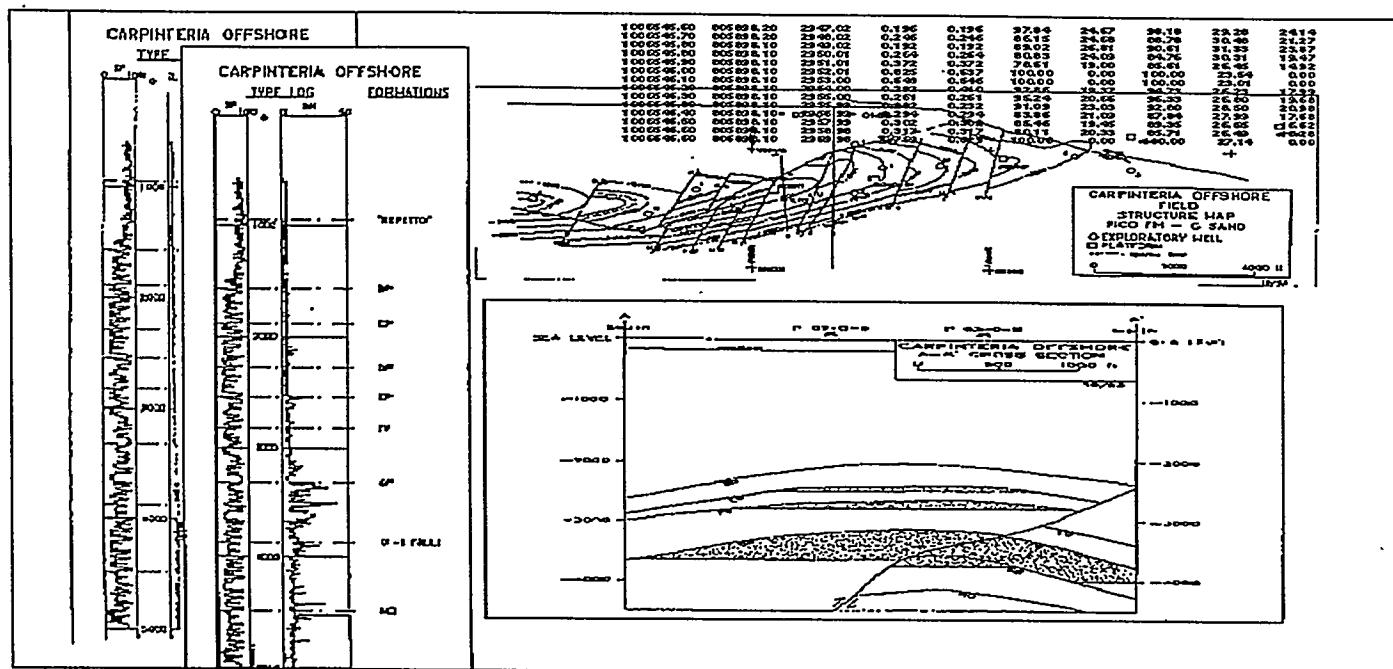


Figure 4. An initial review of data revealed well logs, cross sections, structural maps, engineering and production data, and some commentary on depositional history.

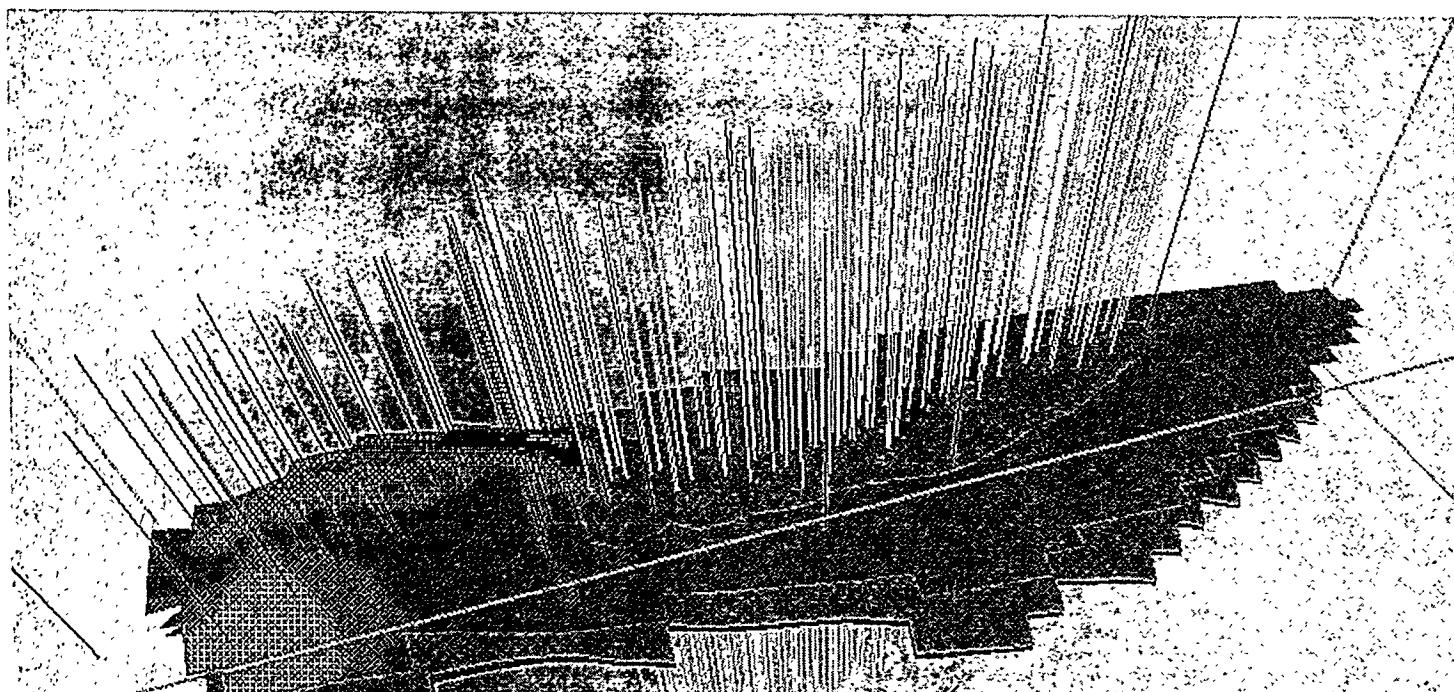


Figure 5. Oil-water contact surface in the E1 sand (extrapolated beyond stratigraphy for visual effect), showing fully oil saturated wells (white) wells with water oil-contact in the E1 (grey) and wells that are water saturated in the E1 (black).

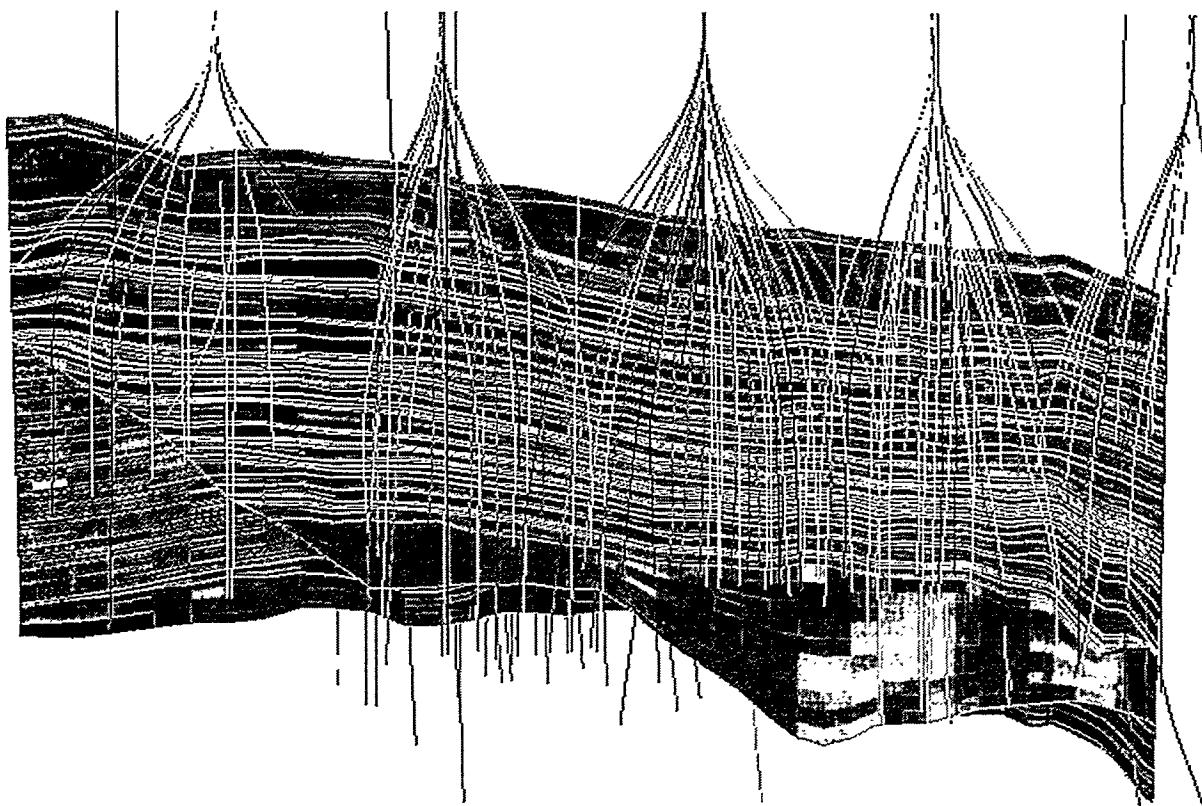


Figure 6. East-West cross section of Carpinteria Field. Hobson thrust is visible on the left.

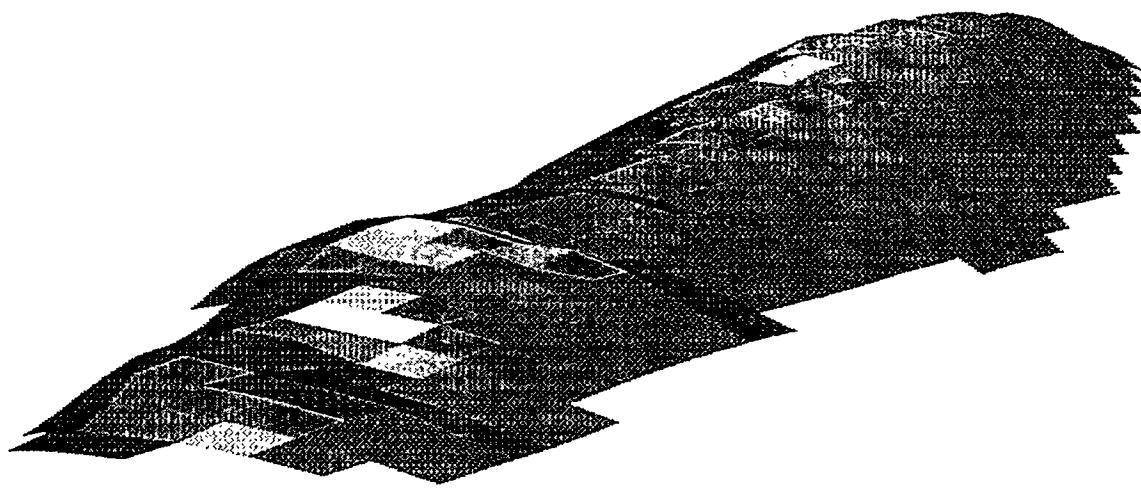


Figure 7. Stratigraphic slice of the Carpinteria Reservoir computational framework – top of C1 sand.

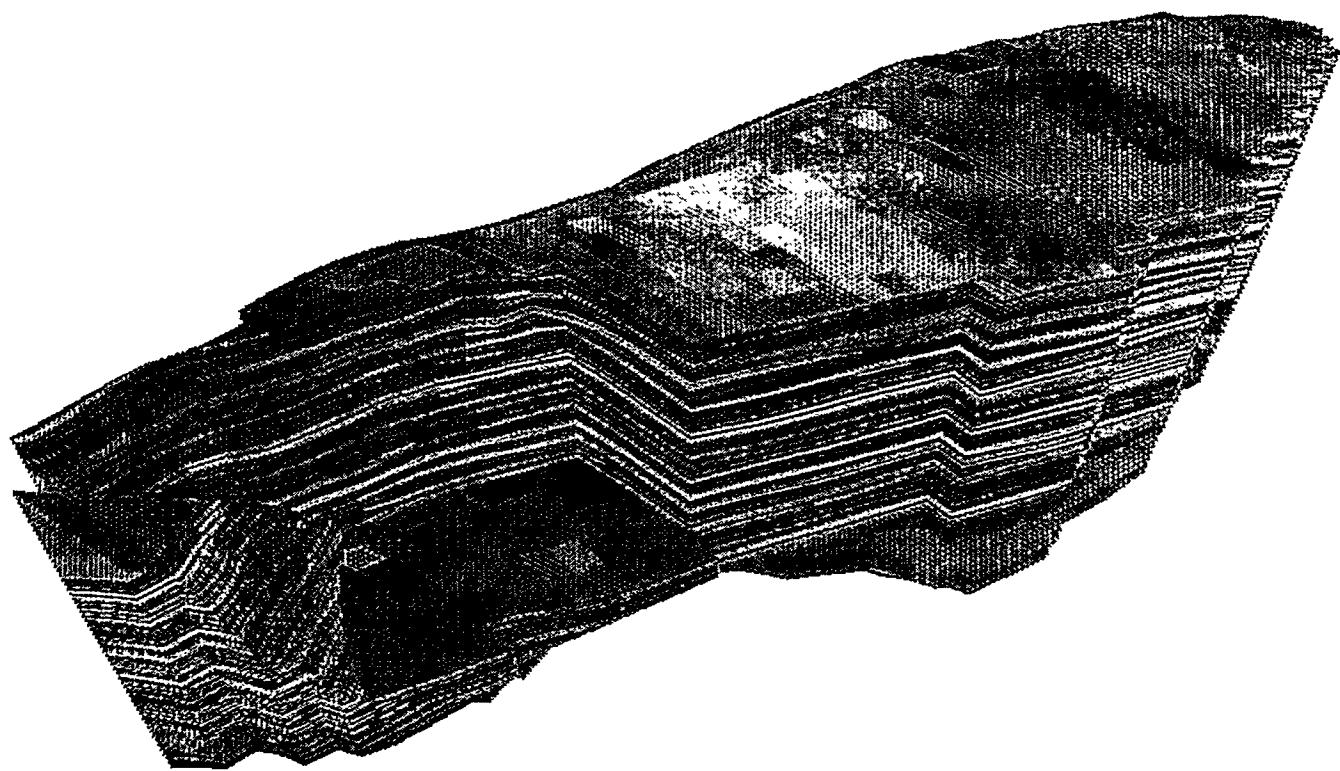


Figure 8. 3D computational framework model, from southwest, showing distribution of attribute "shale fraction". Hobson thrust divides stratigraphy on the west.