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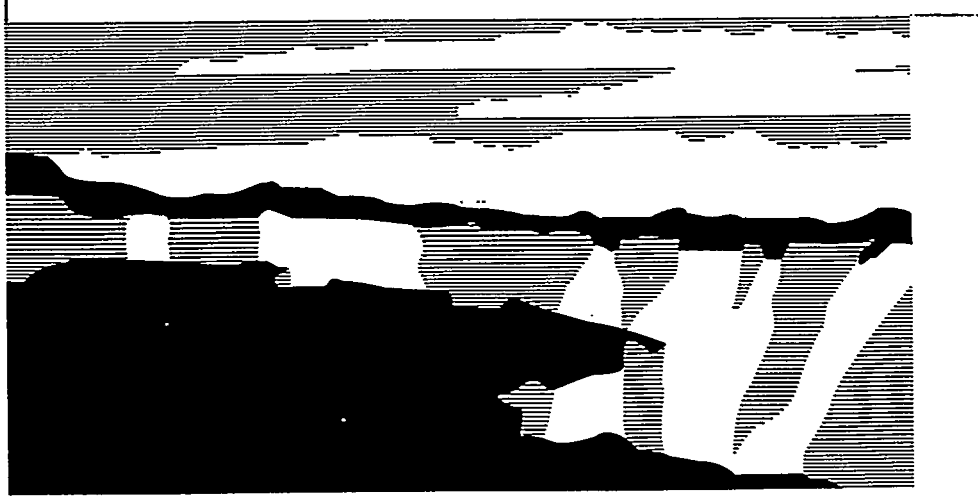

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Integrated Reservoir Management in the Carpinteria Offshore Field

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Abstract

The Carpinteria Offshore Field is located near Santa Barbara, California. The State of California owns the portion of the field nearest the coast, and the U.S. Federal Government the portion of the field that lies beyond a statutory three-mile coastal water limit. This mature reservoir has yielded more than 100 million barrels of oil from five platforms in its 30 years of production. The U.S. Department of Energy's Los Alamos National Laboratory (managed by the University of California) has joined with the State Lands Commission of California, the U.S. Department of Interior's Minerals Management Service, and the independent operator of the field, Pacific Operators Offshore, Inc., in a unique collaboration to redevelop the field. The reservoir management strategy for the Carpinteria Field relies on a long-term investment in simulation tools and expertise. These technologies and expertise are available to all project participants through a virtual enterprise business model.

Project Background

By early 1993, it was clear to researchers at the U.S. Department of Energy's Los Alamos National Laboratory (LANL) that the Internet might be adapted to support electronically linked "virtual" business enterprises. LANL had earlier participated in the earliest forms of networked electronic communications that led to the Internet and the World Wide Web (WWW), and researchers at LANL were now keen to build and demonstrate useful applications for the new medium.

At this same time, domestic oil production was rapidly waning, as major oil companies moved production operations abroad. Independent oil producers increasingly shouldered the burden of domestic production from mature, complex oil reservoirs. But these same small companies were often technologically and financially unprepared to face the challenges of managing such difficult properties.

In 1993 and 1994 the Department of Energy (DOE) opted to redirect some of the computational horsepower of its national laboratories toward this end. The result was the Advanced Computational Technology Initiative. Responding to this initiative, LANL joined with more than 20 oil and gas companies to create the Advanced Reservoir Management (ARM) Project (www.ees.lanl.gov/EES5/arm). The project was focused on demonstrating advanced reservoir management methods to independent producers, and at giving independent operators access to the computational tools and expertise required to carry out such these methods.

As part of the ARM project, LANL and Pacific Operators Offshore, Inc. (POOI) developed and began to execute an integrated reservoir management plan for the Carpinteria Offshore Field. The participants included LANL, POOI, and both royalty owners in the field, the California State

Lands Commission (CSLC) and the Minerals Management Service (MMS). Additionally, the project retained the consulting services of other organizations to fill out the technical competency of the team - Coombs and Associates for petrophysical analysis, and R.G. Heck and Associates for fault analysis. The reservoir management plan was based on state-of-the-art computational tools and techniques, and the reservoir management team was tied together electronically through the Internet, which was at that time in its infancy.

The impetus for collaboration on the Carpinteria Project varies among participating organizations - POOI is interested in increased revenues through 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 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 state-of-the-art technology.

The Carpinteria project pioneered the concept of a virtual enterprise business model in this setting. Simply stated, the virtual enterprise is a combination of companies (and individuals) that join together through the Internet to accomplish a common goal. The companies that work together in a virtual enterprise may be geographically dispersed, as in the case of the Carpinteria project, but they interact in a common electronic workplace every day.

In this project no participant had the expertise and equipment to carry out a project of this scale alone, but each had unique resources to contribute. The project requires the 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 coordinate resources, to direct the project, to monitor progress, and to receive feedback on technical work.

Although the management of this particular virtual enterprise is distributed among the various participants, it need not be so. An independent producing company can 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.

The potential value of the virtual enterprise to the energy industry, especially small producers, cannot be overstated. It enables any small company or even a division of a large company to enlist and coordinate widely dispersed technical resources and expertise, to solve a specific problem inexpensively. A small independent producer can gain access to technical resources that have previously been available only in a major oil company.

Carpinteria Offshore Field Background

The Carpinteria Offshore Field (Santa Barbara, California) was discovered in 1964, and has been developed over three decades from five platforms (**Figure 1**). 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 may have implications for those fields.

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

Increased water production and sand from unconsolidated strata, and declining production contributed to a decision by the prior operator to abandon the California State leases. In the course of abandoning these leases, all wells on the two production platforms in the California State leases were plugged and abandoned, and the platforms were removed. The California State leases thus became unreachable by drilling, except from platforms in the adjoining Federal leases. The abandoned State leases and adjoining federal leases were acquired by, and are now operated by POOI. POOI's long-term plans for redeveloping the reservoir include options for high-angle extended reach drilling, to recover oil from the otherwise inaccessible State leases.

Reservoir Management Approach

In the earliest days of the project, a reservoir redevelopment technical team was formed, and a careful review was made of the expertise and resources that were available, as well as of all work that was anticipated. An evaluation of the effort that might be expended at each organization resulted in a distribution of tasks that took advantage of the resources available (**Figure 2**).

It was clear from the outset that there were many kinds and great quantities of valuable legacy data, but that many of these data contradicted one another, and different interpretations of the data were in conflict one with another (**Figure 3**). Rather than throwing out old interpretations and data, the redevelopment team planned to preserve most of the value in these data by resolving data conflicts case-by-case. The team agreed that some new data were needed. Since generating these data would be an expensive proposition, it was agreed that the first iteration of reservoir characterization would be based on the data at hand. The plan was to create a single, self-consistent geological model that merged as much of the legacy data and interpretations as possible into a visual, intuitive form. Creating this model had never before been feasible – new computational modeling and visualization tools and the collaborative efforts of all of the partners made it possible.

An initial review of available data revealed multiple paper well log traces from more than 200 wells, cross sections and contour maps of productive intervals from previous reservoir studies, engineering and production data, and commentary on the depositional history of the reservoir. The chronology of logs was immediately recognized as a problem, because production had begun shortly after the first logs were taken, and had continued through several drilling programs that occurred over the course of twenty years. Most contour maps of productive intervals had been generated from a subset of the available data, and the faulting interpretations in the field were based almost exclusively on interpreted top of oil column and/or production data.

The first task was to convert the nearly two thousand paper log traces into a standardized digital format. This digitizing work was followed by a uniform calibration of all log traces. (Due to different statutory logging requirements, different log suites had been collected in California leases and Federal leases. This led to a systematic bias in the data, which was corrected in the log calibration exercise.) Directional surveys were used to convert log data to true vertical depth, and true stratigraphic thickness logs were developed from dipmeter data and dip from contour maps of marker surfaces. These corrected depth and thickness logs permitted traces to be correlated without the distorting effects of well deviations or structural dip. These correlations were the basis for a complete re-mapping of tops and bottoms of productive intervals, and a complete re-interpretation of faulting in the reservoir.

Initial well correlations were made from paper versions of spontaneous potential and gamma ray logs, and paper cross sections were generated to guide preliminary rough correlating work. These initial correlations were then refined with the aid of a CAD package. Visually intuitive display panels permitted correlation among as many as 20 well logs at a time. More importantly, the display panels made altering the scale, position, or color of any trace easy, which significantly reduced the time required to make and to check the correlations. Iterations of selecting marker picks, entering the picks in the project database, and visually reviewing the results in display panels proved to be an invaluable method for ensuring the quality of the resulting data set.

Correlated well marker-picks from the entire Carpinteria Field were mapped with a commercial software package. The resulting maps were imported into 3D visualization software, and examined for errors. This visualization proved invaluable for ensuring that the maps honored all available marker-pick data, and for identifying data errors that resulted from the limitations of mapping algorithms or from human error (**Figure 4**).

A lengthy series of automated calculations transformed thousands of digitized well log traces into reservoir property logs (porosity, permeability, and water saturation) for the field's 200+ wells. These transformations were based on petrophysics and on the interpretive experience of the well-log analyst.

As data were collected, they were archived in three different commercial databases – the first for digital well-log traces, marker-picks, and the reservoir property "point" data that resulted from transforming log traces; the second for reservoir engineering and production information, and for well completion and work-over data; and the third for classical reservoir engineering and production allocation information. The database platforms were selected by individual participants. The selected databases were already in use in-house or were chosen because of other needs of that participant. There has been a continuing process of archiving, visually checking, and updating reservoir information, so that the most recent data are always available for the construction of the next-generation reservoir model.

Initially, the geological models of the Carpinteria were based only on stratigraphic layering of mapped marker surfaces. Later, an important geological feature of the reservoir, the Hobson thrust fault, was incorporated into the model, and zones were distinguished by vertical position relative to the Hobson fault (**Figure 5**). These early three-dimensional models proved their value in identifying inconsistencies and contradictions in the data that had previously been impossible to discover. The models were also quickly employed as planning tools, and the first redevelopment drilling targets for the Carpinteria were based on them. As wave after wave of new information was added to successive generations of the geological models, the team made decisions that resolved inconsistencies and contradictions among the various kinds of data. This process resulted in a continually improved model, and an improved supporting data set.

The most current geological model of the Carpinteria reservoir includes many important faults, layers, and individual oil-water contact surfaces in each of the productive zones. The stratigraphy in each fault block in the model is built of the 29 tops and bottoms of pay zone intervals – for a total of 60 (2(n+1)) bounding surface grids (**Figure 6**). Zone top and zone bottom surfaces guide the correlation of properties between wells within a fault block (correlation of reservoir rock properties is based on stratigraphic, rather than Euclidean coordinates).

Multiple oil-water contacts exist in the reservoir and these dynamic contacts must be characterized in the geological model by static data. Oil-water contact surfaces have therefore been repeatedly mapped, incorporated into geological models, compared with interpreted oil column within zones, and resolved chronologically to account for continuing production (**Figure 7**). After several iterations of this process, the team began to suspect that these contact surfaces were not in hydraulic equilibrium, but were tilted. Previous explanations of the eastward dip of oil-water contacts relied on the existence of an unseen stair-step series of north-south trending faults. However, the team was unable to distinguish whether many small sealing faults caused an apparent tilt in the oil-water contact surfaces, or whether the surfaces were indeed tilted. In order to answer this question unambiguously, the team separated oil-water contact data into chronological groups, and conducted a careful re-examination of the data. This re-examination unequivocally supports the interpretation of non-equilibrium tilted contact surfaces.

Faulting in the Carpinteria influences the equilibrium distribution of fluids and the flow behavior of the reservoir. Because of the importance of faults, the team has sought evidence of important faults in order to capture their effects in the geological model and in the dynamic flow model. Previous interpretations of faulting in the reservoir included many small faults to explain not only the dip in oil-water contacts, but also production anomalies between wells. The redevelopment team has not accepted this interpretation, because there is no direct evidence (in the form of missing or repeated log section) to support the existence of many small faults. There are over 200 deviated wells in the field, and if there were many small faults in the reservoir, these faults would have been penetrated many times over. The interpretation now accepted by the team is one of a few large sealing faults. These faults explain 2D marker-surface contour mapping discontinuities and well to well production anomalies, and their existence is supported by missing and repeated log section (**Figure 8**).

Dynamic reservoir simulation is a critical part of the redevelopment effort. Bypassed oil can be located only by understanding the dynamics of fluid movement in the reservoir. Reservoir simulation is a computational tool that can help elucidate the historical movement of oil and water in the reservoir. In this project reservoir simulation is tightly integrated with geological modeling work, so that changes in the description of reservoir geology are reflected in the dynamic simulation, and feedback from the simulation work leads to changes in model geology.

The first dynamic simulation model had no faults. Although it was simple structurally, it had vertical resolution that captured all productive zones. The model was exported from a geological model, imported into a commercial reservoir flow-simulation package, and initialized. The export/import process was supported by an integrated geomodeling/reservoir simulation software platform that avoided much of the tedious task of data reformatting. The fine gridding was upscaled by vertically grouping regions of similar porosity. Although the model was initialized, history matching was never carried out on this full field model.

The current dynamic simulation work is based on a dramatically improved geological model. This second phase of simulation work began this year. During year, the team made a decision on a controversial question, namely whether the model should from the beginning be built to represent the entire reservoir, or only a fault block within the reservoir. There were two alternate paths that met our computational budget and time constraints: 1) Build a coarse scale model of the entire reservoir, and improve the resolution of the model as we moved along. 2) Build a model of a single fault block, and add adjoining fault blocks as the simulation work progressed. The team finally decided to begin with a model of a single fault block. Arguing for this approach was the fact that the single fault block was a simple system that would support studies of several important issues (quantifying drive mechanisms, vertical communication, fault leakage, and cross-flow among zones). Drilling was scheduled within the year, and this too, argued for a model with enough vertical resolution to study localized production effects from new wells.

The fault block that was chosen for simulation lies on the south flank of the Carpinteria, under the Hogan Platform, and is known to the redevelopment team as the "Above North C" fault block (**Figure 9**). This fault block is produced through twenty wells, although some of these wells also produce from adjacent blocks. The model was created with the following assumptions: 1) Boundary faults were assumed to be completely sealing. 2) There are 18 sands that produce in this fault block. The sands are separated by impermeable shales. Each sand behaves hydraulically as a separate reservoir. 3) Allocations of production for wells that also produce from adjacent blocks were made based on the properties of each sand in each fault block.

Production from within the fault block has been co-mingled among the zones, so that allocations for history matching are necessarily based on zone-by-zone estimates. These estimates are based on near-well permeability, so that the allocation estimates are highly uncertain. Still, the model serves as a tool to study the aquifer support and leakage across faults. The team's expectations of a "history match" were modified, and lumped production history was matched in the fault block. Oil production rates were a constrained, and water rates were allowed to vary. A limited number of pressure observations were available in a few wells, and these data were also matched.

The simulation exercise led to the following findings:

1. The boundary faults are not completely sealing in all sands.
2. The wells produce unevenly among sands.
3. A majority of production from this fault block was from a single sand.
4. The North flank aquifer drive is stronger than the south flank drive. (Quantitative estimates of aquifer properties were also obtained.)

5. Additional faults may exist – this possibility is being investigated further.

The Carpinteria geological model from which the single fault block was extracted has been exported in VRML format. The ARM Project web page contains these VRML files, which may be manipulated locally (**Figure 10**). Redevelopment team members use these same pages to stay abreast of the progress of the virtual enterprise.

Recent drilling activity has been based exclusively on the static geological model, and on the current interpretation of oil-water contacts within zones. This model aided the rapid and careful design of wells that target specific sand intervals, and that avoid proximity to other wells, including abandoned wells. This is an extremely difficult design task without the aid of 3D visualization tools (**Figure 11**). Two new wells on the Carpinteria have recently been drilled, and others are in progress or are planned. The two new wells were both successful in producing at or above predicted rates, with low water cuts. These are the first low-water cut wells on the field in more than twenty years.

This integrated reservoir management approach has provided perhaps the only feasible option for redeveloping the complex Carpinteria field. A self-consistent model of the reservoir that honors all available data now supports redevelopment decisions. It is clear that this integrated reservoir management approach will yield even greater benefits as the dynamics of the reservoir are studied.

Conclusions

1. Integrated Reservoir Management approaches are cost effective, but require a large initial investment. An integrated multi-disciplinary studies team may be managed as a virtual enterprise, making world class expertise available to independent operators, while dramatically reducing costs.
2. High-end modeling work requires extensive data preparation and quality control, as the tools do not yet observe, define, or correct data errors. However, these tools offer a valuable visual tool for understanding complex data sets.
3. Well planning and design in complex geological environments is greatly enhanced by the use of a 3D visual geomodeling environment. Visualization tools are especially valuable in drilling design, to avoid interference between wellbores, and to target bypassed oil.
4. A tightly integrated reservoir management approach yields credible, valuable models of geology and reservoir dynamics that lead to meaningful development decisions.

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3. Whitney, E.M., et al: "Integrated Reservoir Management for the Long Term-The Carpinteria Offshore Field," paper SPE 38284 presented at the SPE Western Regional Mtg, Long Beach, CA, June 25-27, 1997.

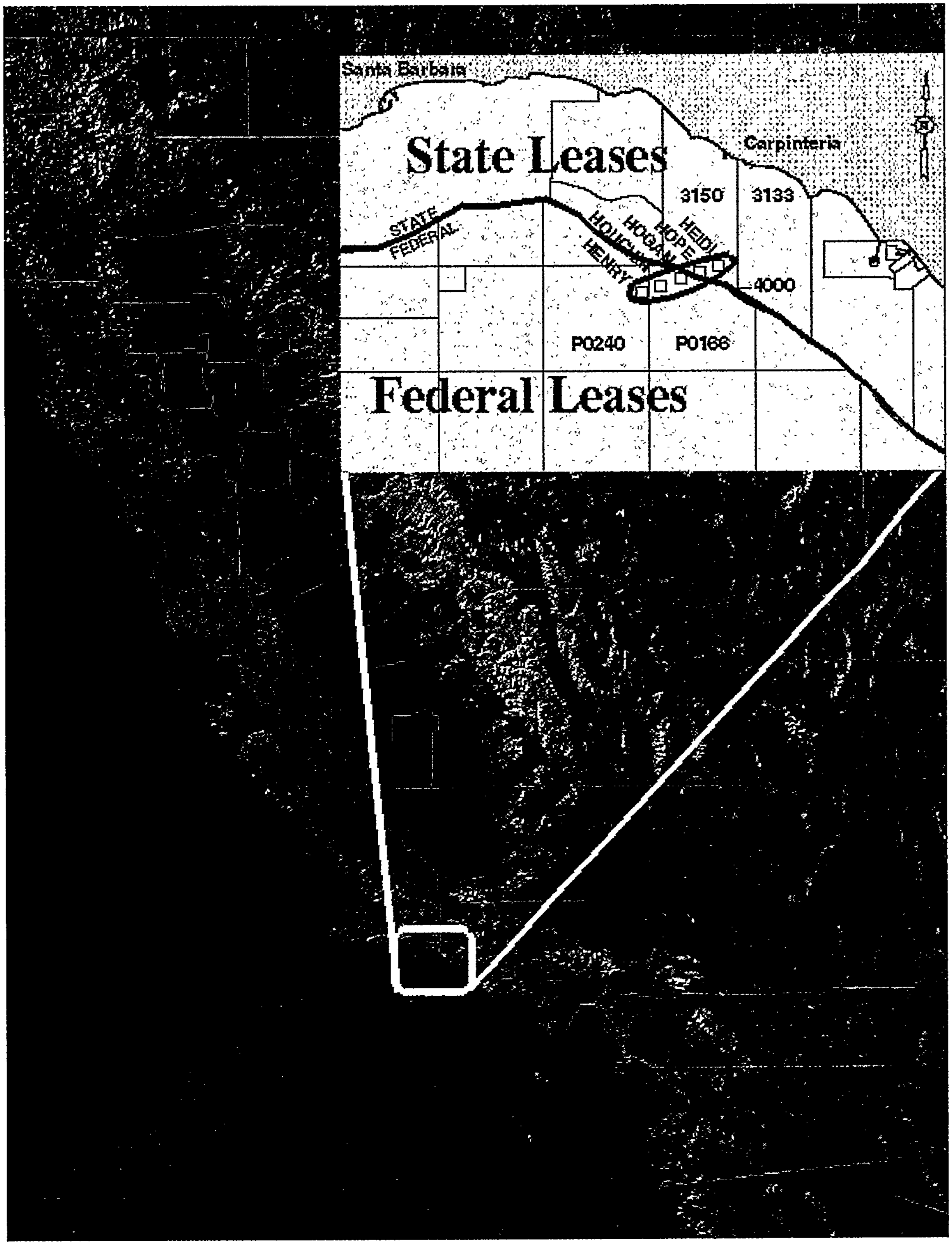

Figure1: Map of the Carpinteria Reservoir location

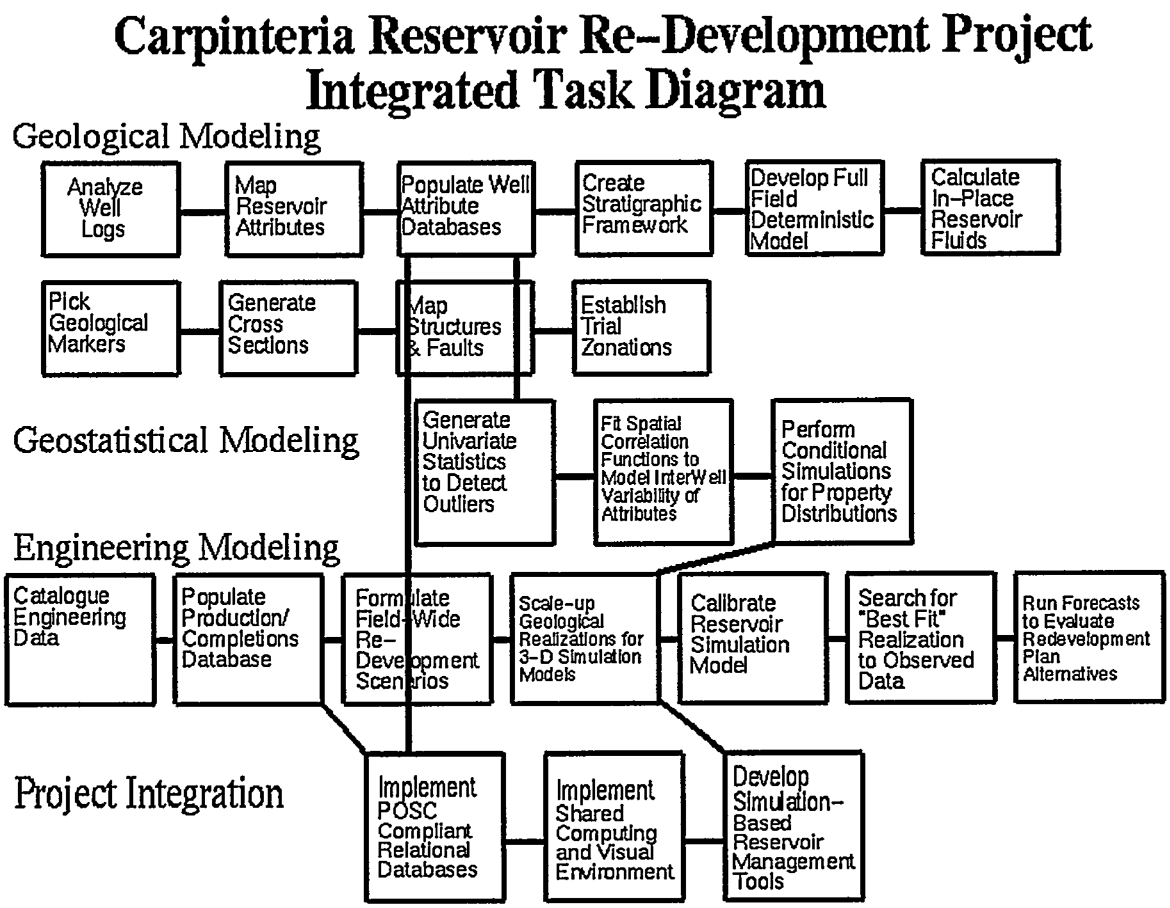

Figure 2: ntegrated task chart for the Carpinteria Redevelopment Project

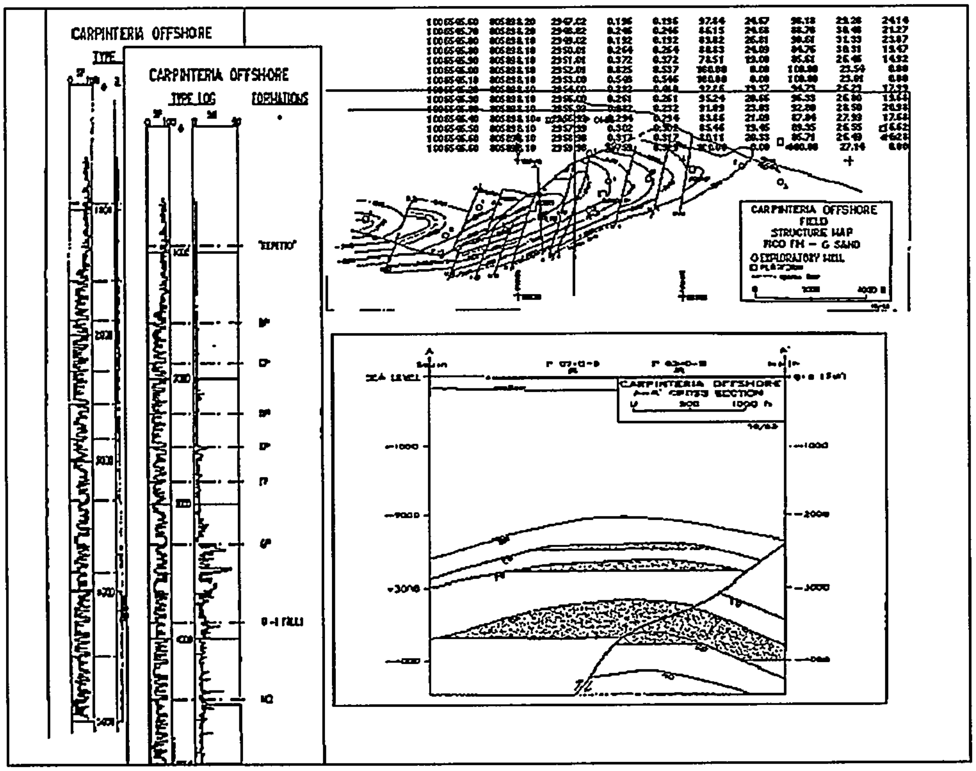

Figure 3: Examples of legacy data from previous studies of the Carpinteria Reservoir

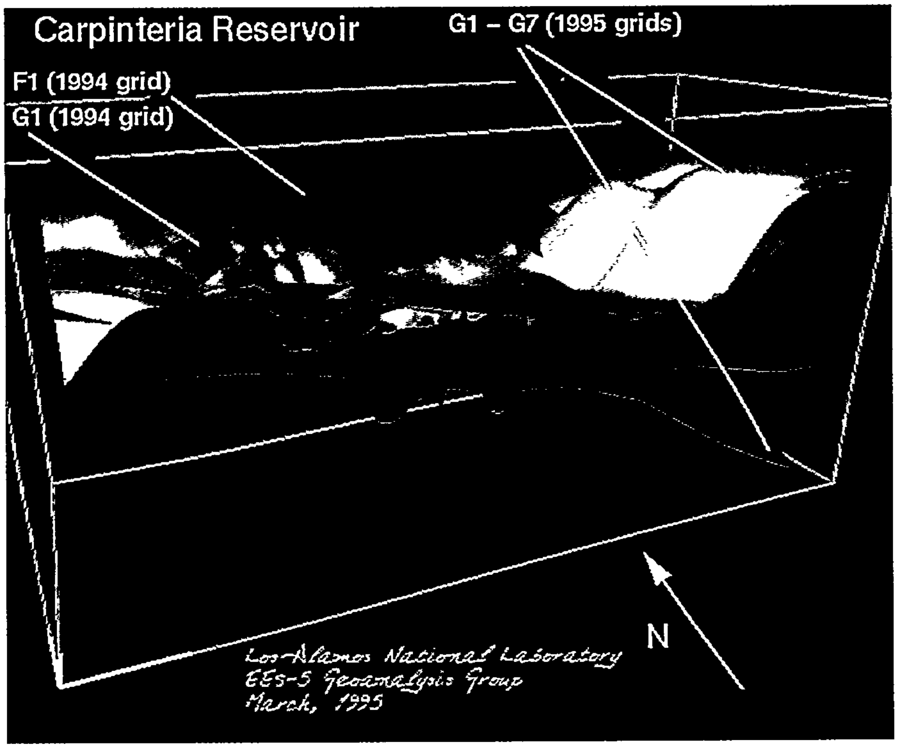

Figure 4: Example of 3D visual quality control – such data conflicts are detected only with great difficulty when analyzing several 2D contour maps

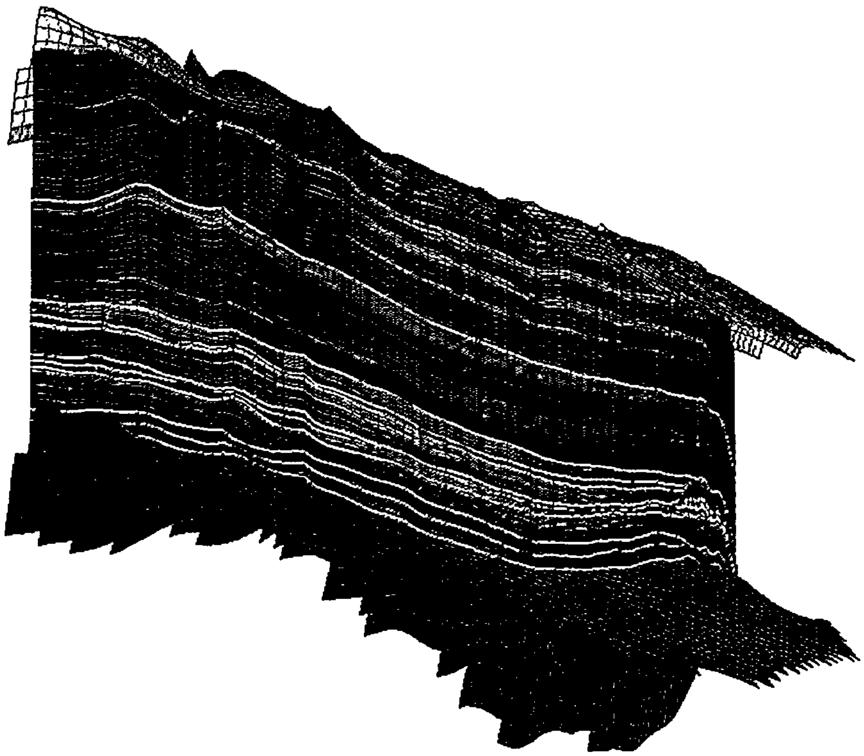

Figure 5: Early version of a stratigraphic framework model of the entire vertical interval of interest in the Carpinteria. Interpreted shale fraction data are distributed laterally within stratigraphic zones.

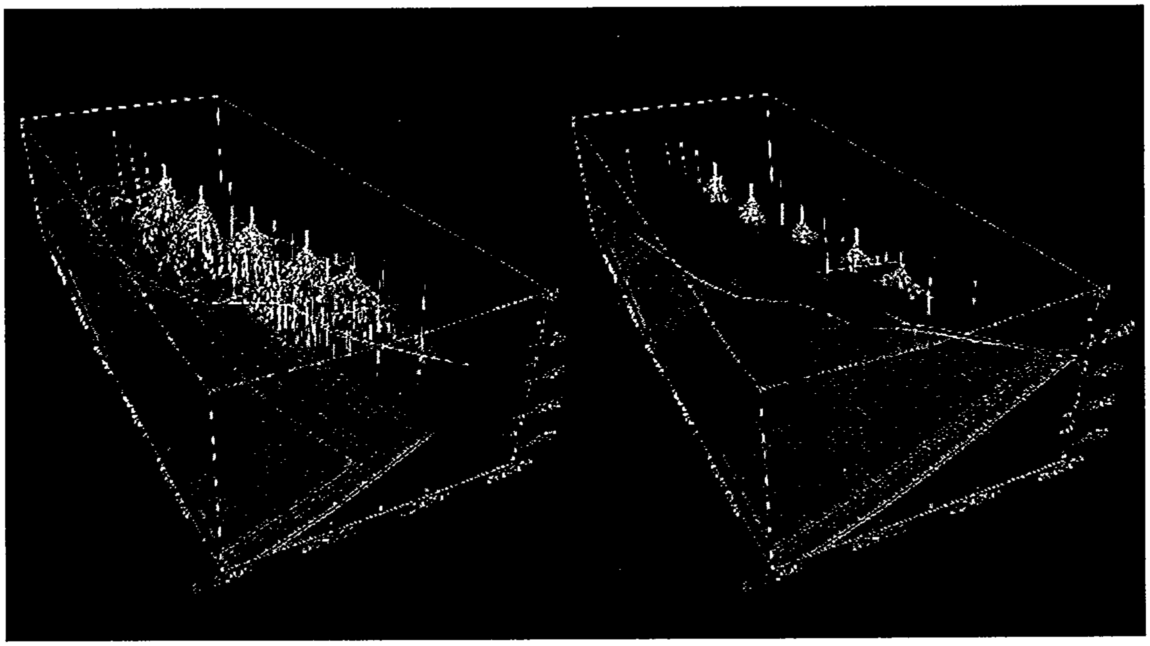

Figure 6: Two views of the current geological model of the Carpinteria, showing existing well traces, stratigraphy, and projections of fault traces

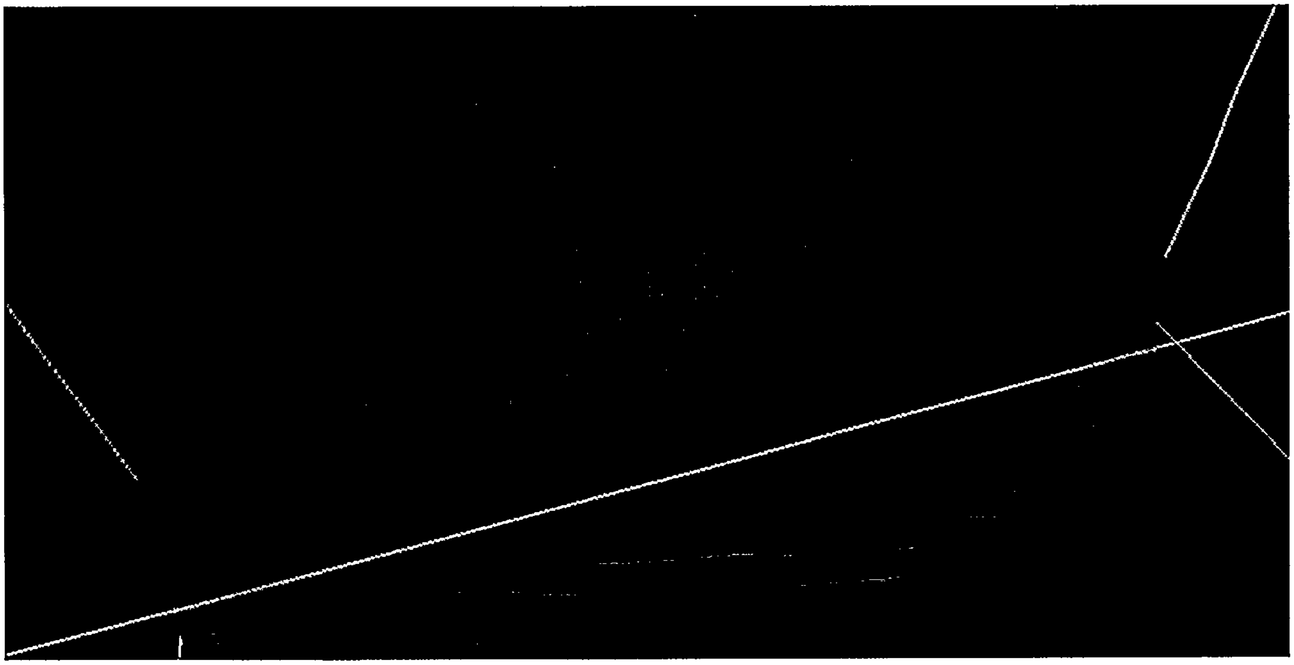

Figure 7: Interaction of mapped marker surfaces and oil-water contact surface in the E1.

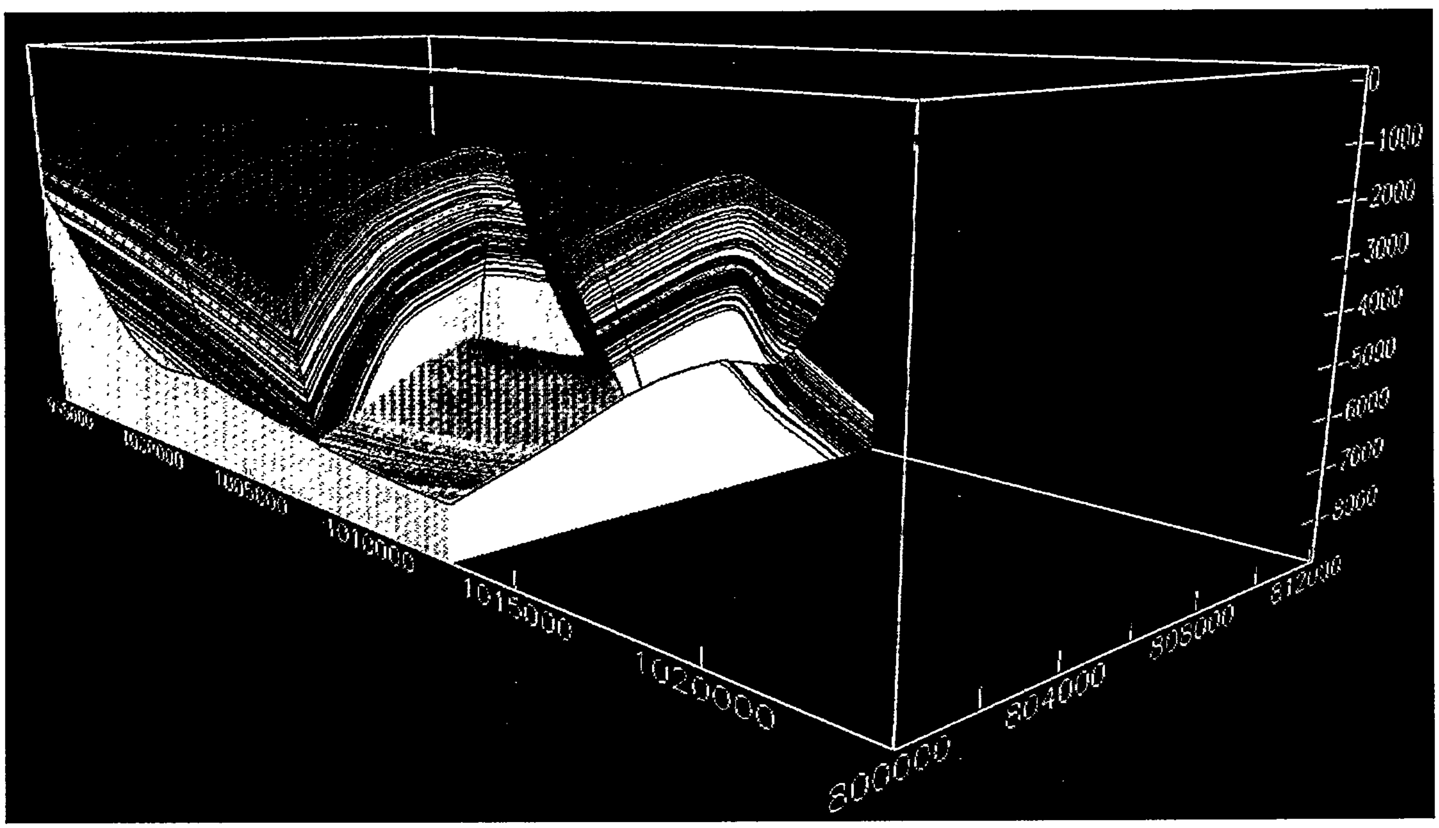

Figure 8: Solid geological model of the Carpinteria, showing several fault blocks.

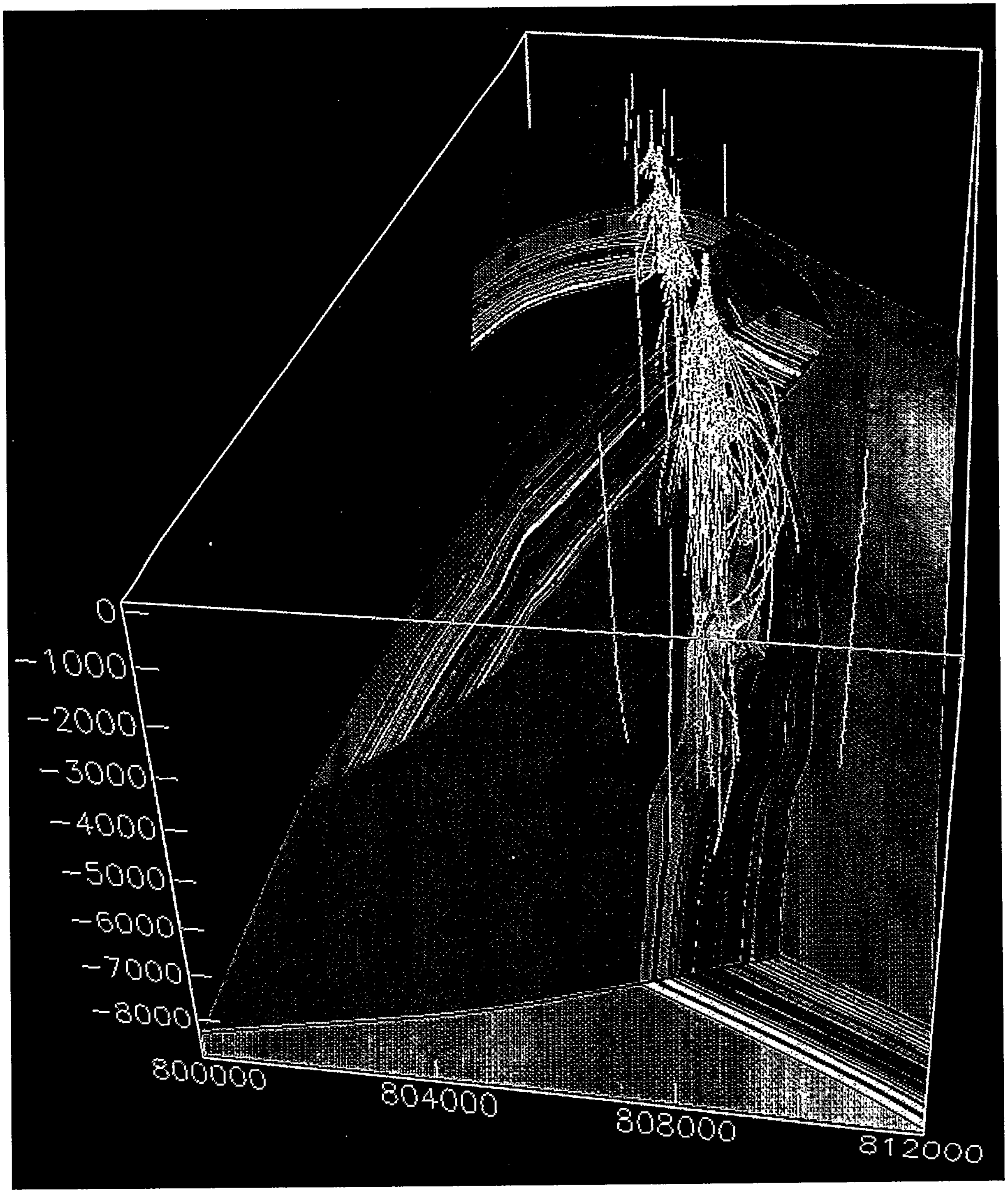

Figure 9: View of the Carpinteria geological model, looking west, with eastern-most fault block removed to highlight stratigraphy in the fault block that was chosen for dynamic simulation.

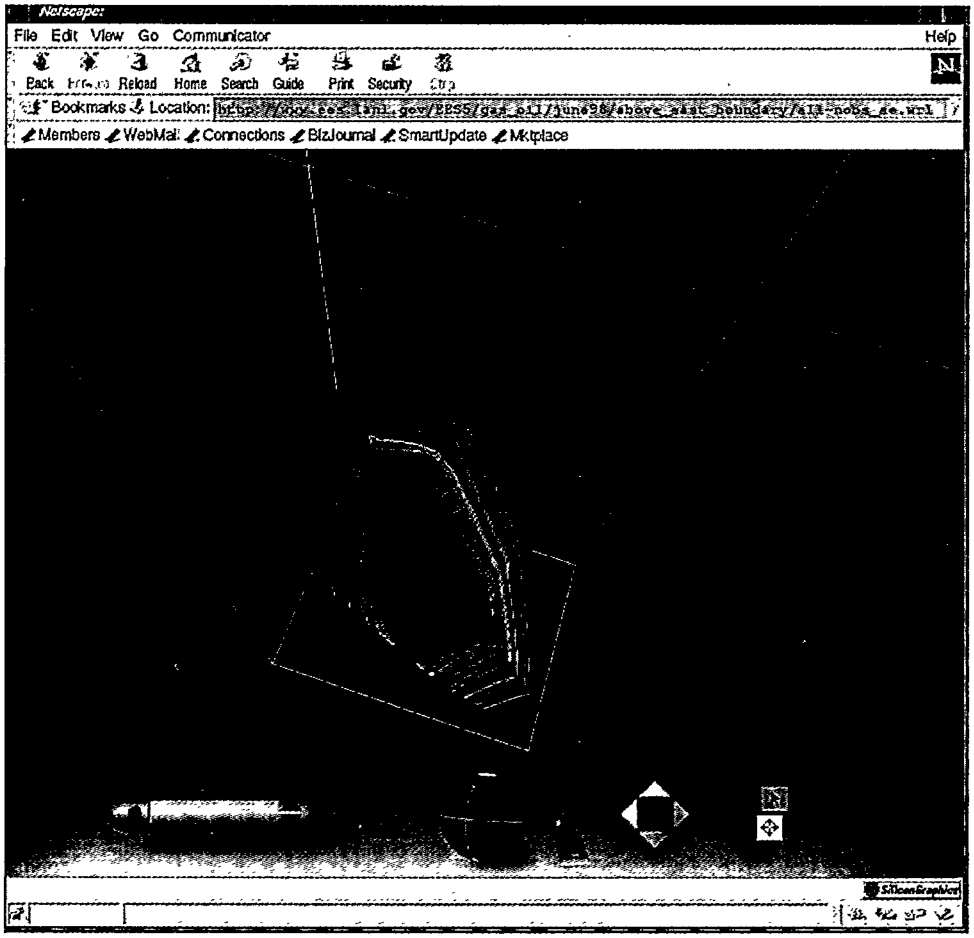

Figure 10: Complex geological models are made available as VRML (virtual reality modeling language) files that are readily viewed with the WWW with a plug-in program and a standard web browser (ees.lanl.gov/EES5/arm/pooi/geo/vrml.html).

Figure 11: Directional concept well trajectories, designed to avoid proximity to producing and abandoned wells.