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3D Scientific Visualization of Reservoir Simulation Post-Processing

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ABSTRACT

This paper describes a 3D visualization software designed at PETROBRÁS and TecGraf/PUC-RJ in Brazil for the analysis of reservoir engineering post-processing data. It offers an advanced functional environment on graphical workstations with intuitive and ergonomic interface. Applications to real reservoir models show the enriching features of the software.

INTRODUCTION

Scientific visualization proves beneficial to the Petroleum Industry. It helps meeting the need to deal with highly active, very dense data sources, which are particularly true for the large amounts of data resulting from reservoir simulations. Reservoir engineers often interpret simulation post-processing results through the use of conventional 2D areal and cross-sectional maps. This is an improvement upon the original methods of revising large data files, but it still presents shortcomings.

The use of post-processing 3D visualization improves even further the scientific inspection of the reservoir mechanisms, providing better and intuitive understanding of how physical properties vary throughout the reservoir.

A scientific visualization system named 3DSIGHT is developed in this work. It is part of an MS thesis¹ undertaken at PUC in Rio de Janeiro, Brazil in association with PETROBRÁS. The general system requirements comprise a flexible architecture with advanced functionality and intuitive user interface. Carefully selected visualization algorithms seek to provide a clear and precise data insight with quality performance. A major goal is to provide a practical and powerful tool for the reservoir engineering routine work.

INTERACTIVE VISUALIZATION MODELS

Interactive visualization is important to permit display and inspection of large quantities of data under a variety of conditions. Interactive visualization models must be applied taking into account the level of interaction between the simulation execution and the

References and illustrations at end of paper

visualization of the resulting images. Marshall et al² classify three interactive visualization models: *tracking*, *steering*, and *post-processing*. In the *tracking* model, the images are visualized during the numerical calculation, and the only possible interaction is to abort the simulation. In the *steering* model, there is a direct control of the simulation during its execution, allowing the user to modify simulation parameters during the visualization process^{2, 3, 4}. Finally, in the *post-processing* model, a dataset is first created from numerical simulations. Later, this dataset is used as input to a visualization system for graphical output and interaction. There are no interactions with simulation parameters and/or images generated during the simulation execution. The main advantage of this model is that the data can be examined repeatedly using different mapping techniques.

RESERVOIR VISUALIZATION NEEDS

Petroleum reservoirs are porous underground rocks from which oil, gas and water are produced. The modeling of reservoirs has incorporated a large number of special features allowing flexibility to the user. The simulation results often involve a few thousand cells, but it is not uncommon anymore to find models that use more than a hundred thousand cells. To justify the effort towards accurate modeling, it is necessary that tools become available to process and analyze significantly large datasets. In order to do so, the computational models are permitting output to files that are expected to be viewed or printed out in a table format and much larger outputs to binary files intended for post-processing. Regardless of the formulation being black-oil, compositional or thermal, maps of properties distributed throughout the entire data volume must become available for post-processing. Computational models display results in different fashions, but these differences can always be overcome with the use of accessory computer programs to filter the data and produce data files compatible with the visualization model presented. These visualization model permits verifying the actual way the computational model is behaving, entailing reservoir responses based on the simulations and

determining the mechanisms behind recovery. Furthermore, it allows defining the physical shape and stratification of the reservoirs in addition to describing the flow behavior of the fluids and energy. For field scale modeling, usually only mass and, less often, energy balances are considered. Two-dimensional visualization models are often used to analyze simulation results. However, the display of three-dimensional structures is essential to the clear visualization of events.

The processes involved in petroleum reservoirs are often discretized in space and time. For full reservoir modeling, the discretization in the vertical direction often involves increments that are a small fraction of the horizontal discretization size. Apart from the errors in approximating the differential equations due to the high contrast in the space discretization dimensions, some difficulties are present for the three-dimensional display.

The reservoirs are often divided into layers to more accurately represent flow units. Due to the thin thickness compared to the areal distribution of the reservoir, it becomes useful to distort the vertical scale to enhance the observation of property behavior. Also, it is convenient to separate layers in search of events related to stratified flow. Cross-sectional surfaces are also beneficial to the study of gravitational effects and preferential flow. The wells through which flow occurs need to be shown in the overall 3D display, indicating where they have been completed for production or injection. Viewing a continuous 3D domain can be rather helpful in identifying regions where property changes are significant. However, computation of properties are only available in a discretized form. In order to construct continuous bodies, adequate forms of interpolation become necessary. Finer discretization grids are becoming available with the increased speed and precision of computers. It is important to analyze data which has been treated accurately to represent the 3D space, but it also useful to visualize data indicating interpolated values for each computed cell, indicating the jumps in properties from cell to cell and permitting display of data actually computed. This permits locating the

sharper gradients which may possibly require refinement for better accuracy. Volume construction using isosurfaces is essential to the clear perception of property variations and location of regions. These variations can often be eliminated with grid refinement. For the clear visualization of these surfaces, it is important that the displayed object be shown from a favorable position. Animation capabilities allow visualization of time dependent processes.

The specific needs of reservoir visualization described above can more effectively be met with a single integrated piece of software. Not only all features are available in one same environment, but also further enhancements can be promptly integrated without modifying the software architecture.

VISUALIZATION SYSTEM

Design Goals

The main design goals set forth in the development of the 3D visualization system are as follows:

- Provide high quality 3D images and animation;
- Use various display methods to view the data with the post-processing model;
- Make visualization usable by the reservoir engineer for developing reservoir models and analyzing their results;
- Provide the user with a complete understanding of the mapping functions and graphical methods used in the display of data;
- Provide an advanced functional environment on graphical workstations;
- Design an intuitive and ergonomic interface with special attention to the metaphors presented to the user;

- Allow portability over various graphical workstations;
- Explore all capabilities available in the graphic system and hardware.

Architecture

The 3DSIGHT visualization software groups modules that comprise the following steps in the visualization process: *data acquisition*, *reconstruction*, and *visualization* (**Figure 1**):

Data Acquisition handles output files generated by numerical simulators running in mainframes, Unix-based workstations and/or personal computers. These files contain the reservoir property data associated with the simulation grids associated with a time-step reference.

Data Reconstruction is the process in which the reservoir geometry and property data are mapped into a workable model. For the 3D geometry, the surfaces for the top and bottom maps defining the reservoir layers are computed. Next, the property values acquired from simulations are distributed over grid cells on the layers. The interpolation between property values may be used depending on whether property continuity is desired. The result is a volume dataset of sampled scalar functions in three spatial dimensions (**Figure 2**).

Data Visualization provides a number of visualization options, allowing the user to interact with the reservoir model. Essentially, the data visualized by the user is the reservoir property volume dataset. Initially, the property values are pseudo-colored according to a color scale. Then, *surface-fitting* (SF) methods for volume visualization are applied. These methods fit surface primitives (usually planar) to constant-value contour surfaces in volumetric datasets^{5, 6}. Finally, the resulting surfaces approximating the property volume are shaded and displayed. Context-cue techniques⁷ are also applied to provide an effective

data insight and presentation by relating the values to the phenomena represented by the data. Simulation grid, bounding box, axes, wells, grid cell dimensions, shaded geological surfaces are elements of the reservoir model. Their representation more accurately presents and enhances the meaningful information.

The system is developed in the C language, the user interface is managed by the X Window System (Xlib/Motif), and 3D graphics are performed by the GL system (Figure 1). The system uses the latest generation of Unix-based workstations with proper hardware for graphic visualization. Currently, it is developed on an IBM RS/6000, model 580.

Visualization Options

Several features are available in the 3D visualization system to meet the reservoir engineering needs and the design goals established. The main features are briefly described below:

- *Selection and visualization of individual layers* with simulation grid, and/or geological surfaces, and/or property volume;
 - *Modification of distance between layers, and/or its vertical resolution;*
 - *Definition of cutting planes over the layers.* Two options are available: (a) pair of axis-aligned planes for each i, j direction, or (b) arbitrary planes with extremes located on any grid cell;
 - *Fence diagram* inside the layer volume;
 - *Display of wells* (vertical, slanted, horizontal) with name labels and completion marks;
 - *Property volume dataset visualization* following two steps: initially, the user selects a threshold for property values, followed by an option of *surface fitting* methods. The available methods are *discrete*—implemented with the *opaque cube* algorithm^{5, 8}, and *continuous*—implemented with the *marching cubes*⁹ algorithm. The *discrete* method considers the volume of all grid cells with corners that brackets the threshold, and the *continuous* method considers the volume of all grid cells with at least one value in the cell corners;
- *Selection of discrete or continuous shading for colors* associated with property values in each grid cell;
 - *Time-step animation control* allowing the user to jump to any time-step or to move forward/backward step by step;
 - *Display of grid cells dimensions*, individual or cumulative;
 - *Camera control* allowing visualization of the entire model from any point of view;
 - *Selection of bounding box planes;*
 - *Information queries of specific grid cells;*
 - *Color editor for the property scale and another for the other display elements (i.e., bounding box, wells, geological surfaces, dimensions, background)* to provide color harmony for better data insight;
 - *Light sources control* enhancing perception of the 3D structures.

RESERVOIR MODELS

The 3D visualization tool developed in this work is used to display actual reservoir cases. Selected examples are used to show the advantages of using such a tool in the modeling process. Although the software makes use of a wide variety of color options, a gray scale is used to generate the figures presented ahead. Ample control can be exercised on the legends

in selecting the property ranges, the number of ranges and the colors associated with them.

Various layers of a reservoir can be displayed simultaneously. Two layers of a reservoir are presented in **Figure 3**. The modeling grid is displayed in both layers, while the bottom grid also includes the distance of each grid node to the origin of the coordinate system. The distance between the layers are chosen to permit a comfortable comparison of the two layers. The vertical scales can also be controlled so that the topographic features can be properly observed. Properties are shown as the actual values calculated for the cells in the computational model. Interpolated values to approximate continuous property changes are presented later. The thickness of each layer can be enlarged as necessary to give a clearer three-dimensional representation.

The pictures can be moved on the screen allowing the proper angle of vision for each reservoir layer. Rotations in any directions are easily done. Advantages can be taken of the light source to either clearly show the surfaces or produce shadows when so desired. Zoom in and out features are also available. **Figure 4** shows the same two reservoir layers presented earlier. This closer view from a different angle shows interpolated property values through continuous color shading. Note that mesh grid is shown only along the bottom layer indicating the modeling cell dimensions.

It is often useful to select a certain portion of the reservoir within a defined property range. In **Figure 5**, two layers of a reservoir are shown. The display of the grid blocks has been limited to the reservoir portion in which the water saturation is below 0.40. The higher hydrocarbon saturation are indicated by the darker shades of gray. Note that in the upper layer the selected reservoir region is made up of one continuous part while in the lower layer the selected ranges are found in two separate areas. The meshed grids are displayed entirely. The flat portions of the grids indicate inactive cells. Three wells are represented in these layers indicating a single vertical completion, a double-layer vertical completion, and a single-layer

horizontal completion. The ease in which wells are represented permits describing wells of varied shapes. The perforations are indicated by a diamond shape object on the cells where the well is completed.

The same reservoir partially shown in **Figure 5** is presented in **Figure 6** indicating the portions of the reservoir which hold more than 40% water saturation. This watered partial view is useful for the observation of water advancement when using the animation option. In these two figures, the choice of volume rendering using isosurfaces takes into account all cells that have at least one corner value within the property range. Another option for isosurface construction considers only cells that have all corners within the range.

Flexibility in displaying multiple layers is helpful in analyzing the physical behavior of reservoirs. **Figure 7** shows a reservoir in which portions of the upper layers are removed to provide a better view of the pressure depletion around the wells. The bottom layer is presented entirely. Grid lines are added to highlight the cell size. Other features such as cell dimensions and vertical scale enlargement can be used to better indicate special features of the reservoir.

In analyzing pre and post-processing data, fence diagrams become useful tools. The advantage of these diagrams is a better perception of the three-dimensional variations of the property displayed. In **Figure 8**, this feature is applied to an entire reservoir layer, but it could as easily be applied only to a selected portion of the reservoir. The fence thickness may be varied as the camera is positioned to promote a better view of the reservoir layer.

CONCLUSIONS

As a result of the work presented, the following conclusions can be drawn:

- 1) The 3DSIGHT system has powerful features as a tool for the analysis of the large amounts of data generated in reservoir simulations and

contributes to the development of the scientific visualization field;

- 2) Scientific visualization techniques are used not only to produce attractive images and impressive demonstrations, but mainly to convey the relevant information for reservoir engineering work;
- 3) Advanced functionality is achieved through a set of visualization options that can be used cumulatively providing great flexibility for reservoir engineering analysis;
- 4) Appropriate metaphors implemented with sophisticated interface design tools provide an ergonomic and intuitive user interface;
- 5) Powerful graphic capabilities are available through the combination of visualization algorithms and graphic hardware;
- 6) The use of transparency levels to locate regions of interest and the simultaneous display of different property datasets associated with the same layer are examples of options which may provide enhancements to the system;
- 7) The system is designed with an objected oriented architecture to permit easy integration with existing 2D post-processing software, providing a rich environment to the reservoir engineer.

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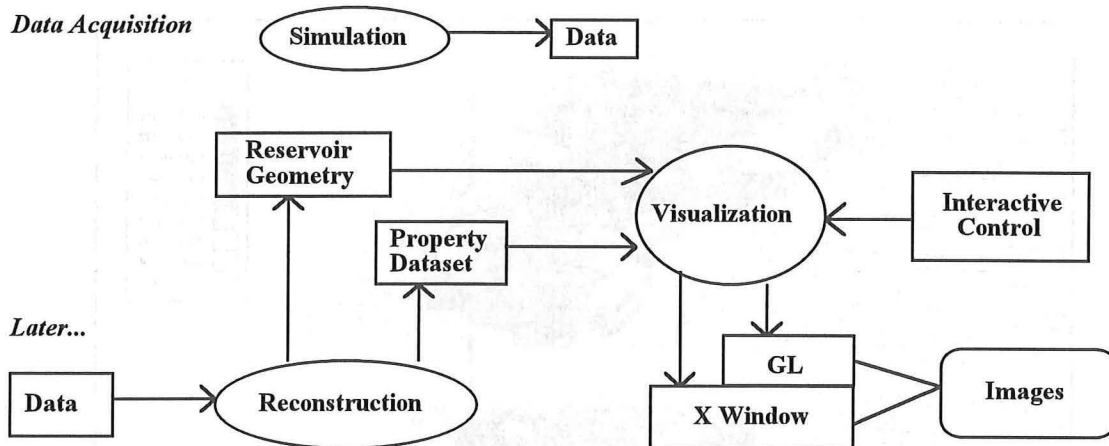


Figure 1: Architecture of the 3DSIGHT system according to the post-processing model.

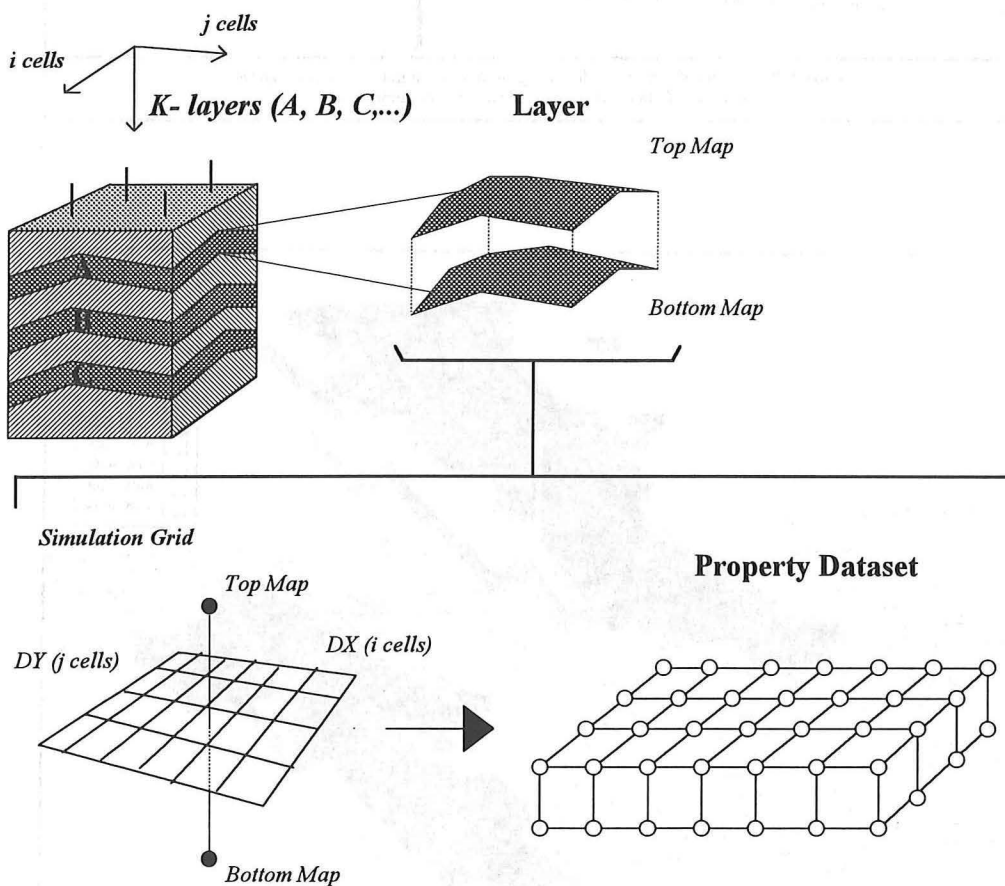
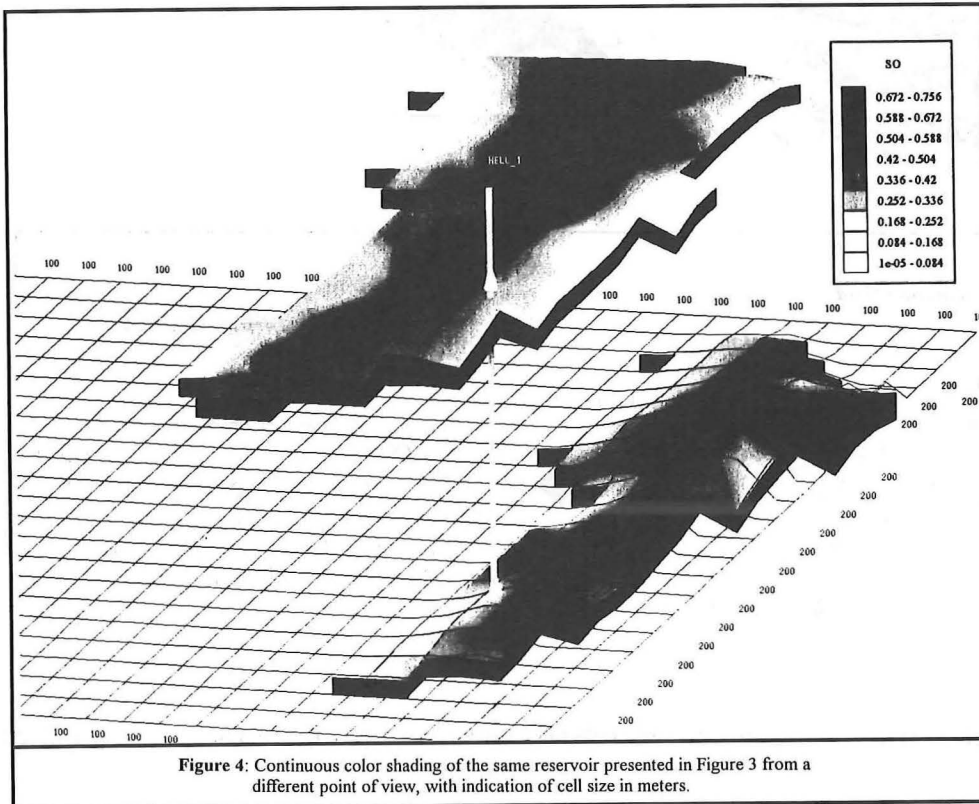
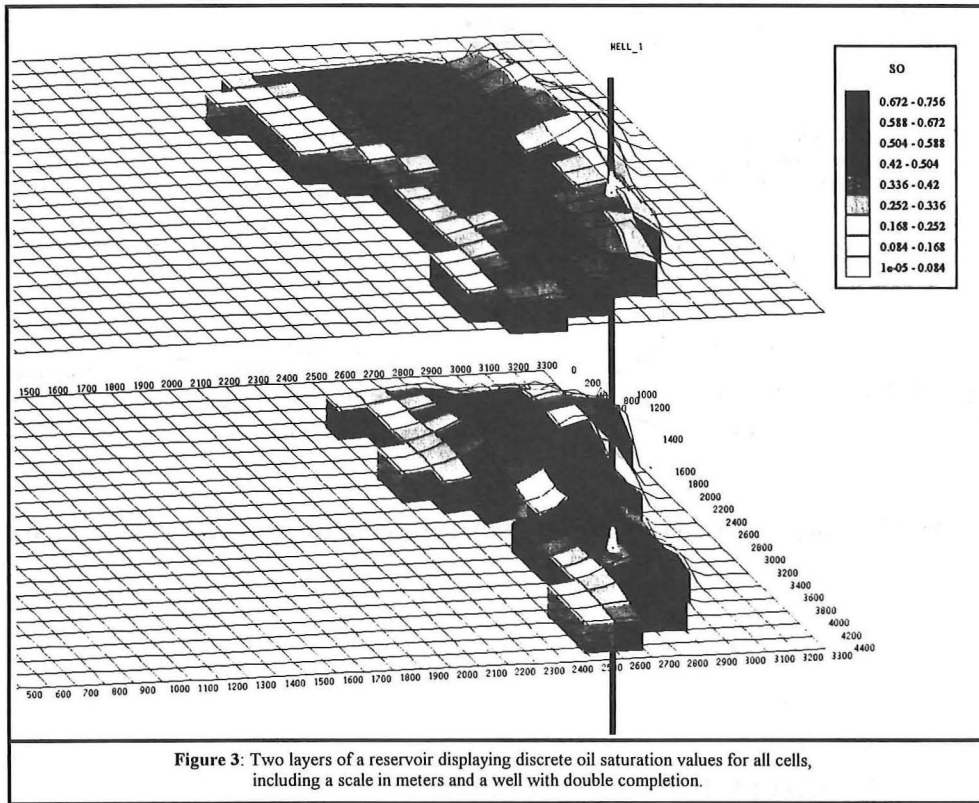
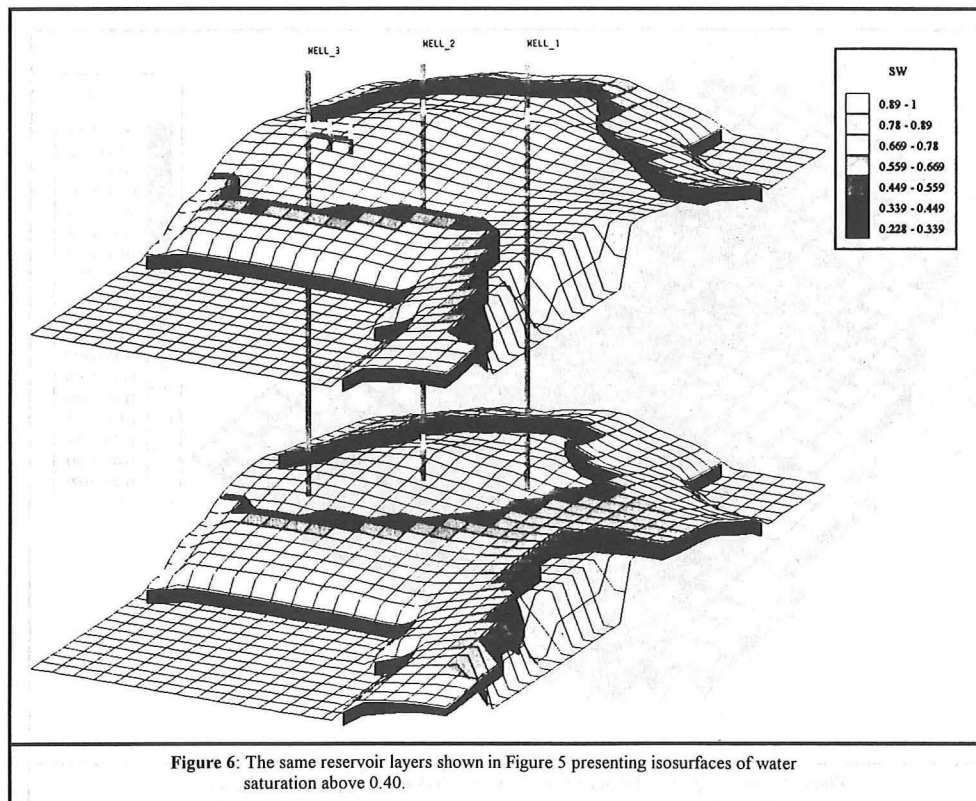
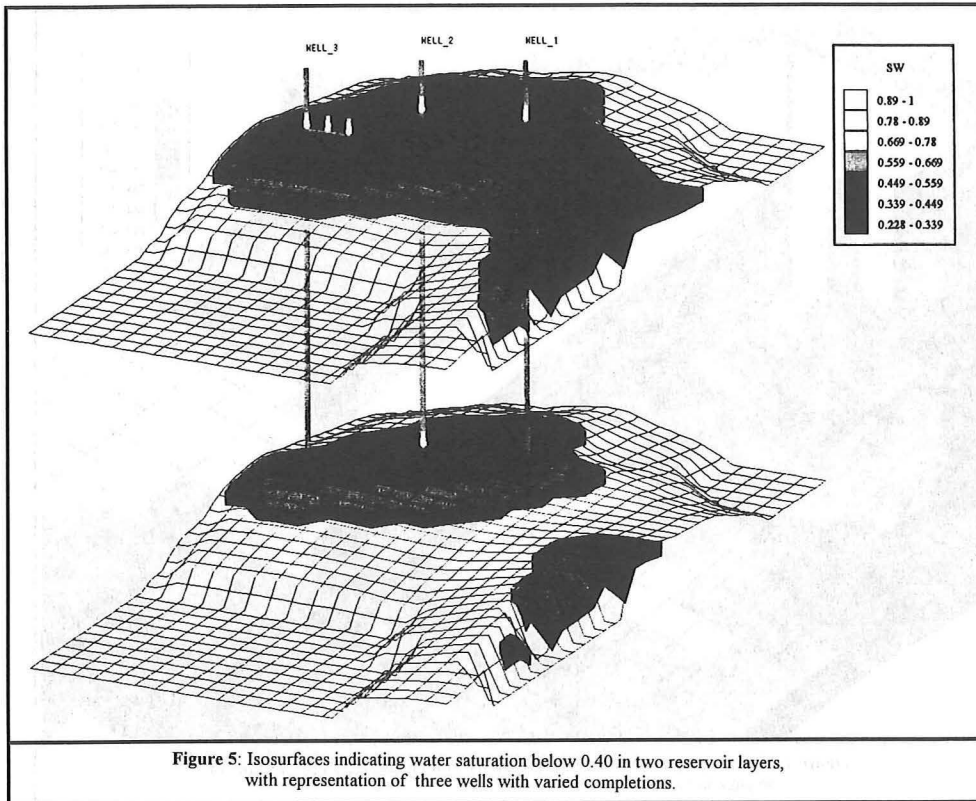


Figure 2: Three-dimensional grid for each reservoir layer with property values known at corner nodes.





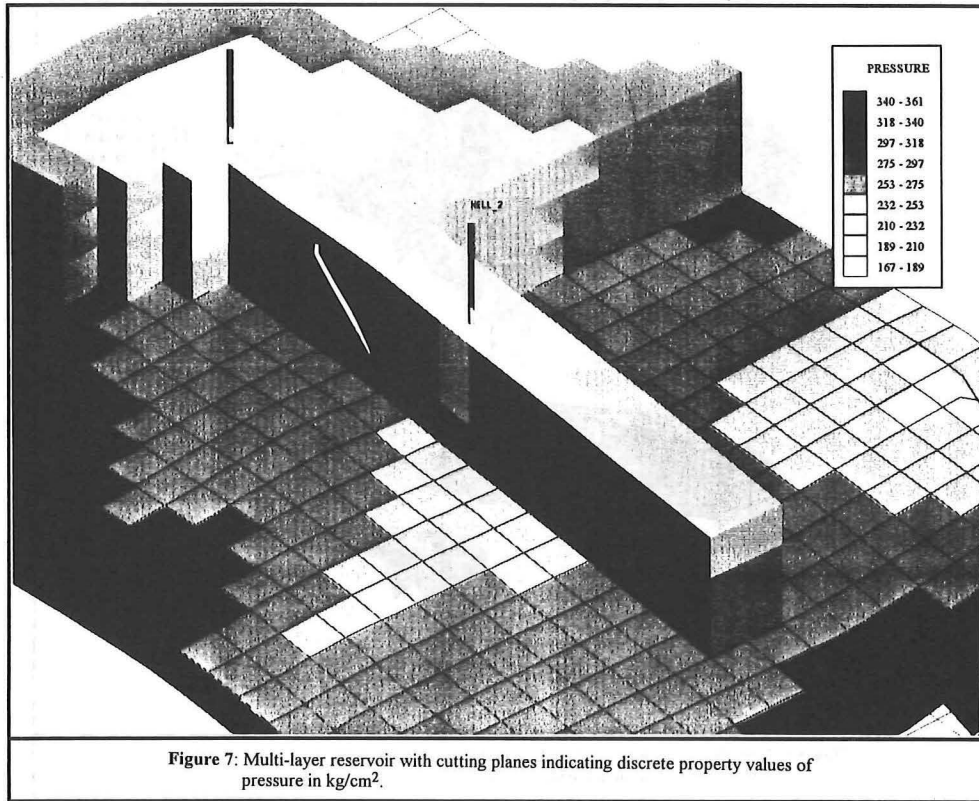


Figure 7: Multi-layer reservoir with cutting planes indicating discrete property values of pressure in kg/cm².

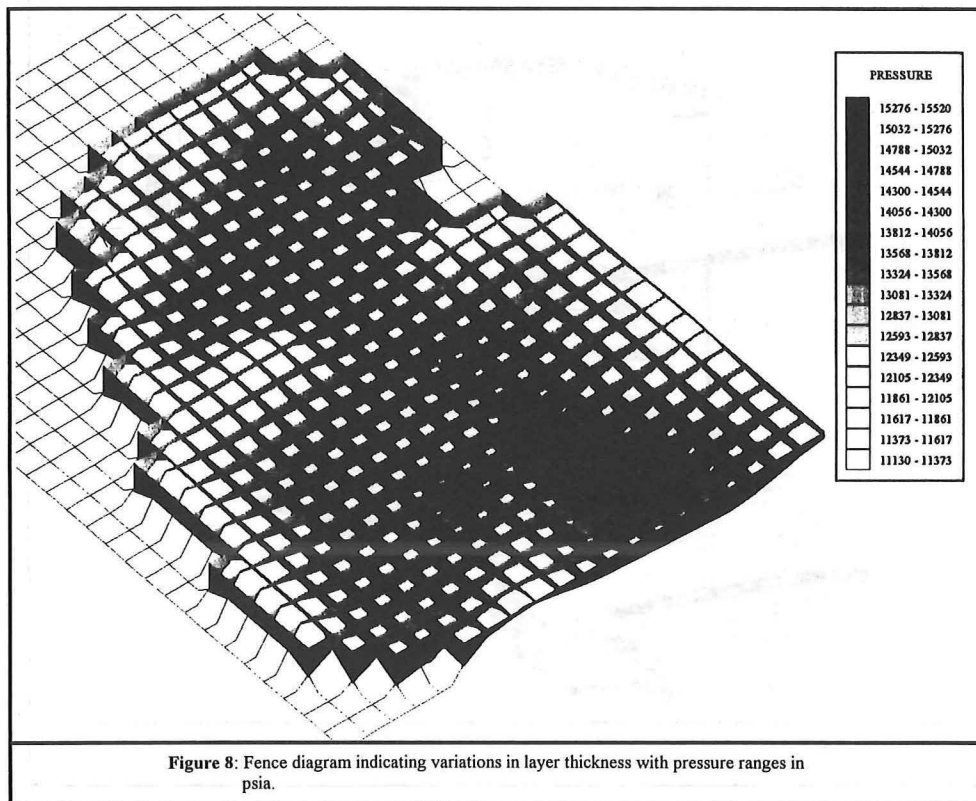


Figure 8: Fence diagram indicating variations in layer thickness with pressure ranges in psia.