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Petroleum Reservoir Simulation in a Virtual Environment

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ABSTRACT

In this paper, we describe an approach to combining a reservoir simulation with 3-D visualization and virtual reality technology. Our prototype VR/visualization system minimizes human-machine interface barriers and provides enhanced control over the simulation, thereby maximizing scientific judgment and use of intuition. We illustrate the practical advantage of using the VR/visualization prototype system in reservoir engineering by visualizing the results of a waterflood in an oil field with a three-dimensional, spatially correlated heterogeneous permeability field.

INTRODUCTION

With the advent of multi-processor computers and the increased use of stochastic methods to characterize heterogeneities, 3-D visualization has become an integral part of modern reservoir simulation. For the most part, however, visualization of simulation results is a post processing step that occurs only after the simulation has run to completion. Given the size and complexity of problems in reservoir engineering, completion of a simulation may take several hours or even days.

Often times simulation results are discarded because of errors in input files or because the given input parameters did not give the desired simulation results. In these cases both the reservoir engineer's time and computer time are wasted.

In this work, we describe an approach to combining a reservoir simulator with visualization software tools and virtual reality (VR) technology. Our goal is to make simulators easier to use and simulation results easier to understand. The benefits of 3-D visualization are fairly well known, however, the visualization environment that we use provides a rich assortment of visualization techniques for examining different aspects of a simulation. In addition, VR output technology provides more flexible and convincing ways to view simulation results.

The key advantage of the prototype VR/visualization system is that the researcher or reservoir engineer sees the output from the simulation as soon as it has been calculated. This allows early detection of errors in input parameters, poorly formulated reservoir scenarios, and other cases in which unexpected problems arise during the simulation that result in the input needing to be revised and the simulation rerun. The VR input device facilitates specification of new three-dimensional input parameters, such as

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References and illustrations at end of paper.

well locations without having to resort to counting grid blocks. Incorporating the simulator into the visualization environment means input parameters can be changed and the simulation restarted without having to exit the visualization environment. Thus our VR/visualization system increases the reservoir engineers interaction with the simulator and decreases the amount of human and computer time lost due to errors in or poorly formulated input.

The following sections describe the basic concepts of virtual reality and visualization incorporated in this work, the reservoir simulator used, and how the results of the simulation have been visualized. We conclude with an application of the VR/visualization system to waterflooding in an oil reservoir.

We initially simulate water flooding in a heterogenous oil reservoir. Visualization of the 3-D output of the simulator shows a region of persistently high oil saturation. Using the VR input device, we are able to reposition one of the production wells and thus to quickly and easily evaluate an alternative drilling strategy.

VIRTUAL REALITY AND VISUALIZATION

In spite of a constant media bombardment that would have us believe otherwise[1], the essence of virtual reality is not "goggles and gloves." Implementations of VR encompass a wide gamut of input and output devices. Rather than the fundamental ideas that drive the technology, the devices themselves have captured the attention of the media.

The basic premise of VR, visualization, and how the two fit together, can best be understood by focusing on the basic concept of the architecture of a typical "graphics pipeline." In the graphics pipeline, a set of geometric objects, such as points, lines, triangles, is submitted to a "renderer." The renderer then processes each of these objects, producing an image. The image is presented to the user on a display device. The user is able to interact with the renderer in order to specify display parameters such as viewer position and orientation. In contrast, visualization is the process whereby the object database is constructed using algorithms in which abstract data is represented geometrically.

The goal of VR is to allow the user to specify, in an intuitive and easy-to-use manner, three or higher dimensional parameters to the visualization process. This idea has been in the graphics community since at least the early 1960's[2] and more recently has become popular as display device technology has rapidly advanced. The result, however, is that most people think of VR as being synonymous with a head-mounted display (HMD) and a data glove. Clearly, many different input devices may be employed by the user to specify parameters to the renderer, to a visualization algorithm, or to a numerical simulator. These include keyboard, mouse, button panel, and dial box. None of these devices lend themselves to "natural" specification of three or higher dimensional input and thus are cumbersome to use for that purpose. Many low-cost VR input devices that may be used for this purpose are available. There is a noticeable absence, however, of widespread use of these devices in the field of scientific computing.

The manner in which graphical images are presented to the user is the subject of VR output devices. Clinical studies[3] have shown that currently available HMD devices result in impaired vision and limbic system dysfunction even after short periods of use. Further, the best HMD devices available (military grade), cost upwards of $100,000 and still don't deliver the spatial resolution required by the most ordinary of visualization tasks. These advanced display devices leave much to be desired both in terms of practical use and affordability. Other ergonomic issues of concern pertain to integration of these devices into a person's workspace. "Suiting up," that is, donning goggles and gloves, takes time and interferes with the work environment in which telephones must be answered, fire alarms go off, *etc.*

The premise of VR, the ability to interact with a computing process in an a minimally-unobstructed fashion, is consistent with advances in recent years of more conventional Graphical User Interfaces and has the potential to change scientific computing in the same way that the "point and click" user interface brought the power of personal computers to the public.

COMBINING VIRTUAL REALITY AND VISUALIZATION

Our prototype system consists of a few discrete components: the visualization environment, the numerical simulator, and the VR input device. These

components have been integrated into a system that may be used to study the effects of well placement in a simulation of a water or chemical flood in a heterogeneous oil reservoir.

The visualization environment consists of a collection of separately compiled and linked software modules. The organization of these modules into a visualization program is facilitated using visual programming. A simple point-and-click interface is used to arrange the modules in a workspace (Fig. 1) as well as to route the flow of data between the modules. A scheduler computes the correct module execution order from a directed graph in which the nodes are modules and the edges are data flow paths.

Most important to our work is the fact that this system is extensible, that is, users can add their own software modules to this environment. It is this flexibility that has made it possible for us to incorporate both the simulator and the use of the VR input/output device into the visual environment. In addition, the visualization environment that we are using supports the execution of modules on remote computers. The simulation may be run on a compute server, such as a massively parallel computer, with the visualization and user interaction being performed on a graphics workstation. (Other such modular visualization environments also are available[4,5].) The simulator was ported to run in this environment for the purposes of interactive control and to provide the flexibility this environment offers in terms of visualization tools.

In its original implementation, the simulator was a batch-oriented code. The user would supply input decks, submit the job, and look at the results offline at a later time. Detection of errors in the simulation input did not occur until after the simulation had run to completion, using up valuable compute cycles, and delaying interpretation of results for days or even weeks. In the current environment, the user is presented with immediate visual feedback depicting the input and the results of the simulation, thus shortening the time between parameter specification and studying the effects of those parameters on the simulation. In addition, the placement of the wells in the simulation is under control of the VR input device. Use VR input devices to specify visualization parameters is not new[6]. The use of VR input to control a simulation is not only a natural extension of this previous work, but greatly increases the effectiveness of the use of the scientist's intuition by

minimizing the barriers between scientist and simulation, allowing the scientist to focus more on the science and less on technology.

DESCRIPTION OF THE NUMERICAL SIMULATOR

The numerical simulator incorporated into the VR/visualization system is an adaptation of UTCHEM, a multicomponent, multiphase chemical flood compositional simulator developed at the University of Texas and widely used in the oil industry[7, 8, 9]. Although the primary focus of the application in this paper is waterflooding in heterogeneous permeable media, the simulator is capable of modeling a variety of processes including micellar-polymer flooding, caustic flooding, cosurfactant-enhanced alkaline flooding, and profile control processes involving in-situ reactions with polymers and crosslinking cations. The simulator allows the use of multiple tracers in any of the above processes and for estimating residual oil saturation for either interwell or single well backflow tracer tests.

Material conservation equations are solved for up to nineteen components that can form up to three separate phases: aqueous, oleic, and microemulsion. For chemical flooding, the phase environment is determined by an effective salinity parameter that takes into account the presence of divalent cations and cosurfactants. Major physical phenomena modeled by the simulator are: dispersion, dilution effects, adsorption, interfacial tension, relative permeability, capillary trapping, capillary pressure, compositional phase density and viscosity, cation exchange, alcohol partitioning, and various polymer properties such as non-Newtonian rheology, permeability reduction and inaccessible pore volumes. Dissolution/precipitation reactions are modeled assuming that the aqueous and solid (mineral) phases are in thermodynamic equilibrium.

The basic solution strategy used in the simulator is analogous to the IMPES (implicit pressure, explicit saturation) method. A pressure equation, derived based on the overall mass-continuity and Darcy's law, first is solved implicitly to obtain phase pressures and phase velocities. The conservation equations then are solved explicitly for total concentrations of components. Finally, phase saturations and concentrations are obtained using flash calculations based on the pseudoquaternary

representation of the phase behavior. A third-order total variational diminishing (TVD) scheme is used to minimize numerical dispersion during solution of the conservation equations.

VISUALIZATION OF SIMULATION RESULTS

In the prototype VR/visualization system, the user supplies the names of the input files for the numerical simulator via a graphics user interface. Once the input files have been specified, the display shows a wireline grid of the numerical grid used by the simulator, the location of the production and injections wells, and an isosurface of the magnitude of the permeability distribution (Fig. 2). Conventional post symbols are used to distinguish between production and injection wells. At this point, prior to running the simulator, the user may change the value of the permeability isosurface displayed, the frequency with which the output of the simulator is displayed, and the locations of the wells. Dial boxes are used to change the first two parameters. To change the location of a well, the user selects the well to move using the mouse and moves the well to a new location using the VR input device. The new coordinates of the repositioned well are automatically written to a file accessible to the simulator.

When the simulator begins to run, the value of the oil saturation is indicated by the color of small cubes positioned at the center of each grid point. Each cube indicates not the point value of the oil saturation at the grid point, but rather the oil saturation (obtained by interpolation) of the region occupied by the cube. The range of values of oil saturation is indicated by a color legend in the lower left corner.

The water flood is shown as an isosurface of water concentration. The isosurface is translucent, allowing the user to look "through it." A wireline mesh is superimposed on the isosurface in order to enhance its three-dimensionality. Fig. 3 shows a close-up view of the region near the injection well at an early time. This image is obtained by using the spaceball to navigate close to the injection well and provides an example of how the user can get a close-up look at early time data.

While the simulation is running the user has control over many aspects of the display, thus enabling the user to interact with the output of the simulator and to investigate different aspects of the output.

In addition to being able to rotate and/or translate image, the user may change

- the size of the cubes that indicate the value of oil saturation and/or select a subset of the cub i.e., display every other cube, every fifth cul etc.,
- the value of the isosurface of the wa concentration shown,
- the value of the isosurface of the permeabi distribution,
- the value of the isosurface of the oil saturation,
- the location of 2-D slices through the saturation,
- (not shown in Fig.s 2 and 3).

The user also may use the VR input device to naviga through the reservoir. This is equivalent to bei able to zoom in, rotate, and translate. Each of the separate steps in the visualization system (with the added VR interface) would require multiple cli on different mouse buttons, together with press the shift key (for zooming in). In contrast, spaceball provides an intuitive way to move throu the reservoir without having to remember "whi button does what." The effect of clicking seve different mouse buttons in sequence can accomplished with a single smooth movement of VR input device.

APPLICATION OF VR/VISUALIZATION SYSTE

We illustrate here the application of t VR/visualization system to convert batch operation the reservoir simulator to an interactive, vis environment for investigating reserv characteristics and processes. The example case waterflooding in a five-spot pattern in the preser of spatially-correlated, permeability heterogeneit generated using the Turning Bands Method w specified variance and correlation lengths. T VR/visualization system was used to visualize performance of waterflooding and to dynamica alter the position of one of the production wells pi to restarting the simulation.

Generation of the Permeability Distribution

The three-dimensional, heterogeneous permeabi distribution used in this study was generated by turning bands method (TBM)[10]. The TBM is a meth

for simulating spatially correlated random fields, either two or three dimensional. In this work, we use an implementation of the TBM developed by A. Tompson[11], which uses an exponential-decay covariance funciton. Because the method converts what would be a calculation in two or three dimensions to a series of one-dimensional problems, it is computationally efficient[12].

THE TBM generates random fields from a normal distribution with zero mean and a specified variance. In the present application, the random field generated is converted to a lognormal field with a geometric mean of 0.5 and a log-variance of 0.35. The resulting permeabilities are scaled to give values in units of millidarcies. The correlation lengths for the horizontal permeabilities are 40% of the size of the reservoir in the horizontal directions and 20% of the size of the reservoir in the vertical direction. The correlation lengths for the vertical permeabilities are 20% of the size of the reservoir in both the horizontal and vertical directions. In Fig. 4, permeability magnitudes in the range of 600 to 700 md are shown in white.

Simulation Input Parameters

The five-spot pattern used for simulation studies is shown in Fig. 2. It has a central injection well surrounded by four production wells. The injection rate is set at 10% pore volumes/year (33.2 ft^3/day). Pattern balance is maintained by setting the production rate for each well at one-quarter of the total injection rate (8.3 ft^3/day). Each well is perforated along its entire length. The distance between the injection well and each production well is 52.5 ft. The reservoir is 105 ft by 105 ft and 55 ft in depth. The reservoir has been divided into 21 grid blocks in each horizontal direction and 11 grid blocks in the vertical direction for a constant grid spacing of 5 ft. The reservoir has a constant porosity of 0.2, an initial oil saturation of 70%, and an initial water saturation of 30%.

The numerical simulator requires many other input parameters describing chemical and physical processes, *etc.* For the purpose of the application described here, only parameters describing spatial reservoir properties (*e.g.*, porosity and permeability) and well locations and injection/production rates are given. A quadratic functional form for relative permeabilities has been used for both water and oil.

Description of Simulation Results

Fig.3 shows a close-up view of the region near the injection well at an early time (26 days). The effect of the heterogeneity in the permeability distribution is evident as shown by the asymmetry in the isosurface of water. Fig. 5 shows a later (49 days) view of the reservoir from above it, looking down into. Because the cubes that indicate the value of the oil saturation do not touch, the user is able to look through the reservoir and see the cone of water surrounding the injection well. Once again, the effect of the heterogeneous permeability distribution is evident from the asymmetry of the water flood.

A user sitting at the color workstation on which the VR/visualization system is running would be able to rotate the display in order to get a better view of the output results and to look for areas in which low permeability zones have resulted in higher oil concentrations than in surrounding areas. Fig. 6 shows such a view at a simulation time of 75 days. The dark isosurface spreading across the reservoir is an isosurface of relatively high (0.69) oil saturation. Between the rightmost (foreground) well and the central injection well, there is a pocket of oil extending over half of the depth of the reservoir. This pocket is evident at earlier times and persists for longer times (not shown).

In order to demonstrate the value of the VR/visualization system for identifying candidate regions for infill drilling, the simulation was stopped, and using the VR input device, the rightmost production well was moved closer to the oil pocket as shown in Fig. 7. In addition, a change in the perforation of the injection well was made so that the well would not be perforated near the top or bottom, but only for the middle 50 ft.

After making these changes, the simulation was restarted from the visualizaton environment. Fig. 8 (26 days) shows a nearly identical view of the region near the injection well as shown in Fig. 3. The water isosurface near the injection well is no longer pinched in the middle as in Fig. 3, but is more symmetrical with respect to the injection well. Fig. 9 shows a view comparable to Fig. 6. The slight repositioning of the production well has had the desired effect. The pocket of oil so prominent in Fig. 6 has been produced.

CONCLUSION

The VR/visualization system described in this paper provides the following advantages to the reservoir engineer:

* the opportunity to view simulation results as they are generated,
* a rich assortment of visualization tools and techniques for examining simulation results,
* the use of a VR input device to specify 3-D input parameters such as well locations and perforation zones,
* the use of VR/visualization to study field development strategies (e.g., infill drilling, perforations, etc.)

Taken together, these advantages enhance the reservoir engineers intuition for formulating different strategies for solving reservoir problems. He or she is able to start to see simulation results soon after commencing a run, while the thought process that led to the formulation of the input scenario is still fresh in his/her mind. Similarly, by using a variety of visualization techniques to examine simulation results at a single time step, the reservoir engineer is able to get a better feel for what is happening in the reservoir as the simulation proceeds. Seeing the simulation results while the simulator is running sparks the reservoir engineer's curiosity about what would be the effect of changing one or another parameter, so that the thread of reasoning is not lost between the start and finish of the simulation. Not only does the reservoir engineer's attention stay focused on the strategy that he/she has formulated to solve the problem at hand, but less time is lost because input errors or poor solution strategies could be detected early in a simulation.

In the simple case used to demonstrate the applicability of our VR/visualization system, the need for repositioning one of the production wells was indicated by the persistence of a region of high oil saturation. Where to reposition the well also was fairly clear. Moving the well 30 ft. gave the desired effect of removing the oil pocket and convincingly demonstrates the practical advantage of using a VR/visualization system, such as ours, to understand simulation results and to formulate new solution strategies.

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FIGURE 1   Workspace of visualization environment showing network of software modules.
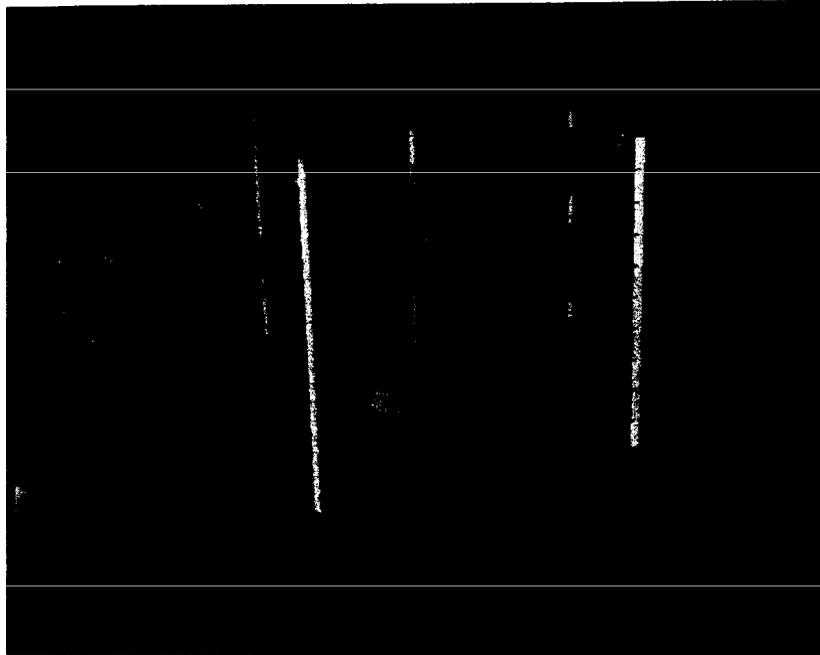
FIGURE 2   Placement of injection well (center well) and
surrounding production wells in numerical grid.
Isosurface of permeability magnitude (670 md) is
also shown.

Time Step 26.4⁴
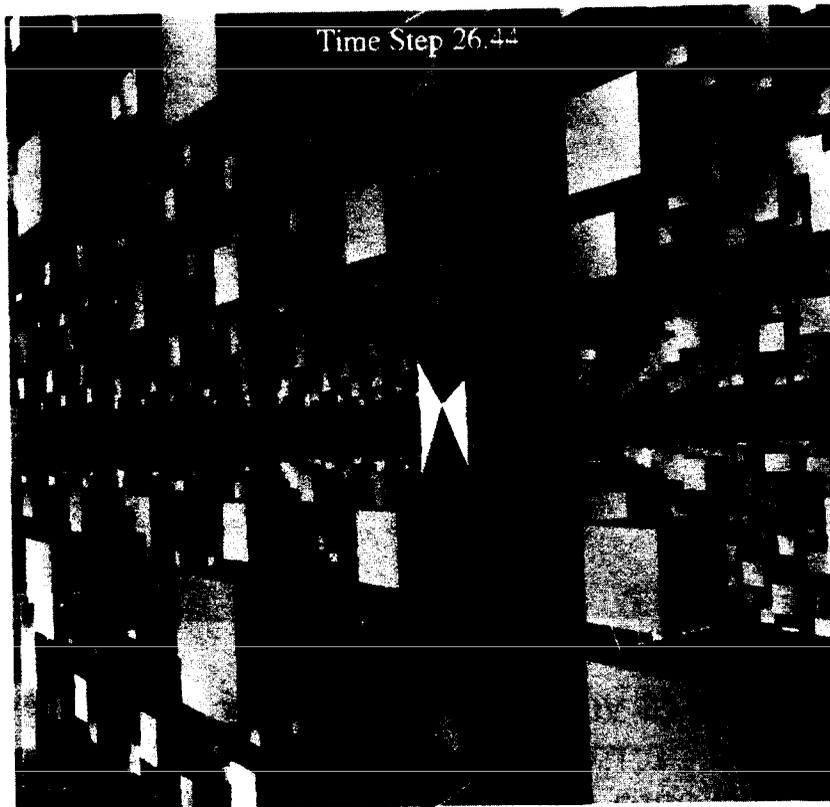
FIGURE 3   Close-up view of the region of the reservoir near
the injection well at a simulation time of 26 days.
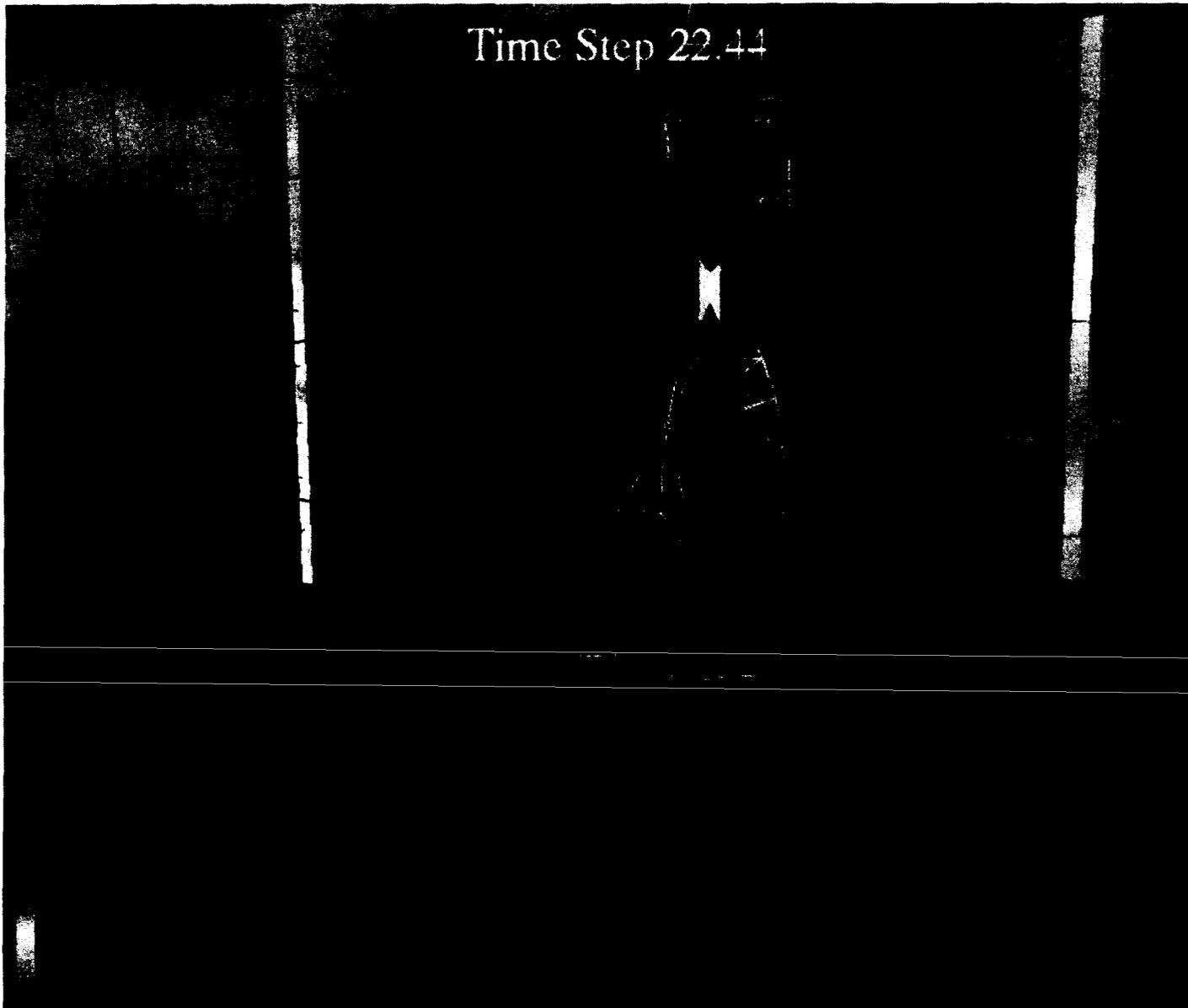The value of the isoconcentration of water is 0.6.

FIGURE 4   Use of volume rendering to show heterogeneity in the permeability distribution. White regions indicate permeability magnitudes between 600 and 700 md. (Waterflood at early time [26 days] is also shown.)
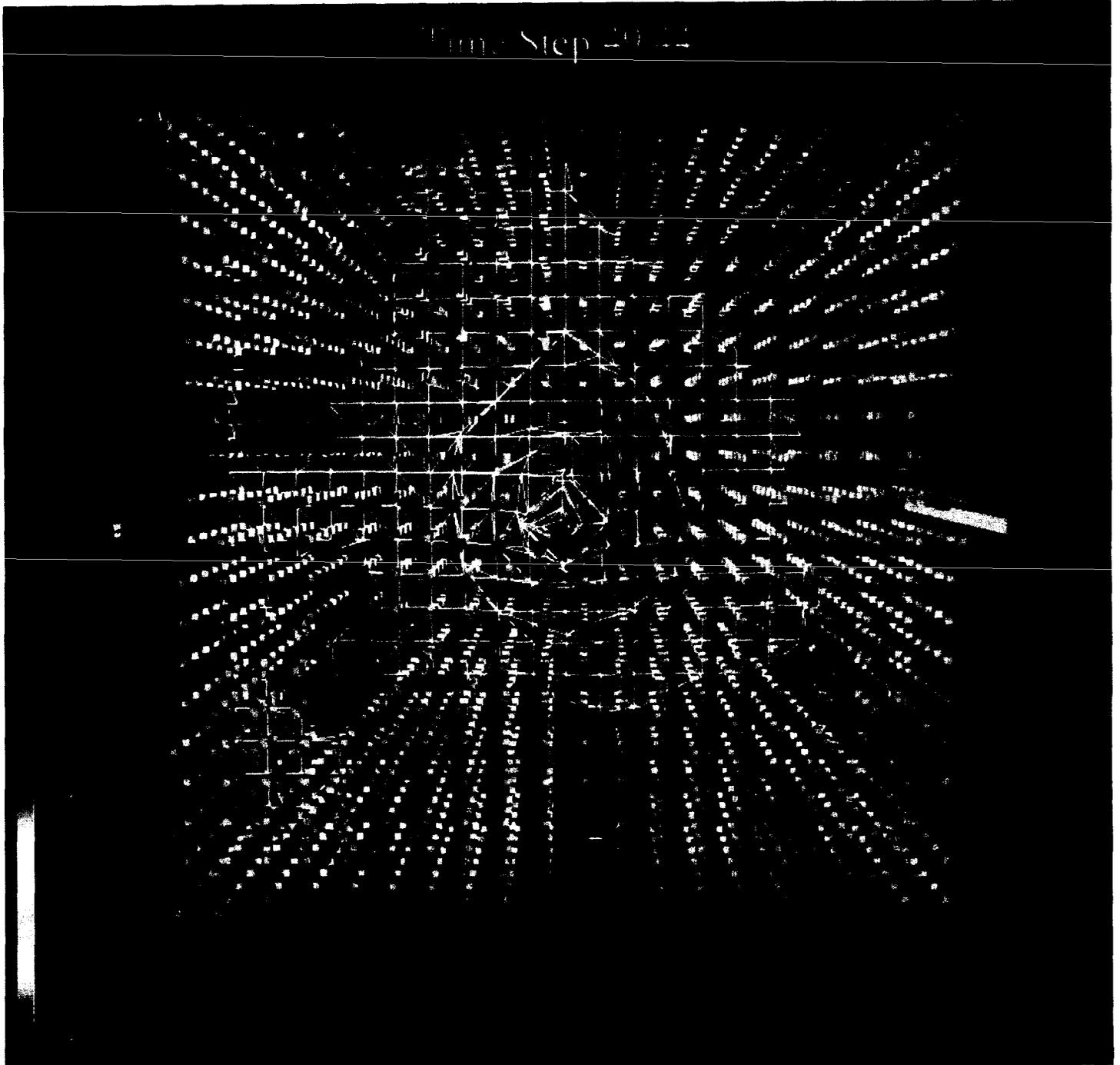
FIGURE 5   Effect of heterogeneities in permeability on the
waterflood at a simulation time of 45 days. Value
of isoconcentration of water is 0.6. The view of the
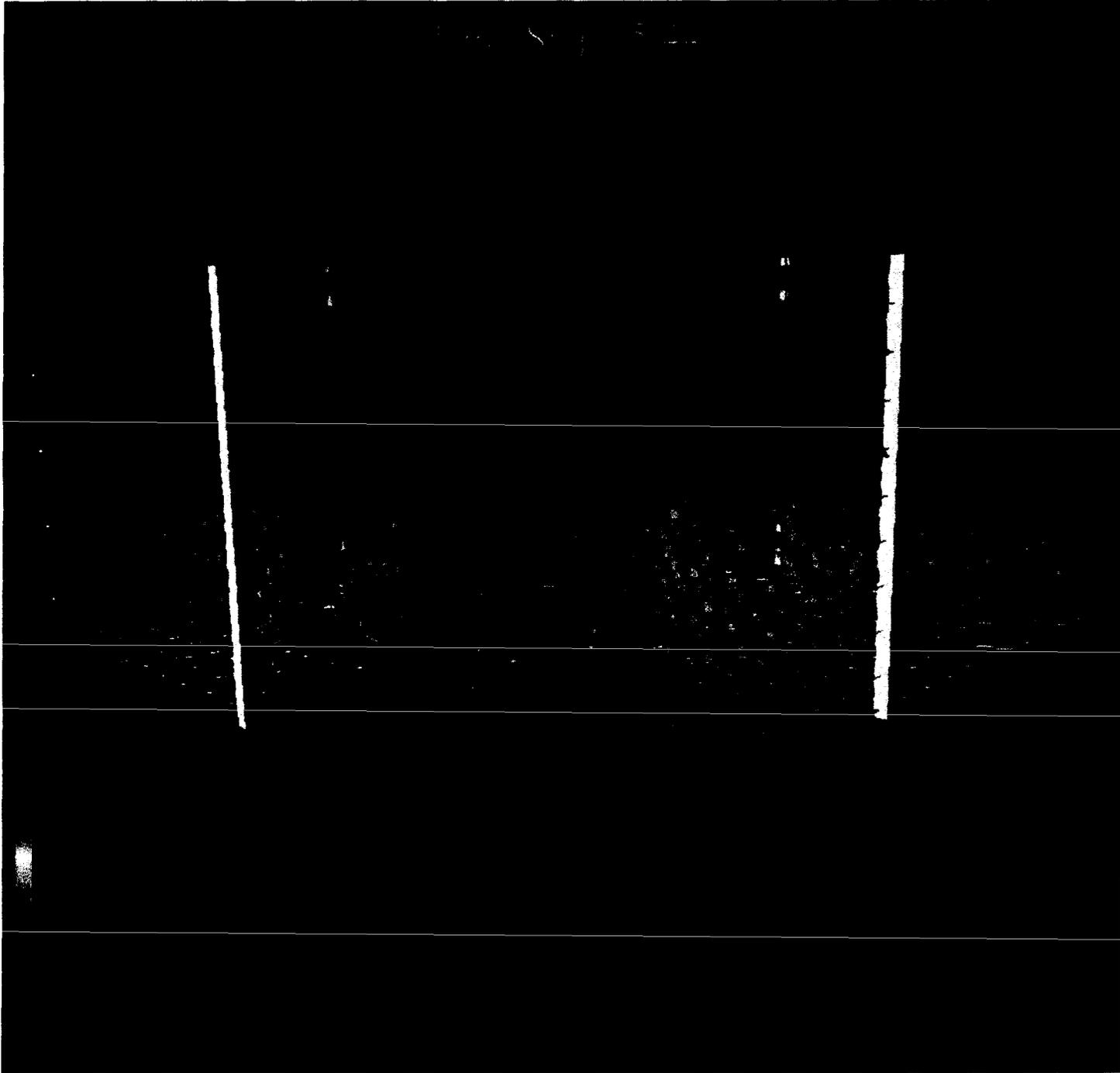reservoir is from the top looking down into it.

FIGURE 6   Isosurface of high oil saturation (value of 0.69) shown by dark horizontal surface and vertical finger at a simulation time of 75 days.
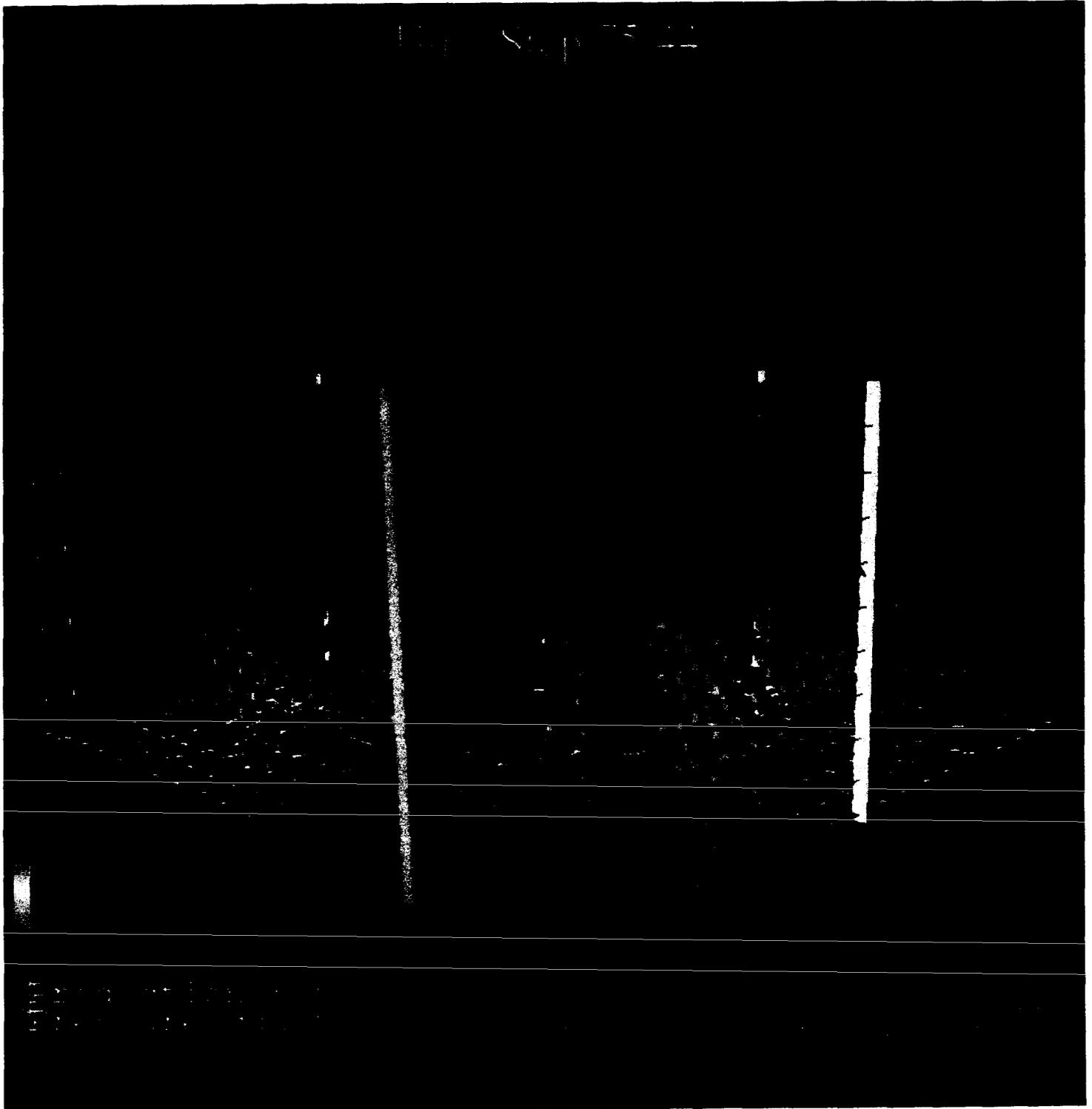
FIGURE 7   Repositioning of production well, prior to restarting
the simulation, to counter vertical finger of high oil
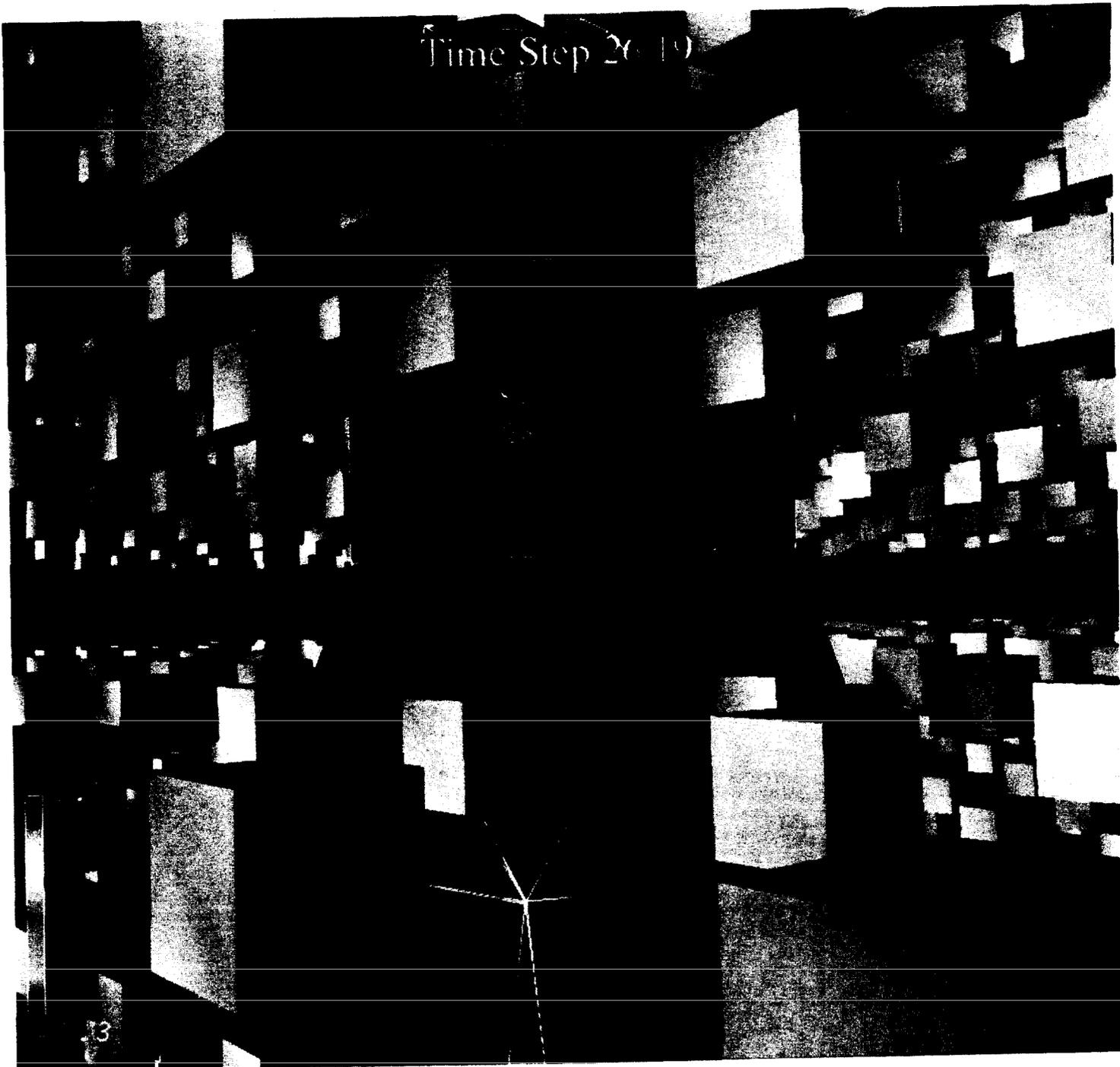saturation. The simulation output is identical to
that of Figure 6.

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FIGURE 8   Effect of changing the perforation of the injection well on the waterflood shown at a simulation time of 26 days. The close-up view of the region of the reservoir near the injection well is comparable to the view shown in Figure 3.
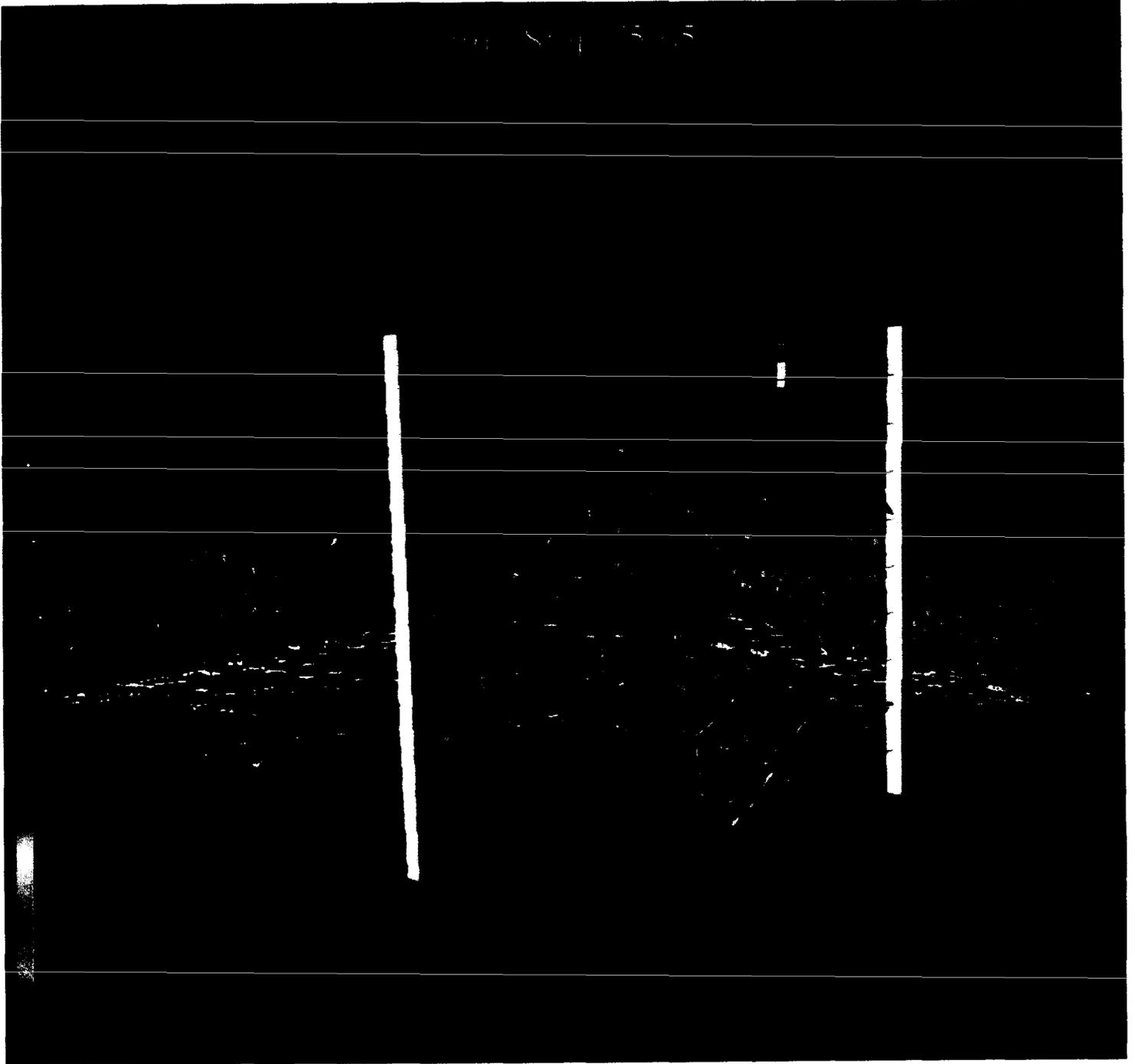
FIGURE 9   Effect of repositioning production well on region of
high oil saturation. Simulation is shown at a time
comparable to that of Figure 7.