Simulation and Analysis of a Borehole Transient Electromagnetic Reservoir Monitoring System

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Abstract: Waterflooding and steam-flooding are used worldwide for secondary and enhanced oil recovery (EOR). Recently, carbon dioxide (CO_2) flooding has attracted global attention as a means of EOR as well as for carbon capture and sequestration (CCS) applications. All these processes cause significant changes over time in the fluid composition of oil reservoirs. In this paper, we demonstrate the feasibility of a borehole transient electromagnetic (TEM) system that can map the fluid dynamics of these processes. This mapping can delineate bypassed pay and yield the extent of flooding. The operator can then use this information to maximize oil recovery efficiency by designing appropriate flooding patterns and controlling the injection rates.

We first validate COMSOL simulations for simple one-dimensional layered models with our in-house fast semi-analytical code. Then we use COMSOL to simulate the proposed borehole TEM system in two-dimensional and three-dimensional models of waterflooded and CO_2-flooded reservoirs. These simulations not only prove the efficacy of this technology in providing deep and azimuthally sensitive measurements, but also help us understand how the TEM diffusion process responds to electrical resistivity contrasts.

Keywords: Enhanced oil recovery (EOR), carbon capture and sequestration (CCS), transient electromagnetics (TEM), reservoir monitoring.

1. Introduction

As existing oil fields age and new oil fields with ‘easy’ oil become more and more scarce or inaccessible, maximizing hydrocarbon recovery from existing reservoirs has never been more important. Secondary and enhanced oil recovery (EOR) processes such as waterflooding and steam-flooding are used worldwide to increase oil recovery from mature fields. These processes involve injecting fluids such as water and steam into the hydrocarbon reservoir to pressurize the reservoir and displace the hydrocarbon towards the production well. Over the last few years, carbon dioxide (CO_2) flooding has also been successfully used for EOR [1]. CO_2-flooding also benefits the environment by serving as a carbon capture and sequestration (CCS) method. Factors such as geology, formation permeability, and fluid viscosities complicate these EOR processes. To optimally develop these EOR processes, it is critical to map the fluid composition of the reservoir over time. This mapping can indicate the progress of the flood fronts, the sweep efficiency of the flooding process, and pay zones bypassed by the flooding process.

We recently introduced a novel borehole system for reservoir monitoring using transient electromagnetics [2] that can map the fluid dynamics of EOR processes. This paper describes how we used COMSOL Multiphysics to demonstrate the feasibility of the above reservoir monitoring system. We also show how COMSOL helps to better understand the underlying physics of the system. This understanding is invaluable for designing system parameters and for interpreting system measurements.

The remainder of this paper is organized as follows: Section 2 introduces transient electromagnetics and its physics. Section 3 presents the models and COMSOL simulations and their results that form the core of the feasibility study. Section 4 discusses the results of the feasibility study and puts them in context. Section 5 presents the conclusions of this work.

2. Transient Electromagnetics

Hydrocarbons and EOR fluids (water, steam, CO_2, etc.) have very different electrical resistivities. Therefore, electromagnetic technologies have the potential to map different fluids in the reservoir. Transient electromagnetics (TEM) measurements, in their simplest form, involve a transmitter and a receiver coil, often with some spacing in between. Figure 1 shows the basic principle of a typical TEM measurement system [3-5]. The transmitter is driven by a constant direct current for a sufficient length of time so that any transient effects, caused by switching on the current, die down. This generates a static primary magnetic field around the transmitter. Suddenly, at time t_0, the current is switched off. This abrupt change in the primary magnetic field induces an impulse of electromotive force (emf) in the formation. This emf causes eddy currents to flow in the formation. The electrical resistivity of the formation weakens the eddy currents and they diffuse outwards from the transmitter over time. The speed of the diffusion process increases with formation resistivity. The receiver coil measures the rate of change of the secondary magnetic field generated by the diffusing eddy currents in the time range $\tau \in [t_1, t_2]$. Thus, the primary magnetic field is absent while the receiver is measuring the signal emanating from the formation. This is an advantage of TEM that allows much smaller transmitter-receiver spacing. Our reservoir monitoring system exploits this feature by placing the transmitter and receiver in the same borehole. TEM systems are also inherently broadband, which enables a single transient to capture three-dimensional (3D) spatial information about the formation. TEM technology has been used in surface geophysics for decades [3], but the system discussed in this paper is the first single-well application of this technology.

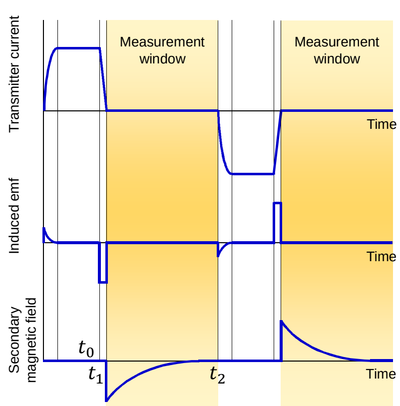

Figure 1. Basic principle of a typical TEM measurement system.

Neglecting propagation effects in the time range of interest, the governing equations for TEM diffusion are obtained by simplifying Maxwell's equations as follows:

$$\nabla \times \mathrm{H} = \boldsymbol{\sigma} \cdot \mathrm{E} + \mathrm{J}_e \tag{1}$$

$$\nabla \times \mathrm{E} = -\, {}^{\partial \mathrm{B}}\!/_{\partial t} \tag{2}$$

where $\mathbf{H}$ is the magnetic field intensity, $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic flux density, $\mathbf{J}_e$ is external current density, and $\boldsymbol{\sigma}$ is the electric conductivity tensor for an anisotropic formation. Introducing the vector magnetic potential $\mathbf{A}$ defined as $\mathbf{B} = \nabla \times \mathbf{A}$, we can rewrite equations (1) and (2) as

$$\boldsymbol{\sigma} \cdot {}^{\partial \mathrm{A}}\!/_{\partial t} + \nabla \times \mathrm{H} = \mathrm{J}_e \tag{3}$$

3. COMSOL Simulations of Borehole Reservoir Monitoring System

We use time-dependent studies in the AC/DC Magnetic Fields (mf) application mode of COMSOL 4.2a to simulate the borehole reservoir monitoring system. When solving models such as the ones described in this paper, the predefined mesh distributions do not work well. We need to define a reasonably fine mesh in regions of interest and those with high contrasts of electromagnetic properties, while ensuring a reasonably coarse mesh away from these regions. Furthermore, when using the transient solver, the default tolerances almost always need to be tightened. We model the transmitter as a line current loop with loop area A_{coil} and constant current $I = 1/A_{\mathrm{coil}}$. The current is turned on at time 0. Modeling the transmitter excitation as step-on rather than step-off is very convenient because then the initial condition can be set as $\mathbf{A} = \mathbf{0}$ everywhere. The step-on excitation does not affect the transient signals except for changing their signs. The receiver is modeled as a point at which the measured voltage is given by $V(t) = -\mathrm{d}B/\mathrm{d}t$. Hence, the transmitter-receiver moment-area product is unity. The boundary condition imposed on all external boundaries is magnetic insulation, $\mathbf{n} \times \mathbf{A} = \mathbf{0}$. The outer boundaries are placed far enough to not affect the solution in the region of interest. Practically, the domain size is set to be ten times the skin depth of the least conductive part of the formation at the lowest frequency of the acquisition spectrum (5 km for 1 Ω ·m formation and lowest frequency 1 Hz).

Figure 2 illustrates how eddy currents originate at the z-directed transmitter and diffuse with time in a homogeneous formation with unit resistivity. The line plots on the right show the corresponding transient signals measured by a coaxial receiver placed 10 m away.

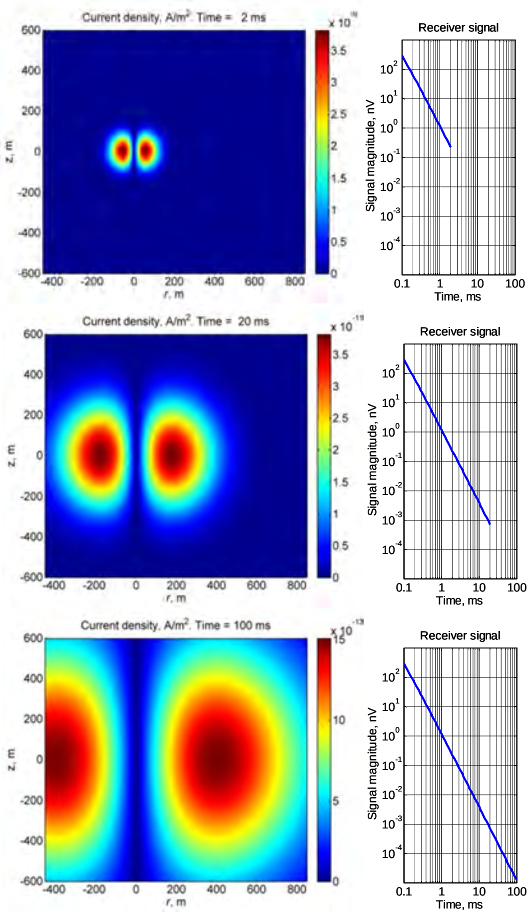

Figure 2. Eddy current density resulting from z-transmitter in homogeneous formation; and coaxial z-receiver signal at different times.

It can be shown that for homogeneous formation, at late time,

$$V(t) \propto \sigma^{\frac{3}{2}} \Big/ t^{\frac{5}{2}} , \qquad (4)$$

where $V(t)$ is the receiver voltage, t is time, and σ is the formation conductivity. Due to the huge dynamic contrast of the transient voltage, TEM signals are usually displayed on log-log scale.

3.1 Validation

We first validate COMSOL simulations for simple one-dimensional (1D) layered models with our in-house fast semi-analytical code. These validation models also provide rough estimates of the coarsest mesh that will still yield solutions with acceptable accuracy. Figure 3 shows a three-layer 1D formation model which is one of the many 1D formation models we used for validation. The middle layer is 10 m thick and the transmitter T is placed at its center, while the receiver R is placed 10 m away from the transmitter. The top and bottom layers have resistivity $\rho = 40\ \Omega \cdot \text{m}$ and the middle layer has resistivity $\rho = 0.5\ \ \Omega \cdot \text{m}$. In COMSOL, this formation with z-transmitter may be represented by a two-dimensional (2D) axisymmetric model. For an x- or y-directed transmitter, the COMSOL model would need to be 3D.

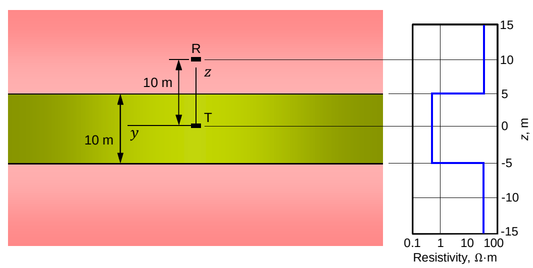

Figure 3. Three layer 1D formation model for validation of COMSOL simulations.

Figure 4 shows that the coaxial receiver signals obtained for this model from COMSOL and our in-house code are in excellent agreement throughout the time range. The small error at the very late time occurs because the domain size is still not large enough and the external boundaries influence the solution at the very end of the diffusion process.

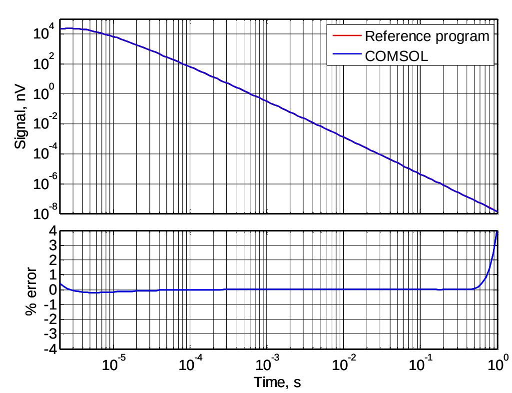

Figure 4. Coaxial receiver signals; and relative error in COMSOL solution.

3.2 Two-Dimensional Waterflood Model

Having built confidence in COMSOL TEM modeling, we proceed to the 2D waterflood model [2] shown in Figure 5. The top and bottom layers consist of shale (2 Ω·m resistivity) while the middle layer is a 10 m thick oil reservoir (40 Ω·m resistivity). Salt water with resistivity 0.5 Ω·m is injected through an injector well several kilometers away from the producer well. Neglecting heterogeneities in the reservoir, the floodwater front can be assumed to be planar as it advances from the right towards the producer well. We assume that the producer well is cased with a non-conductive non-magnetic material such as fiber-glass (at least near the reservoir). The transmitter T and receiver R are embedded over the well casing in or near the reservoir layer. For convenience, we position the transmitter in the middle of the reservoir and the receiver is placed 10 m away. The origin of the coordinate system coincides with the transmitter. The distance of the floodwater front from the producer well is denoted by D2B. This model is solved for different values of D2B to simulate the measurements as the floodwater front advances toward the producer well.

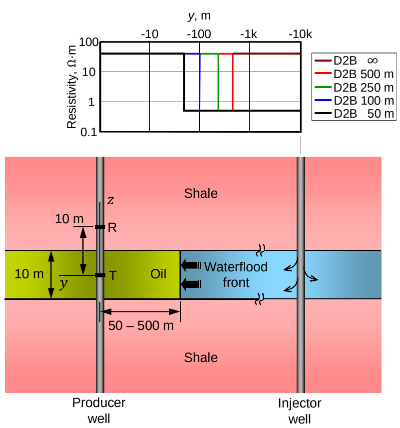

Figure 5. 2D formation model with TEM system in reservoir and floodwater front approaching from an azimuthal direction.

Incremental changes in transient signals over time, rather than the transients themselves, indicate how the floodwater front advances over time. Therefore, we define the incremental signal $\Delta V(t)|_{\mathrm{D2B}}$ as

$$\Delta V(t)|_{\mathrm{D2B}} = V(t)|_{\mathrm{D2B}} - V(t)|_{\text{no flood}} \qquad (5)$$

where $V(t)|_{\text{no flood}} = V(t)|_{\mathrm{D2B}=\infty}$. The incremental signal may also be considered the absolute sensitivity of the transient signal to the floodwater front position. Figure 6 shows the incremental coaxial (zz) signals and incremental cross (zy) signals for different values of D2B. The zx signals are all zero owing to the 2D geometry of the model.

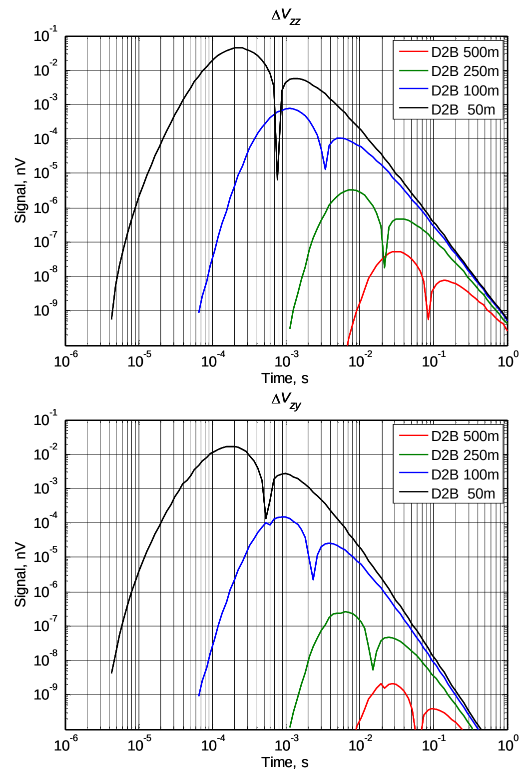

Figure 6. Incremental coaxial (zz) and cross component (zy) signals for different values of D2B.

3.3 Three-Dimensional CO_2 flood Model

In this section, we present a 3D model of a CO_2-flooded reservoir, as shown in Figure 7. In this case, the transmitter and receiver are embedded over the injector well casing. As before, the casing is assumed to be non-conductive and non-magnetic. The water-saturated reservoir is 10 m thick and has resistivity 2 Ω·m. It is sandwiched between shale layers with resistivity 4 Ω·m. CO_2 is highly resistive (100 Ω·m). The source of three-dimensionality in this model is the eccentric elliptical CO_2 flood fronts, as shown in the upper plot in Figure 7. Such flood fronts may be caused by inhomogeneous and/or anisotropic permeability in the reservoir. The flood front ellipses form different stages of CO_2-flooding as they increase in size. We define the incremental signal at Stage n as

$$\Delta V(t)|_{\text{Stage } n} = V(t)|_{\text{Stage } n} - V(t)|_{\text{Stage } 0} \quad (6)$$

where $V(t)|_{\text{Stage } 0}$ denotes the signal before CO_2-flooding has started.

Figure 8 shows the incremental coaxial (zz) signals and incremental cross (zy) signals for different stages. The zx signals are all zero because the model is symmetric about the y-z plane.

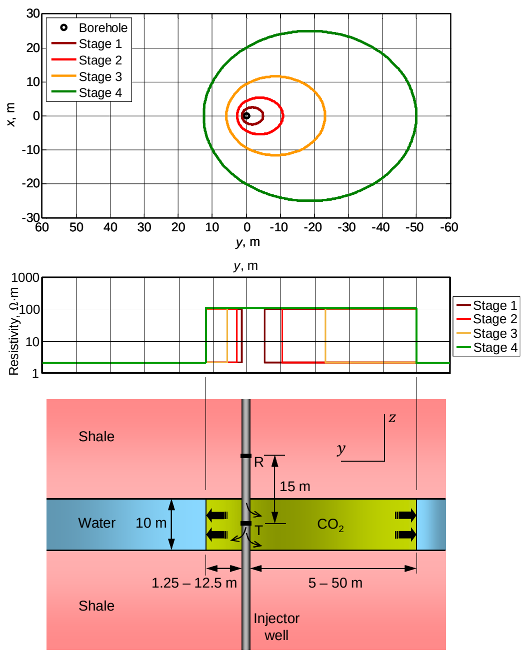

Figure 7. CO_2 flood front progressing elliptically; and 3D formation model with TEM system in a CO_2-flooded reservoir.

4. Discussion

We simulated the models of sections 3.2 and 3.3 for triaxial transmitters and receivers, but only presented simulated signals corresponding to the z-transmitters for the sake of brevity. It should be noted that all the incremental signals show some common characteristics. First, they are negligible at very early time. Second, they reach maximum amplitude after which they change signs. The sign change manifests itself as a notch (called a zero-crossing) on a log plot. However, the incremental signals from different cases vary significantly in terms of their amplitudes and their temporal characteristics. It is clear from the distinctive transient signals in Figures 6 and 8 that the borehole TEM reservoir monitoring system is sensitive to dynamic fluid distributions in the reservoir. Typically, simultaneous analysis of multiple transient components (main: xx, yy, zz; cross: xy, xz, yx, yz, zx, zy) can yield the extent, as well as azimuthal profile, of flooding. A detailed analysis or interpretation of the simulated signals is out of the scope of this paper. Instead, we focus on the insight that COMSOL provides us to the working of the borehole TEM reservoir monitoring system and the TEM diffusion process.

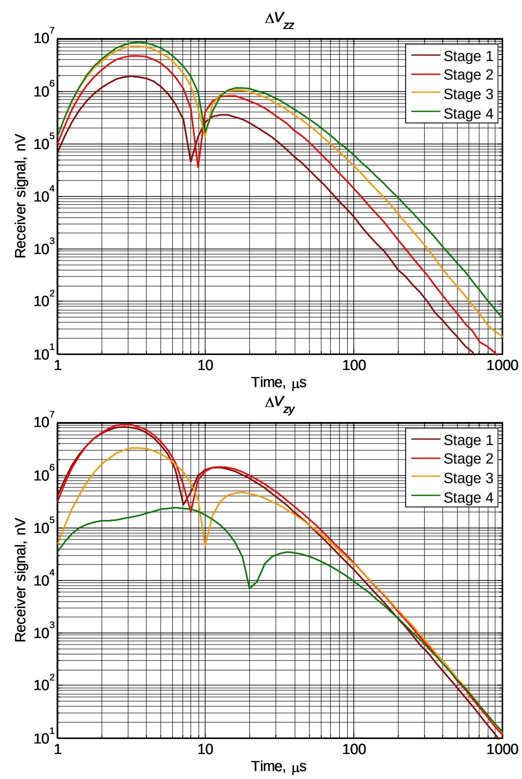

Figure 8. Incremental coaxial (zz) and cross component (zy) signals for different stages.

Consider the eddy current density colormaps in Figure 9. These plots correspond to the black curves in Figure 6 (D2B = 50 m). Note that the colormaps are normalized at each instant, as indicated by the colorbar amplitudes. From the plots in Figure 9, it is clear that eddy currents flow preferentially in more conductive parts of the formation. At 0.08 μs, the eddy currents are well contained in the resistive reservoir, very close to the transmitter. As soon as the eddy currents reach the conductive shale, they diminish rapidly in the resistive reservoir. By 4 μs, the eddy currents have diffused completely into the conductive shale. At this time, the currents do not 'see' the flood front. It is as if the flood does not exist. Therefore, at 4 μs, the current density map for D2B = 50 m is identical to that for D2B = ∞. Therefore, the incremental signal $\Delta V_{zz}(4\ \mu\mathrm{s})|_{50\ \mathrm{m}}$ is negligible as shown in Figure 6.

Now, consider the current density image at time 83 μs. By this time, the currents have 'seen' the extremely conductive waterflood front. Over the next few hundred microseconds, the current density will diminish inside the shale layer and increase in the flood zone. During this time, the current density image is the most different from the one with no waterflooding. Consequently, during this time the incremental signal $\Delta V_{zz}(t)|_{50\ \mathrm{m}}$ would have the maximum amplitude, as shown in Figure 6. The currents rapidly decay in the conductive shale layer, but develop very slowly in the waterflood zone close to the flood front (recall that TEM diffusion is slower in more conductive formation). As the eddy currents penetrate deeper into the flood zone (see current density map at 469 μs), gradually the current decay in the shale layer becomes less significant and is soon dominated by the current development in the flood zone. This crossover behavior causes $\Delta V_{zz}(t)|_{50\ \mathrm{m}}$ to change its sign and we see a zero-crossing in $\Delta V_{zz}(t)|_{50\ \mathrm{m}}$ (Figure 6) at approximately 800 μs.

As the distance between the flood front and the borehole increases, the amplitude of $\Delta V_{zz}(t)$ decreases and the zero-crossing shifts to a later time. This distance-to-time mapping offers an intuitive way to interpret TEM signals from the formation.

Some practical considerations are also worth mentioning here. The incremental signals in Figure 6 are in the femto Volt range, which is too small to reliably measure. However, recall that these simulations were done for unit transmitter-receiver moment-area. In practice, we have the technology to obtain an effective transmitter-receiver moment-area of 10^5 Am^2. Furthermore, flood fluid movements in the reservoir are typically slow (in the range of months to years), whereas each transient signal is acquired in less than 1 second. Therefore, heavy stacking and filtering is expected to increase the signal-to-noise ratio to an acceptable level.

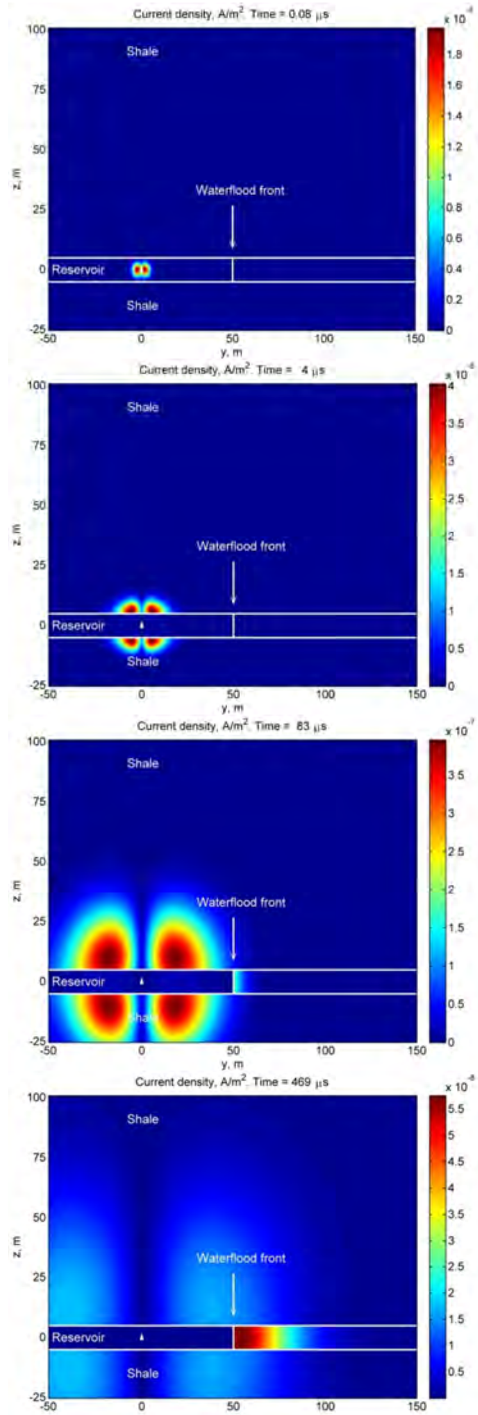

Figure 9. Time-lapse current density maps for the 2D waterflood model.

5. Conclusions

This paper presented the simulation and analysis of a borehole transient electromagnetic reservoir monitoring technology. This technology has the potential to map changes in fluid distribution in reservoirs over time. COMSOL played a critical role in demonstrating the value of this technology in realistic models of enhanced oil recovery and carbon capture and sequestration. In this paper, we described these models and how we used COMSOL in this feasibility study. With the help of COMSOL, we not only proved the efficacy of this technology, but also delineated the behavior of the transient electromagnetic diffusion process in the presence of resistivity contrasts. We plan to continue to use COMSOL to study more reservoir monitoring benchmarks as well as to optimize multi-sensor placement in wellbores.

6. References

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