Long Offset Transient Electromagnetic (LOTEM) for monitoring fluid injection in petroleum reservoirs – Preliminary results of Fazenda Alvorada Field (Brazil)
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This paper was prepared for presentation at the 10th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 19-22 November 2007.

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Abstract

This work presents the preliminary results obtained using LOTEM (“Long Offset Transient Electromagnetic”) method in a producing petroleum field in Northeast Region of Brazil (Bahia State). The main goal of the study is to produce subsurface images for monitoring fluid injection after EOR (Enhanced Oil Recovery) operations. Five stations were selected, and a careful processing was applied in all of them to remove noisy data. A preliminary one-dimensional (1D) interpretation was done using forward models, where it was possible to observe oil/injected water contacts.

Introduction

Fazenda Alvorada field is a mature oilfield located at the North of Bahia Sate, in the Recôncavo Basin, Northeast Brazil. As it is an old reservoir, enhanced oil recovery techniques are often applied to increase production. Most common techniques consist in inject water or water steam. In the case of Fazenda Alvorada field, salty water was injected to displace the oil in the reservoir. On the other hand, the use of geophysical electromagnetic techniques to image fluid injection is not something new. LOTEM surveys for that purpose were performed in Mexico (Cardadora et al., 2003) and Australia (Strack et al., 1989), for instance. Frequency-domain (multi-Frequency) techniques were also used in Fazenda Alvorada area (Dias et al., 2006). The high constrast of electrical properties between the oil and water (salty water) generally provides enhanced subsurface images where is often easy to observe the oil/injected water contact. Unfortunately a producing oilfield is quite often a high noise area. Limitations of gain to avoid signal saturation needs to be applied in some cases, restricting receiver (RX) sensibility. To keep a good data quality some cautions must be taken regarding to data acquisition (variations in station location and stacks) and processing (filtering). In the case of data interpretation, 1D models could not produce such a detailed image of subsurface layers as 2D or 3D models, but are faster and can provide preliminary approach, helping to reveal the main subsurface structures.

Geology Framework

Recôncavo Basin is the place of the first major discovery of petroleum in Brazil. It’s located in Brazilian North-East region, spreading out through 11,000 km² in on-shore of the state of Bahia, between 11°30’ and 13°S parallels. It’s separated from the Turano Basin, northward, by the Aporã High, and separated from the Camamu Basin, southward, by the Barra Fault (Figure 1). It is also bounded by pre-cambrian outcrops, through Salvador (eastward) and Maragogipe (westward) fault systems. During 50 years of exploration, 5,400 wells were drilled and roughly 31,290 Km of 2D seismic lines and 762 km² of 3D seismic lines were surveyed. Due to that great amount of datasets, this basin is classified as a “school-basin” (Antunes, 2003).

Figure 2 shows a geologic cross-section of the studied area, where it's possible to observe the petroleum reservoir (Sergi Fm. – orange), the sealing formations (Candeias and Água Grande – green) and other sedimentary structures as: below the reservoir (Aliança Fm. - pink) and at the top of the cross-section (Barreiras Fm. - yellow), and the granite basement (red). Comercial production started at the early 1940’s, resulting in 80 accumulation discoveries. Two petroleum trends, in NE-SW and NW-SE directions can be seen in Figure 1, which shows the distribution of the oil and gas fields in the basin, Candeias Fm. Shales (mainly TAUã Mb.) are the generators. Main oil-kichens are placed at structural lows (Camaçari, Miranga and Alagoinhas-Reconcavó Basin has three main petroleum systems: pre-rift, rift-Candeias and rift-llhas, with 15 different exploration plays. The basin architecture in horsts and grabens puts the pre-rift reservoirs, which are located at the highest blocks, in lateral contact with the generators shales. In this case there was a direct migration. The same occurs with the reservoirs surrounded by Gomo Mb. Shales (rift-Candeias). In the rest of the situations migration occurred through the faulting system. Pre-rift system (Sergi, Água Grande and Candeias Fms.) represents 60% of oil proven reserves (2.7 billions of barrels). Sergi Fm. is the main reservoir (fluvio-elic), with mean porosity around 18% and mean permeability around 800 md. Main fields of this system are Dom João, Água Grande and Buracica. Rift-llhas system represents 25% of the proven reserves. Main fields are Miranga, Araçãs and Taquipe. Rift-Candeias system represents 15% of oil proven reserves. Main fields of this system are Candeias, Riacho da Barra, Fazenda Balsamo, Rio do Bu and Fazenda Alvorada (Antunes, 2003).

Methodology

In this work, the LOTEM (“Long Offset Transient Electromagnetic”) technique was used for imaging subsurface. In this technique, the distance between transmitter (TX) and receiver (RX), known as offset, is
approximately equal to or larger than the exploration depth (Strack, 1992). The transmitter consists of an electric dipole, generally tens of meters or kilometers long (Figure 3). The most popular TX configuration is a grounded electric dipole, which is connected to a motor-generator able to produce electrical currents between 5-100 Amps. A synchronization unit (clock) changes polarity in certain times ("t"), generally at two seconds. RX's are generally connected to air loops or coils used for detect the vertical magnetic field (Hz) in some sites (stations) along a profile. Some systems were also able to measure the 2 components of horizontal electrical field. Apparent resistivity can be estimated from the voltages measured at the receiver (U), the TX-RX offset (r), the coordinate perpendicular to the dipole (y), the injected current (I) and effective coil area (A). Equations (1) and (2) show how is possible to estimate apparent resistivities for early times and late times (t \rightarrow \infty) (Strack, 1992), using the vertical magnetic field measurement.

\[ \rho_{ET}^{L} = \frac{2\pi I^5}{3D_0Ay} U(t)_m, \]  

\[ \rho_{ET}^{L} = \left( \frac{D_0Ay}{40\pi \sqrt{\pi U(t)_m}} \right)^\frac{2}{3} \left( \frac{\mu_0}{t} \right)^\frac{5}{3}, \]  

where \( D_0 \) is the transmitter dipole moment. More details of LOTEM method can be found in Caldwell & Bibby (1998), Commer (2003), Hördt & Muller (2000), Hördt et al. (1992), Hördt et al. (2000) and Sheng (1986).

**Field Data Acquisition**

The equipment used consisted of a T-15 transmitter and a V-5 Receiver manufactured by Phoenix Geophysics Ltd. Maximum current injection in field conditions was 11 A, using 660 V. TX dipole consisted in 1 Km of wire, connected to 5 aluminum plates in each side (Figure 3). The plates were placed in holes of 0.5 m depth. Salt water were scattered bellow and above the plates, in order to minimize contact resistivity. TX signal was a quarter-sinusoidal (fin) wave type, with a 32 sec period and 275 msec turn-off time. TX remained at the same site during the whole survey. A square multi-turn air loop consisting of 50 coils were used for detect the vertical magnetic field (Hz) in some sites (stations) along a profile. That loop was connected to a V5 receiver unit, which controls the data acquisition and storage process. Coil spacing is roughly 100 m. Minimum T-R offset was 1000 m. As the area is a functional petroleum field, it’s common to find power lines, electric pumps, radio communications devices, metallic pipelines, which worked as noise sources. We try to keep as far as possible from those noise sources, moving the station site whenever it was needed. In some cases, due to tough topography, it was necessary to use stakes to keep the loop as plane as possible.

**Data Processing**

Basic processing of LOTEM (Strack, 1992) data consists of:

1. Editing (Deletion of noisy data);
2. Stacking;
3. Filtering (mainly recursive);
4. System response correction.

Those steps were performed using the TETX software, developed by Phoenix Geophysics Ltd. The best results were achieved when the decay curve is clearly observed, for this reason the number of stacks we used varied between 60-100. The measurement of 100 stacks took 1 hour. For this work full dataset stacking was used instead of selective staking. Main source noises were the 60 Hz and its harmonics (120, 240, 300, etc.). A recursive notch filter was used to eliminate those noises. System response was obtained at the field running a calibration measurement with the receiver very close (30-40 m) to transmitter dipole, close enough to get ground response. After that, V5 automatically run the system response correction.

**Data Interpretation**

Figure 5 shows 1-D forward modeling results, obtained through the MODALL software from Elsevier Science Publisher (Strack, 1992). The measured (observed) data is also plotted in the same figure for comparison. It’s possible to observe that there are good matches for all the stations. The worst result was for station E700, probably due to buried pipelines nearby. Best match occur at station 500. Figure 6 shows the final 1D model used for the comparison showed in Figure 5. The reservoir (Sergi Fm.) seems to be at the blocks with resistivity higher than 300 ohm.m. Low resistivity values \( \leq 5 \text{ ohm.m} \) could be associated to shales of the formations: Candeias and Água Grande, which are above the reservoir; Aliança, which is below the reservoir; and Itaparica, which separates reservoir in two parts. The 30 ohm.m blocks represents part of Sergi Fm. where the water content is high. Basement is not observed, once the signal seems to be trapped by the low resistivities of Aliança Fm. Figure 6 shows a resistivity section obtained using an inductive multi-frequency (Frequency-Domain-FD) equipment (Dias et al., 2006). Dotted square marks the same area, of LOTEM stations. Our results seems to be in a good agreement such to the multi-frequency (Figure 7) as well as the geological cross-section displayed at Figure 3.

**Conclusion**

This work aims to present a preliminary results of the results obtained with a LOTEM field campaign in a producing petroleum field in Northeast Region of Brazil. Data quality was reasonably good at the 5 stations presented, although it was a noisy area. Preliminary interpretation was done using 1-D forward models with a good overall match with the observed data. The reservoir, the surrounding sealing shales and oil/injected water
contact could be observed. Basement was not observed at the 1D models. Association of the layers to the geological formations were done only considering the geological cross-section (Figure 3) and resistivity values, provide by the 1D models. Comparison to the results of another EM method (inductive multi-frequency) also showed a good agreement. We hope that further works could gather information from boreholes and other geophysical methods, datasets from other stations and other profiles. Thus, more detailed models could be tested. Topography correction was not performed in those models. Maximum level difference was approximately 30 m for station E400, and 2 m for other stations.

Acknowledgments

This work was supported by PETROBRAS/UFBA through a research project: “Avaliação da resposta eletromagnética de reservatórios de petróleo submetidos à injeção forçada de fluidos”. The authors would like to thank: Marco Schinelli (PETROBRAS); Phoenix Geophysics Ltd. – Toronto/Canada, specially Leo Fox, Carlos Guerrero, Mitsuro Yamashita and Lu Yi; UENF/LENEP and UFBA/CPGG. We are also very grateful for Prof. Carlos Dias for our valuable discussion and the field technicians Remilson Rosa and José Mota for their dedication during the fieldwork.

References


Figure 3 - LOTEM acquisition layout.

Figure 4 – Field Acquisition layout.

Figure 5 – Plots of the observed data and 1D forward modeled results.
Figure 6 – 1D forward model used to produce results showed in Figure 5.

Figure 7 – Resistivity section obtained using inductive multi-frequency technique. Dotted area is the same of the LOTEM stations presented here. Modified from Dias et al., 2006.