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Using Electromagnetics to Map Lateral Fluid Variations in Carbonates in SE Asia

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ABSTRACT

Exploration for hydrocarbon is often difficult when the overlaying strata is of high seismic velocity as it is for basalt, salt and carbonates. Many the world reservoirs are in carbonates. Mapping the reservoir laterally is thus difficult and developing carbonate reservoirs is expensive. We propose to use controlled source electromagnetic (CSEM) method to image the fluid better.

In SE Asia commonly magnetotellurics, a passive method, is being used [1], but they are less sensitive to deep subsurface resistivity variations as CSEM. Pioneering work with CSEM was done in the 1980s in Australia and Europe [2] where CSEM was used to map resistive reservoirs / carbonates. Since then, the equipment and modeling methods have significantly improved, and the problem is addressed more cost effective thus reducing exploration cost by several fold.

Applying a new differential measurement methodology and using 3-dimensioanal (3D) anisotropic model derived from well logs and 3D modeling we are able remove near surface anomalies and illuminate the deep the reservoir target and its lateral variations. Thus, we have a cost-effective solution for many exploration and production problems associated with carbonates.

Keywords: Controlled source electromagnetic; porosity mapping; carbonate exploration; differential measurements.

1. INTRODUCTION

Electromagnetics (EM) has been historically used for hydrocarbon exploration problem since the 1920s [3,4]. Historically, electric field measurements are used with distances between the current injecting electrodes of 2-3 times the depth of exploration. The large-scale averaging limits the usefulness of the methods. Magnetic fields which were also sometimes used mostly respond to strong electric current flowing in the more conductive part of the subsurface [3]. Passalacqua [5] and Eadie [6] studies the effect of thin resistive layers on the electromagnetic signal and noticed that above thin hydrocarbon bearing reservoir we can see an enhanced anomalous response. More recently, Passalacqua et al. [7] applied this to water flood of oil reservoirs. Vozoff et al. [8] carried out one of the first surveys of combining EM with seismic in a more thorough way in Western Australia. Key to their success was a thorough analysis of the seismic and log data and deriving a detailed modeled with 22 layers – very unusual for that time. Fig. 1 shows this log and the resulting layered model. The layer boundaries were derived almost exclusively from seismic data alone followed then by forward modeling. A subsequent test of the methodology with more input from the EM sensitivities was carried out over an oil field in Southern Germany [2]. While the results were not as spectacular as in Australia, the well logs of several wells were matched for both magnetic and electric fields. The data also showed that both magnetic and electric field contribute to the information content with the electric field dominating in the resistive / oil bearing strata and the magnetic field in the more conductive / brine nearing ones. Later, when developing CSEM for marine applications, similar sensitivities were reported by Eidesmo et al. [9] and Constable [10]. They are the main reason for the commercial success of marine CSEM.

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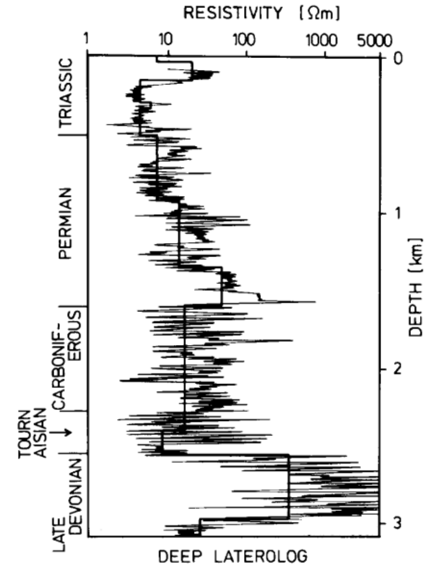
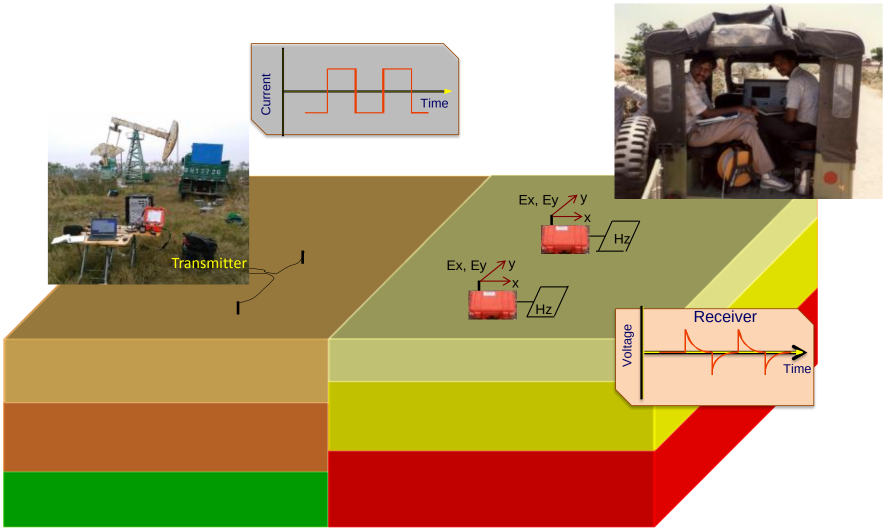


Fig. 1. Resistivity log from the survey in Western Australia (Kora) and the equivalent resistivity model (heavy solid line). The layer boundaries were fixed using seismic interpretation (after Vozoff et al. [8])

A typical CSEM survey layout is shown in Fig. 2 with a grounded dipole transmitter and multicomponent EM receivers. The method uses the time domain EM where an induction current propagates downwards and outwards with time. While Strack [3] still assumes the distance between transmitter and receiver (offset) had influence on the depth of investigation, Spies [11] showed that it did not, as the same target reservoir will show up at the same time window (though the amplitude varies with offset). At that time acquisition system were not fine-tuned enough to exploit that like any standard system nowadays [12]. The method we use is known as Lotem [13] for Long Offset Transient EM, but the offset has little influence. A typical survey setup is shown in Fig. 2. To recognize 3D structures or lateral variations, offset plays an important role because you want to minimize the effects caused by structures between transmitter and receiver. One way to overcome this, is to acquire time-lapse data and focus on variations in the reservoir fluid content. In this case, the 3D structure does not change, and their response can be subtracted leaving only the anomalous reservoir response. While there were many correction attempts [3,14], the real answer will only come from realistic 3D fully anisotropic models where the models are consistent to the measurements inside the reservoir on reservoir-scale. Consistency is obtained via calibration; thus, we start with the borehole logs to obtain insight into the sensitivity of the different measurement components. We carry out a petrophysical analysis of the log and establish layer boundaries consistent with the logs. Then, we scale the log data including EM sensitivities yielding an anisotropic model which, with geology and seismic, gives the 3D anisotropic model.

2. BACKGROUND METHODOLOGY

We prefer to use CSEM in the time domain as it focuses the available energy at any given time to a limited volume. The grounded dipole transmitter generates horizontal and vertical induced current system that then generates a secondary response mostly from resistivity contrast at the layer boundaries shown in Fig. 2. Typically, the currents injected are between 50 to several hundred Amperes. At the receiver we measure the EM response. While we can measure all components, it is sufficient to measure two electric field in horizontal direction, Ex and Ey, and the time derivative of the vertical magnetic field, Hz. The current switching is repeated to obtain multiple measurements that get averaged for improved Signal-to-Noise ratios. To interpret the measurements, we need the Earth's model which we derive from the log as illustrated in Fig. 3. In the figure on the left, we have the resistivity log. When only a standard resistivity log is available, we still can derive the anisotropy from the cumulative transverse resistance (sum of resistivity -thickness product of all layers) and the cumulative conductance (sum of conductivity -thickness product of all layers) to obtain equivalent conductances and resistances as shown in the example in Fig. 3 [15,3]. Here, we interactively adjust layer boundaries (consistent with petrophysical analysis) to fit each layer to a straight line. The cumulative conductance produces the horizontal resistivity, Rh, for the model and the cumulative resistance the vertical resistivity, Rv. These values are the end members of all possible models explaining this log.



Fig, 2. Typical survey setup for a CSEM system. Here, a time domain system is depicted with a grounded dipole transmitter and multi-component receiver. The respective current waveforms are shown for the square wave current injection and the received voltages (magnetic field exemplary). Also shown are picture of the equipment in the field

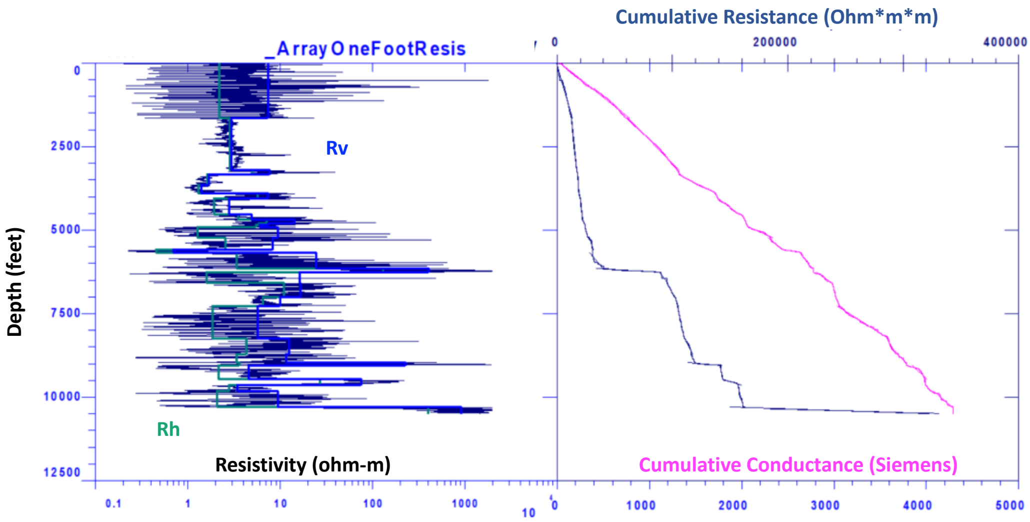


Fig. 3. Example of analyzing the resistivity log and generating an anisotropic model. On the left: the model derived from the equivalent model resulted from fitting the cumulative curves on the right layer-wise

Inclusion of seismic data and geology gives the lateral extend of the model. In the absence of seismic data, we must estimate lateral variation from known geology and boreholes. Fig. 4 shows another example where this is done in two steps: once for the entire logging interval and then again in detail for the reservoir section. Because of the potentially high resistivity contracts, it is important to carry this out in detail because even a small layer at great depth could have a large effect on the data at surface if the resistivity contrast is high enough. On the right of Fig. 4 is the 2D view of the 3D model which includes a reservoir. We assume the model extends laterally in the same fashion.

Usually for EM methods an offset between transmitter and receivers of 3-5 times the depth of penetration is used. To map lateral fluid variations in carbonates, we want to reduce the offset (using time domain methods) to understand where the information comes from. For this we use a methodology called Focused Source ElectroMagnetics (FSEM) [16-19]. It employs differential measurements sensitive only to the volume below the sensors similar as it is done in focused borehole logs [20]. This means that we relatively enhance the anomaly from the reservoir and subtract near surface and other effects not of our interest.

Fig. 5 shows 2D sensitivities for standard CSEM setups for frequency domain (top left) and time domain (bottom left), and 2D sensitivities for the FSEM setup for both frequency (top right) and time (bottom right). We can see that for the frequency domain in CSEM setup the sensitivity comes from between transmit and receiver. In the time domain CSEM but we have two preferred sensitivity volumes, one below the transmitter and one below the receiver. On the right of the figure, we apply 3-electrode receiver, i.e., take the difference between two electrical dipole measurements close to each other. Then the resulting sensitivities straight below the receivers. Thus, with FSEM we are getting predominantly information from below the receiver.

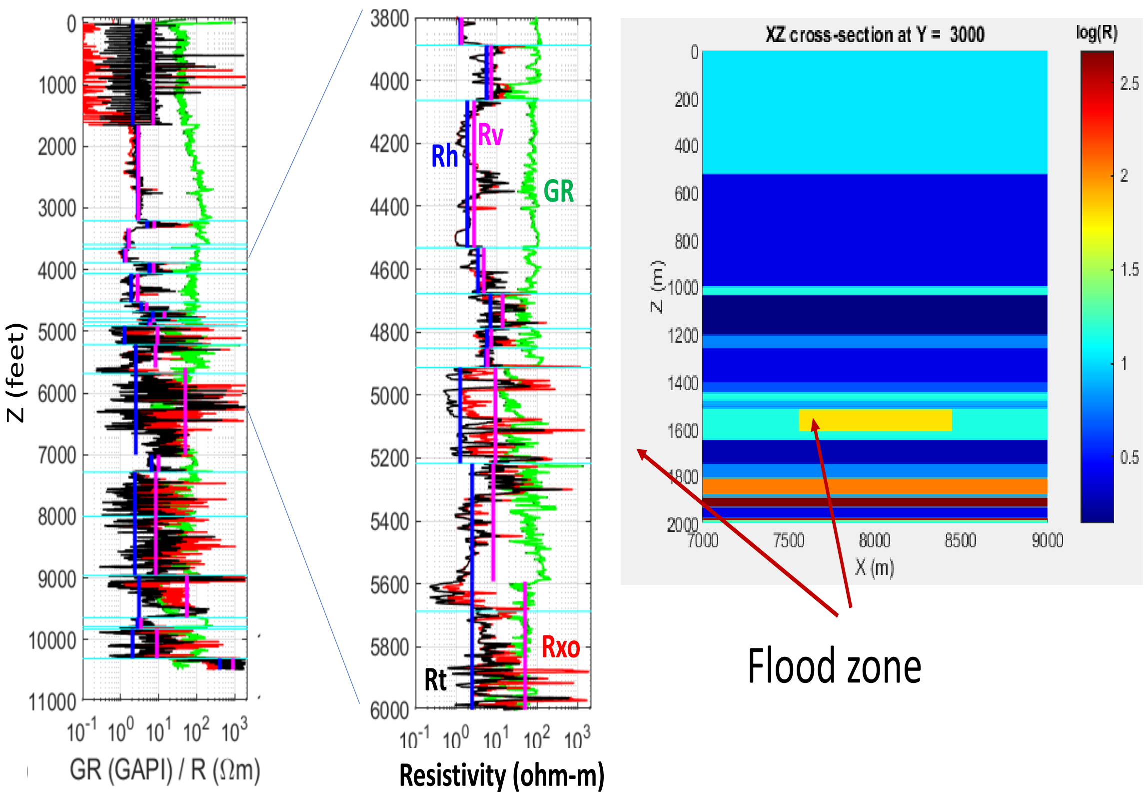
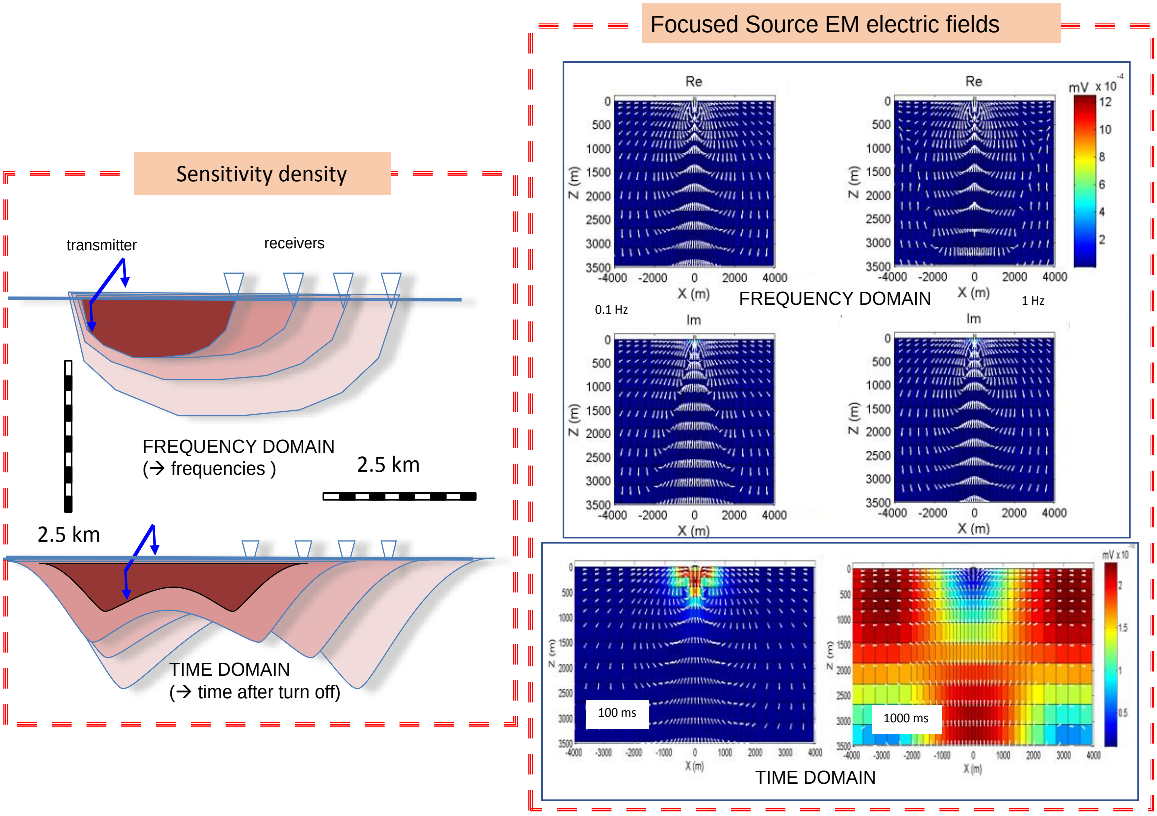


Fig. 4. Generating a layered anisotropic model from a resistivity log. On the left superimposed on the logs is the blocky model. On the right is the cross section of the 3D model that includes also the reservoir zone (Flood zone).

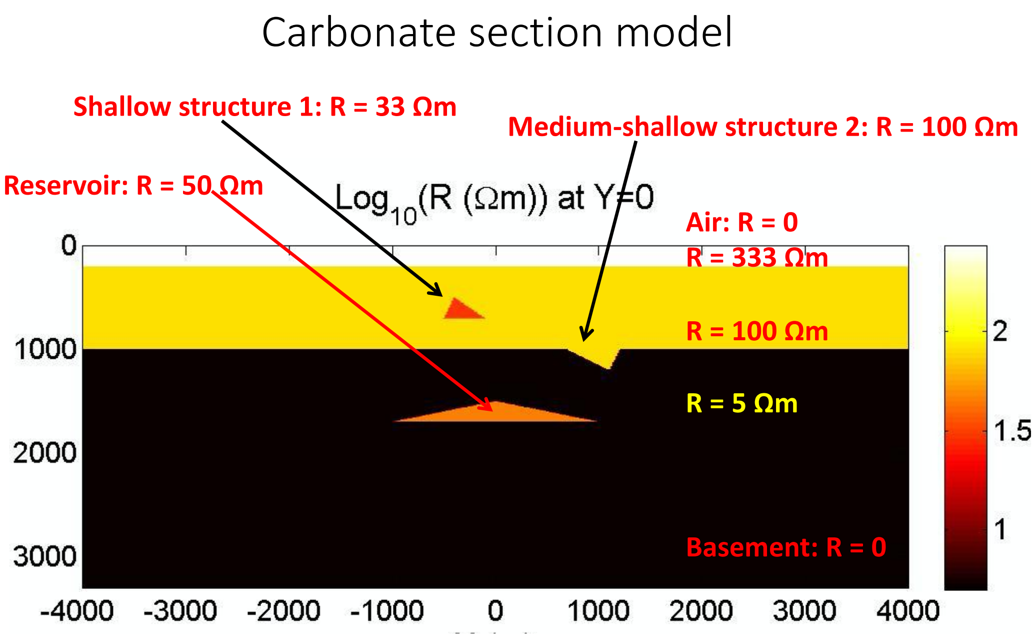


Fig, 5. 2D sensitivities for time and frequency domain CSEM methods (left) and for differential measurements which we call Focused Source EM (right) Receiver sites are marked by the triangles. For frequency domain, they show that the sensitivity depends on transmitter-receiver offset and for time domain we obtain information for a volume below both transmitter and receiver. When we employ the FSEM measurement mode on the right, we see that the information comes from mostly directly under the receivers

3. MAPPING POROSITIES IN CARBONATES IN SE ASIA

In SE Asia, there are several areas where mapping carbonates is important. In Western Australia, an application to map lateral fluid variations is described by Vozoff et al. [8]. In Indonesia, several oil fields have carbonate reservoirs and large in-fill drilling programs have been reported [21]. In Papua New Guinea mapping near surface lateral variation are causing big problems with static corrections of seismic and EM data [1]. Finding the sweet spots and imaging the fluids inside carbonates is important as seismic is not very accurate due to the high velocities in carbonates [22]. Similar exploration problems exist around the Saudi Arabian carbonate platform [14]. Since the geologic details of these oil fields are proprietary, we selected an oil field from Papua New Guinea which represents all these field as analogue. The reservoir is in Jurassic sandstones with overburden of 1000-1500 m of carbonates and 800-1500 m of shales [23]. The resistivities were taken from magnetotelluric data by Hoversten [1]. We included in the model shallow structures whose effect happens to be very strong: they change the standard CSEM inline dipole-dipole response beyond recognition, as shown in Fig. 6.

As aforementioned, the focus of the information is always of great concerns. We thus calculated 2D sensitivities for frequency and time domain CSEM and show here the time domain results as the response is slightly stronger. The target is approximately 1500 m deep: See the model in Fig. 6. The modeling is based on a program published by Davydycheva and Druskin [24].



.**Fig. 6. 3D model setup of the carbonate model with near surface inhomogeneities. The resistivity values represent typical SE Asia carbonate fields**

Fig. 7 show the anomaly due to a resistive reservoir for both 'complete' (cross-dipole receiver) and 'axial' focusing (3-electrode receiver in-line with transmitter) and for standard LOTEM applied to the model in Fig. 6. The anomaly is significantly enhanced by at least a factor of 6 and more. Next, we include an unwanted near surface inhomogeneities to the model. The CSEM response in Fig. 8 is clearly influenced by near surface effects.

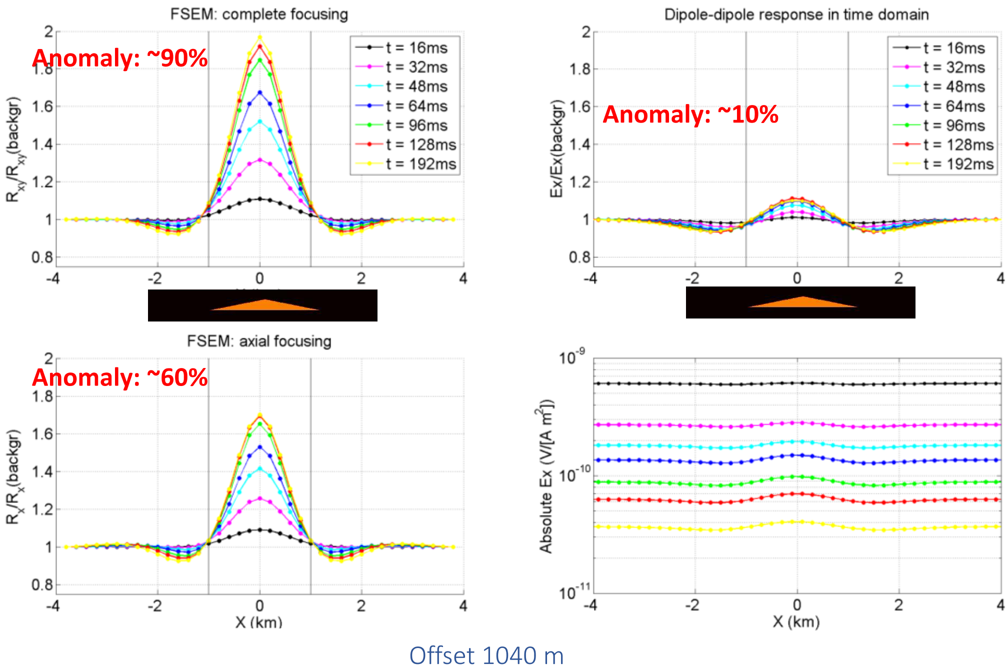


Fig. 7.3D model response along the profile above the model in Fig. 6. for FSEM 'complete' and 'axial' focusing and standard Lotem inline electric fields

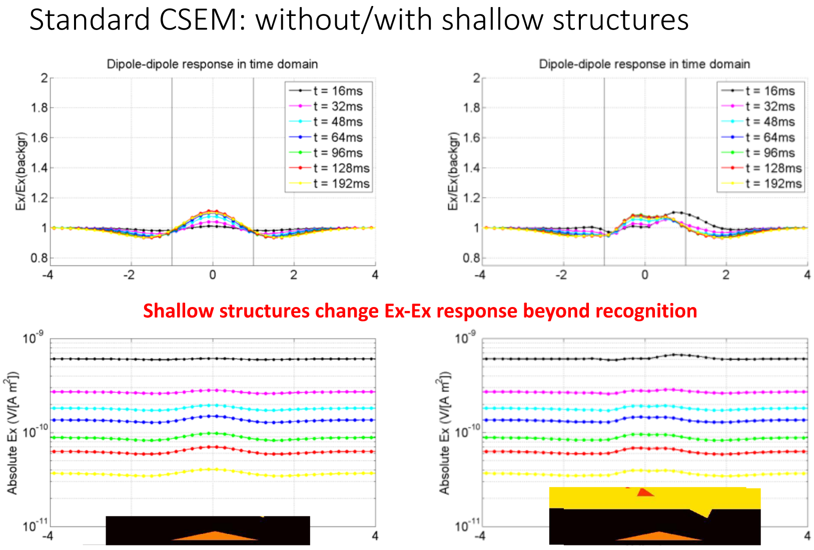


Fig. 8. 3D model response along the profile above the model in Fig. 6. without (on the left) and with near-surface structures (on the right). The Lotem setup was used

Fig. 8 demonstrates that the Lotem response is strongly affected by the shallow structures, which disturb the curve shape. Displayed are different decay times after current switching.

Fig. 9 shows FSEM responses to the same models. The anomaly is much stronger and we clearly can see that responses of the shallow structures are time separated from the deep ones. The anomalies in Fig. 9 are stronger than in Fig. 8 and lateral subsurface location can be read directly from the curves.

We then subtract some responses at earlier and later times. This removes the shallow effect as shown in Fig. 10. There are still some minor indications of the near surface seen in the larger side lobe.

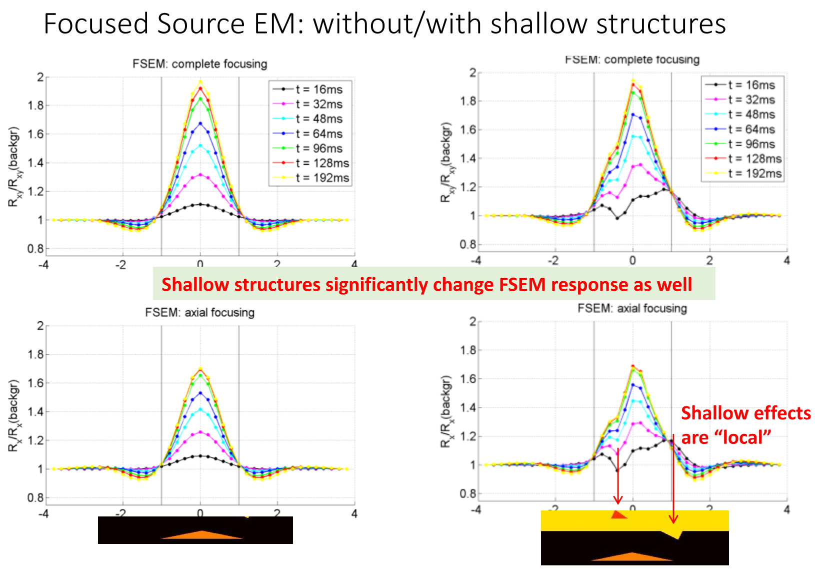


Fig. 9. 3D model response along the profile above the model in Fig. 6. without (on the left) and with the near surface structures (on the right). The FSEM setup was used

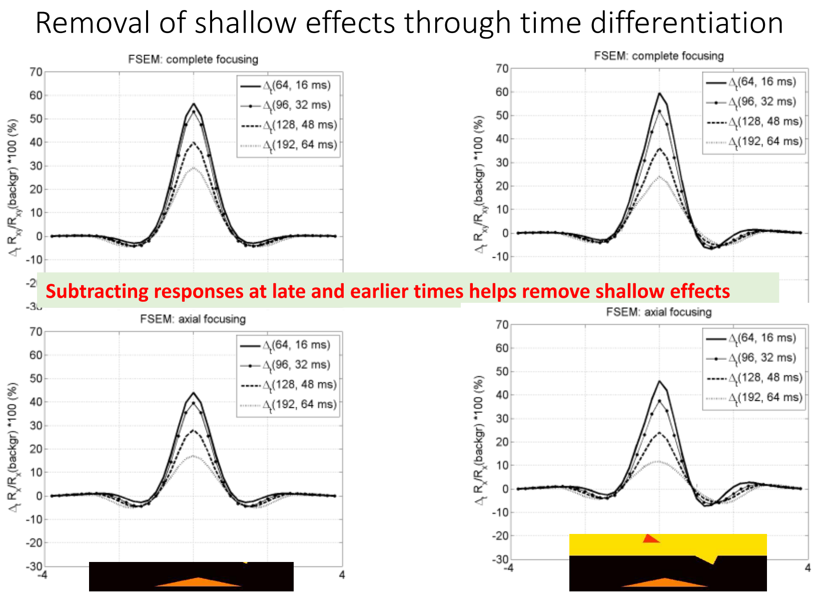


Fig. 10. 3D model response along the profile above the model in Fig. 6 without (on the left) and with the near-surface structures (on the right). The unwanted shallow effects have been subtracted

4. CONCLUSION AND OUTLOOK

Seismic has difficulties imaging fluids in carbonates due to the high acoustic velocities. While electromagnetics has been used to address this problem for about 40 years, the limitations are low EM sensitivities and near-surface effects. We combine the application of new focusing and 3D modeling methodology coupled with modern acquisition technology.

The sensitivity can be addressed by selecting a controlled source method that is sensitive to both the near surface conductive anomalies as well as hydrocarbon related resistive variations. We then take differential measurements and couple them with a 3D anisotropic model derived from logs to get highly accurate response. Differentiation of the measurements and removal of the early-time anomalies allows us to focus our subsurface image mostly on the reservoir.

Considering that new equipment acquires the data Cloud based in real time, we can now apply complex imaging even during acquisition quality control.

Similar application can be shown for sub-basalt imaging [25] and for sub-salt applications [26,27].

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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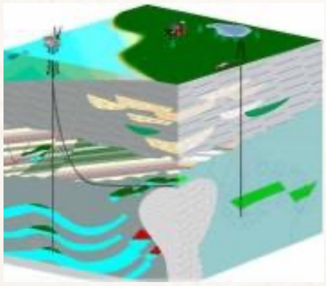

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