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Assessment of the Behaviour of Surface to Borehole EM Telemetry in Horizontal Well

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Hydrocarbon exploration has evolved over the years from shallow subsurface to deep subsurface prospecting in both onshore and marine environment. In accordance, technical development has encouraged exploration of unconventional reservoirs and development of deeply buried ones. The deeply buried carbonate reservoir in the Tarim Basin have attracted considerable attention (Lee, 1985; Neil, 1997; Jin et al., 2009, 2015). Such deeply buried reservoirs requires careful and accurate well landing and borehole navigation through multiple regions of HC accumulation and precise well closing process involving accurate selection of positions for screens and so on.

Success of directional drilling operations relies increasingly on two way data transmission from the bottom hole assembly (BHA) to the surface. The transmitted data are responsible for effective drilling operation and the quality of the borehole in terms of structure sustenance and in placement relative to the payzone. Therefore, for effective real time characterization, accurate well placement and effective exploitation of HC reservoirs, two-way communication of specific information to be transmitted on demand must be transferred in real time with appropriate speed. Electromagnetic telemetry (EMT) is the bi-directional transmission of data from the BHA to the surface as electromagnetic signals. The EMT system is used as an evolving technology for measurement while-drilling (MWD), especially in horizontal drilling to offset breaks in mud pulse transmission and increase transmission rate (Lee, 1985; Neil, 1997; Jin et al., 2009). EM signal are transmitted through the drill string, well casing and the formation adjacent to the wellbore. However, the transmitted signals are greatly influenced by attenuation due to formation and mud conductivity, and surface properties. Hence, EM telemetry is most reliable in areas where formation and mud properties cooperate. Therefore, simulation of EM telemetry behaviour turns out to be indispensable in designing and optimizing an electromagnetic telemetry system, and evaluating the feasibility and guiding a successful deployment for specified well configuration.

Several studies on BHA to surface EM telemetry (to be refered to as uphole EMT in this paper) has been carried out over the years (Xia and Chen, 1993; Schnitger and Macpherson, 2009; Willgoos, 2017; Hughes, 2018; Zeng et al., 2018), with little consideration on surface to BHA transmission (to be refered to as downhole EMT in this paper). Therefore in this study, we assessed the behavior of downhole EM telemetry in deep subsurface prospecting and the characteristics of uphole EM telemetry with repeater system. Also, we evaluate the performance of downhole EM telemetry when there is sudden water influx into adjacent formation during directional drilling.

Frequency domain simulation tool in Comsol multiphysics software (DeGauque et al., 1987), which was designed using the Finite element (FE) method, was used for the simulations carried out in this study. Perfectly matched layer boundary condition was implemented at the outer surface of each work space. Also, a large number of elements were created with scaling for finer meshes to be used near the borehole. Fig. 1 shows the model representation used in this study. For this study, the underground formation is assumed to be horizontally layered media.

The main objective of this section is to understand the characteristics of downhole EM telemetry (as defined in this abstract) in deep horizontal well. As shown in Fig. 1, subsurface geology similar to that of Tarim basin, where very thick conductive basin sediment and sedimentary rocks overlays a resistive reservoir was considered in this study. The resistivity and thickness of the model layers are given sequentially from top to bottom as 8 Ohm.m/3800 m, 300 Ohm.m/1000 m and 800 Ohm.m/half space. The well has a vertical section that runs to a depth of 4000 m and a horizontal directional part that is 3000 m long. The drill string and well casing diameter were set as 0.3 and 0.6 m, respectively. The resistivity of the string and casing, and drilling fluids were set as $1.0e^6$ and 2.5 S/m, respectively, unless specified otherwise. The EM signal

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with propagating frequencies of 5 to 20 Hz, and an input current of 0.1 A was transmitted through dipole antenna, with the drill string used as the stationary antenna and the other antenna is set few meters to a thousand meter away. Voltage across a 0.3 m insulator gap was measured at a measured depth (MD) of 6750 m, along the drill string. Several simulations were carried out to understand the effective system configuration for downhole transmission.

First, the effect of change in the dipole length on the magnitude of current distribution along the drill string and measured voltage across the insulated gap is considered. The mobile electrode's position is varied between 50 m to 1000 m. Conventional changes in current distribution along the drill string with depth were observed for the different dipole lengths. Fig. 2a and b shows the current distribution along the drill string for six dipole lengths; 50 m, 100 m, 150 m, 250 m, 500 m, and 1000 m at frequencies 5 Hz and 10 Hz. Conventional change in rate of change of current distribution with depth were observed at the interface between the resistive lower layers and conductive upper stratigraphy at depth of 3800 m. However, decrease in attenuation rate due to increase in layer resistivity is less conspicuous in the vertical section than in the horizontal section due to the presence of borehole casing. This change is characterized by smaller steady change in amplitude of current flow through the horizontal section of the drill string, which is within the resistive formation (Fig. 2). Furthermore, the largest current distribution was observed when the source dipole length of 1000 m was used. Fig. 2c shows the change in EM telemetry signal strength with change in dipole length. The value of simulated voltage across the insulated gap shows large increase in value with increase in dipole length within the first 200 m and a steady increase after this, with dipole length of 1000 m having the highest value. However, the steady increase is expected to continue for more hundreds of meters. Conventional increase in amplitude with decrease in frequency was also observed, with the largest difference observed between frequencies 10 and 15 Hz. The maximum voltage for frequencies 5 Hz, 10 Hz and 15 Hz are $1.4e^{-3}$, $1.2e^{-4}$, and $5.8e^{-6}$ volts, respectively.

Furthermore, we study the behaviors of downhole EM telemetry system with oil based mud (OBM), water based mud (WBM) and transition between them. The resistivity of the drilling fluid included in the model was varied between 0.1 and 1000 Ohm.m to represent different scenarios. The drilling fluid was set within the vertical section of the well with a TVD of 4000 m. In this second case, we set the dipole length as 150 m and maintained the other parameters in the model used in previous section. The maximum voltage in this case is recorded when the drilling fluid is less than 10 Ohm.m for most of the operating frequencies (Fig. 3b). This value remained constant for drilling fluid of 100 ohm.m, when the operating frequency is 5Hz. Fig. 3a shows the simulated current flow along the drill pipe. We can see that there is a clear steep descent of current magnitude within the conductive layer, and a lesser descent from 3800 m and along the horizontal section due to reduction in current leaks into the resistive layer. The behaviour of the current

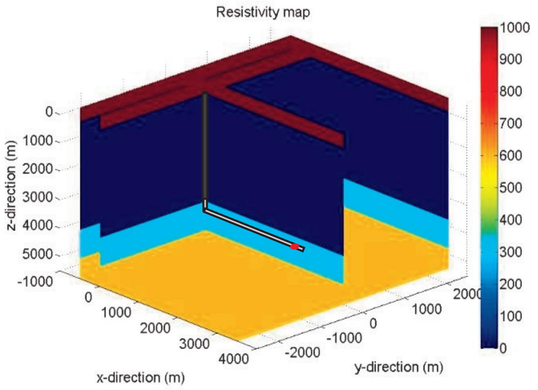

Fig. 1. 3D geological model showing the horizontal well and subsurface formation distribution. The insulating gap position on the drill string was indicated by a red mark close to the drill bit.

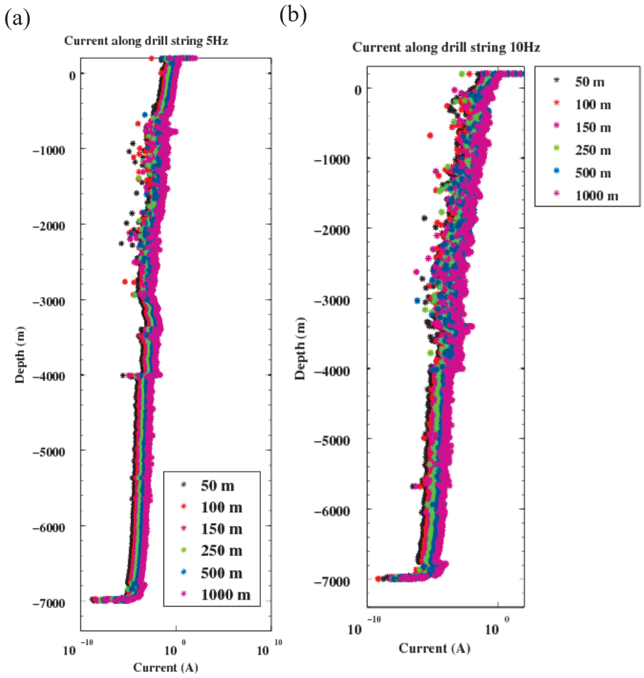

Fig. 2 Comparison of current distribution along the drill string in cased well at frequencies.

(a) 5 Hz; (b) 10 Hz; and (c) Plot of downhole EM telemetry signal strength against source dipole length. The source dipole length varied from 50 m to 1000 m. Distinguishable increase in magnitude of current distribution is observed as the source dipole length increases from 100 m to 1000 m for both frequencies. Further, increase in EMT signal strength was recorded with increase in source dipole length from 50 m to 1000 m from $5.8e^{-6}$ v to $1.2e^{-4}$v for operating frequency of 10 Hz. This shows that the applicable depth extent of downhole EM telemetry can be increased by increasing the dipole length to a maximum length of 1000 m for the given total measured depth.

distribution along the drill string agrees with the voltage plot (Fig. 3a), where the model with fluid resistivity of 10 Ohm.m has the largest current flowing through the drill string.

The third example considers the behaviour of downhole EM telemetry with change in the conductivity of the insulated gap. Water based drilling fluid with 0.4 ohm-m

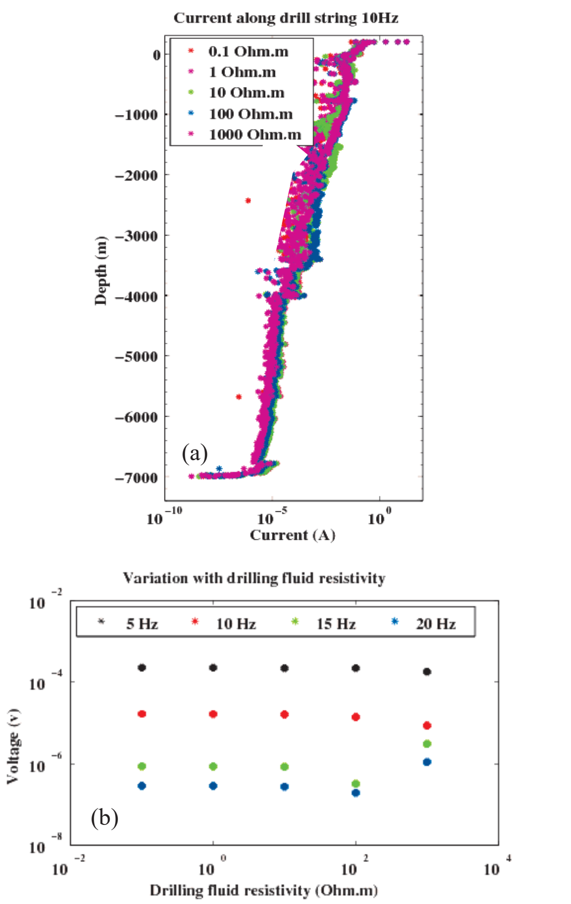

Fig. 3. Results obtained by varying the drilling fluid resistivity value.

(a) Comparison of current distribution along the drill string for models with varying drilling fluid resistivity value and (b) Plot of downhole EM telemetry signal strength against drilling fluid resistivity. Five resisistivities were considered to simulate transition from water based mud fluid to oil based mud. The drilling fluid resistivity value considered were 0.1, 1, 10, 100, and 1000 Ohm.m for operating frequency ranging from 5 to 20 Hz. The source operating frequency for the presented current distribution plot is 10 Hz.

resistivity was used in this case. We assume the conductivity of the insulated gap varied from 0.05 Ohm.m to 1000 Ohm.m. Thickness of the gap is maintained as 0.3 m. The plot of the strength of telemetry signal with respect to the gap conductivity for frequencies 5, 10, 15, and 20 Hz are shown in Fig. 4a. From this figure, we observed that the downhole telemetry signal strength increases with increase in the insulating gap resistivity from 0.05 to 200 Ohm and then stays the same thereafter irrespective of the propagating frequency. However, the change in signal strength from about $2.9e^{-4}$ to $3.0e^{-4}$ v for insulating gap resistivity of 200 and 1000 Ohm.m is small and could be considered less significant while choosing the insulating gap resistivity, with 10 Hz propagating frequency.

Lastly, considering the geology and the structural setup of some of the deep reservoirs in China, in particular the Tarim basin (pls refer to Tian, 2015; Tian et al., 2017 for more on geology of Tarim basin), we considered the effect of water-flooding, that is, sudden water influx into formation or well, on downhole EM Telemetry using the

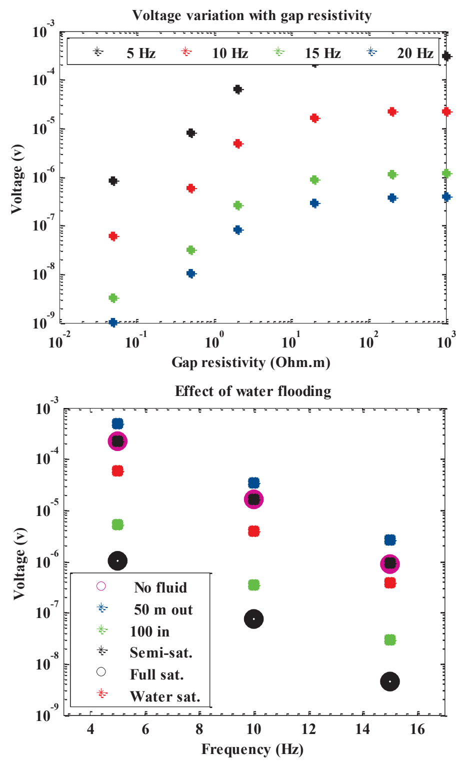

Fig. 4. Plot of downhole EM telemetry signal strength (a) against insulating gap resistivity and (b) with variation in the property of the fluid influx into formation. The gap resistivity value considered were 0.05, 0.5, 2, 20, 200, and 1000 Ohm.m for operating frequencies 5, 10, 15, and 20 Hz. Notably large reduction in signal strength with order of magnitude of −2 to −4 was observed as the water front is situated behind the insulating gap. Such sharp decrease will render the downhole EM telemetry ineffective.

initial model. 10 Ωm Horizontal cylinder with sides 900 ´ 200 ´ 200 placed at a depth of 4000 m, with its boundary at 100 m above and below the drilled well was used to simulate water advancement in a given reservoir. Five different models were considered based on the resistivity and position of the cylinder; (1) 10 Ohm.m brine filled cylinder placed 50 m away from the insulating gap (50 m out), (2) 10 Ohm.m brine filled cylinder placed 100 m behind the insulating gap (100 m in), (3) 150 Ohm m cylinder representative of transition region defined by mixture of HC and brine water, with the head of the cylinder placed 700 m behind the insulating gap (fully saturated zone), (4) Partly transition region and water filled regions on a 900 Ohm.m cylinder (semi-saturated), and (5) 10 Ohm.m brine filled cylinder, representative of water flooded region, placed 700 m behind the insulating gap (water saturated). The obtained result shows decrease in voltage due to water influx from about $2e^{-5}$ to $7.5e^{-8}$ for 10 Hz operating frequency.

A check on the change in EM telemetry signal strength with frequency shows a steep decrease in signal strength with frequency. The obtained signal strength for models 1, 2 and 5 indicates an initial increase in signal strength as the drill bit closes in on water saturated region with lower conductivity Fig. 4b. This is followed by a sharp decrease in measured signal strength as the insulated gap is immersed in the conductive saturated region. However, as the water advances, it looks to represent an elongated conductive layer which causes the EMT signal strength to increase again. In general, the occurrence of water flooding and/or drilling into water saturated region in reservoir could lead to loss of EM telemetry signal due to immense signal attenuation over the water flooding region. Furthermore, the effect of water front ahead of the insulated gap has proven to be minimal, as compared to large decrease in signal strength for water front 100 m behind the insulated gap. Although this effect is small, it thus show that resistivity measurement at bit for look ahead drilling could be a useful tool in early identification of water front interface and characterization of water intrusion effect or effect of lateral increase in water saturation on EMT response. The results from this study confirms the complexity in the application of EM telemetry with change in reservoir property and fluid property as suggested by Zeng et al. (2018) and Fayemi et al. (2018).

In general, the downhole electromagnetic telemetry signal strength increases with increase in source dipole length and resistivity of the insulating gap along the drill string. Considering the range of values for 5 to 10 Hz frequencies and the low level of noise at the BHA, introduction of repeater into the system is not a necessity when the dipole length is very large and the insulating gap resistivity is above 20 Ohm.m. However, for a well with total depth (TD) higher than 7000 m, the above considered factors might not be enough to ensure the transmission of signal from the surface to the BHA.

We assessed the application of electromagnetic telemetry in guided borehole drilling of deep horizontal wells with thick conductive overburden. Considering conventional BHA recordings system, the increase in source dipole length boosts the telemetry signal strength without increasing the magnitude of transmitted current. In addition, optimum signal transmission from surface to BHA is attained with insulating gap resistivity higher than 100 Ohm m. These two factors represent major controllable properties in downhole EM telemetry. Furthermore, the adverse effect of water flooding on the amplitude of EMT signal was established. The effect on recorded BHA EMT response is dependent on the level of water saturation and position of the waterfront with respect to the insulating gap position. In addition, the consideration of the change in EMT signal strength with brine water influx in front of the drill string shows the possibility of the application of EM method in look ahead technique. Lastly, further consideration of EMT signal with cross well measurement system is advised.

Key words: electromagnetic telemetry, horizontal well, water front, borehole drilling.

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