The potential of magnetotelluric using for reservoir monitoring

Ronghua Peng[1], Xiangyun Hu[1], Yunxiang Liu[2], Zhangxiang He[2]
[1]China University of Geosciences, Wuhan, China
[2]BGP Inc., China National Petroleum Corporation

SUMMARY

Reliable monitoring of subsurface changes is critical for engineering and environmental surveillance. Information about fluid redistribution in the subsurface is key element for effective management in reservoir production. Electromagnetic inductive methods particularly the CSEM methods have gained much attention and much effort has been put to its feasibility and reliability for monitoring in land and offshore reservoir over last several years. While few considers magnetotelluric techniques (AMT/MT) which employs natural sources for this purpose. Here, we conducted a series of numerical experiments to investigate the potential of magnetotelluric for land reservoir monitoring. 3D forward modeling demonstrates that time lapse changes in MT responses are small but measurable with required prior information and careful analysis. Additionally, through the analysis of derivatives of time lapse MT responses, we are able to accurately locate the oil-water contact within the reservoir during its production. The image derived from derivatives of MT responses at different production stages of the same depleted zone demarcate the areal extent of injected fluid and highlight the flooding front during production.

Keywords: magnetotelluric, 3D forward modeling, reservoir monitoring, flooding front location

INTRODUCTION

The ever-growing demand for optimizing reservoir production and predicting and managing geologic hazards from environmental and engineering community has advanced the development of time-lapse geophysical technologies over the past twenty years. Nowadays, time-lapse geophysical technologies have been widely accepted as a standard tool to monitor subsurface mass transfer and property changes both spatially and temporally. Over last decades, many researchers considered the applicability of electromagnetic inductive methods particularly the CSEM methods using for reservoir exploration and monitoring (e.g. Orange et al., 2009; Wirianto et al., 2010;). A number of numerical studies have convincingly demonstrated that EM techniques are potentially applicable to reservoir production monitoring though much further work is necessary (e.g. Lien and Mannseth, 2008; Black and Zhdanov, 2009). Compared with CSEM methods, magnetotelluric techniques which employ a passive and natural source has some distinct advantages: it has wider spectrum bandwidth available which could provide monitoring for deeper target; also it has much flexibility to deploy and is naturally suitable to continuous monitoring without much additional cost.

Enhanced oil recovery is the primary goal for time lapse monitoring. During reservoir production, saline water is usually injected into the reservoir to displace the resident oil, which creates variations in electrical conductivity distribution within reservoir due to changes in fluid properties. Hence, this leads to changes in MT responses. The main problem is whether or not the small changes in resistivity structure correlated with fluid properties can be resolved by MT responses. MT is a volumetric measurement subjected to diffusive process, whose resolution is proportional to the periods of inductive field. Hence, numerical experiment is necessary to explore the potential of magnetotelluric using for reservoir monitoring. Here, we have carried out a numerical simulation of 3D MT forward modeling for two discrete stages along the reservoir production (i.e. preproduction & 50% production).

TIME LAPSE MODEL

In order to examine the potential use of magnetotelluric for reservoir monitoring, we presented a simplified 3D model of reservoir production. The initial model before production is a 3D canonical model (Fig. 1a.) consisting a resistive reservoir unit(4 km×2 km×1 km) of 100 ohm-m buried 1 km beneath the surface of a 10 ohm-m sedimentary background. For simplicity, we assumed that the resistivity of background model be constant during reservoir depletion, hence the changes in MT responses were entirely ascribed to the variations in electrical conductivity structure resulting from oil displacement with injected saline water. To generate time lapse MT responses, we altered the initial model to simulate 50% production stage by displacing oil with 1 ohm-m saline water through two injection wells on the both sides of reservoir (Fig. 1b). We assumed that the reservoir was depleted by lateral flooding and the resistivities of the saline water and formation water are identical.

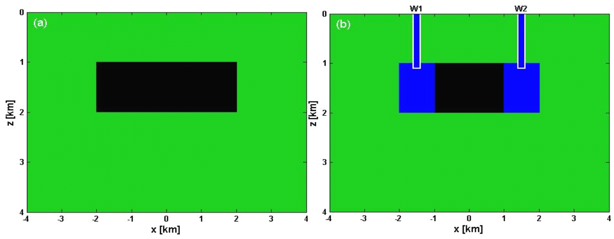

Figure 1. A cross-section sketch of 3D simplified reservoir model. (a) the initial reservoir (in black) embedded in a half-space sediments; (b) the 50% production stage in which injected saline water (in blue) dispaced one half of oil within reservoir.

3D FORWORD MODELING AND TIME LAPSE ANALYSIS

MT responses data were computed using 3D parallel algorithm based on stagger-grid finite difference method (cf. Mackie et al., 1993; Mackie et al., 1994; Li et al., 2012). Fig. 2 shows the time lapse differences in MT responses measured on surface between preproduction stage and 50% production stage. The results in Fig. 2 show the effects of frequency on the absolute amplitude of response difference caused by reservoir production. The absolute differences can identify domains with changes that lie above noise level which is independent with responses (e.g. random cultural noise). The left two panels in Fig. 2 plot the time lapse differences in apparent resistivity responding to different frequencies from 10 Hz (top) to 0.1 Hz (bottom). At high frequencies (10Hz to 1 Hz), the absolute differences in apparent resistivity is very small (less than 1 ohm-m) to be detectable. This might be correlated to the strong attenuation of high-frequency electromagnetic waves in the earth. The right two panels in Fig. 2 show the changes in impedance phase due to reservoir depletion. The results show that the frequency which is most sensitive to changes in reservoir for phase lies in the vicinity of 1 Hz. The absolute changes in impedance phase at this frequency could be up to 10 degrees, while differences in 10 Hz are smaller than 1 degrees. On the other hand, Fig.2 suggests that the behaviors of time lapse differences for different polarizations (xy- and yx-polarization) are quite different. The first and third columns are the responses of xy-polarization whose electric field is polarized along x-direction while the second and rightmost columns for yx-polarization in which the electric is parallel to y-direction. The time lapse differences for xy-polarization are spatially confined to the depletion zones within reservoir but their amplitudes are far smaller and can hardly be detected. While for yx-polarization, the changes are higher than that of xy-polarization in same frequency but the anomalous region are too diffusive to locate the flooding fronts.

Fig.3 displays the relative differences of apparent resistivity at different frequencies. The relative differences is very useful to determine domains with changes that lie above a noise level such as measurement repeatability errors (e.g. instrumental noise, modeling errors) which may cancel the time-lapse effects (Lien and Mannseth, 2008). The top panels in Fig. 3 show that the relative differences for xy polarization could reach up to 20~30% at 0.1 Hz. While for yx polarization (shown in the bottom panels of Fig. 3), the relative differences are much higher than that in xy polarization at same frequencies. The relative differences in apparent resistivity for yx polarization at 0.1 Hz could reach up to 40% (bottom-right panel of Fig. 3), which far exceeds the assumed measurement errors.

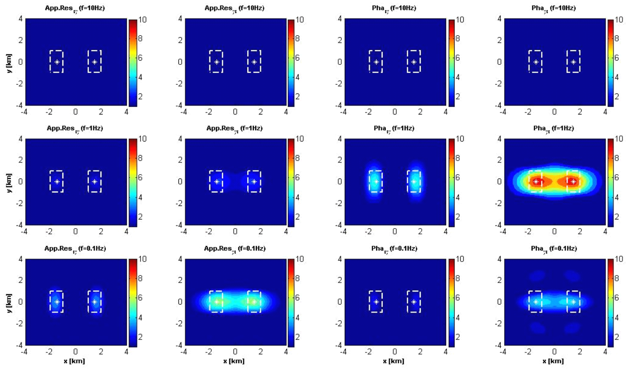

Figure 2. Time lapse differences in MT responses. The top to bottom panels plot time lapse differences at frequencies of 10 Hz, 1Hz, 0.1 Hz. The absolute differences below 1 ohm-m and 1 degree are suppressed in apparent resistivity and impedance phase, respectively. The white dashed line outlines the lateral extent of injected saline water within reservoir.

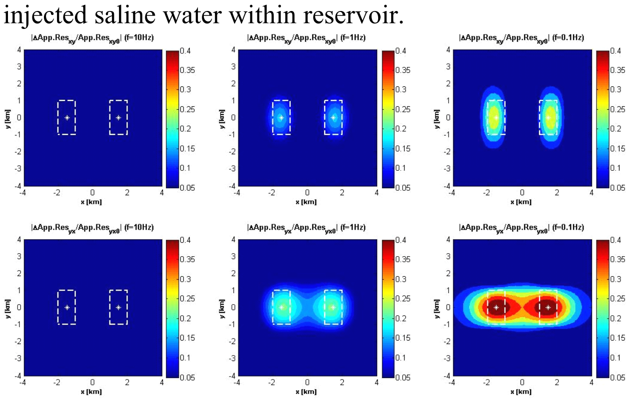

Figure 3. Time lapse relative differences of apparent resistivity for two polarizations at frequencies of 10 Hz, 1Hz, 0.1 Hz. The relative differences below 5% are suppressed. The white dashed line outlines the lateral extent of injected saline water within reservoir.

FLOODING FRONT DETECTION

Different from an exploration setting, the primary goal for 4D reservoir monitoring is to determine the lateral variations in subsurface conductivity structure, which is closely related to the fluid distribution within reservoir. Compared with reservoir exploration, the location and initial resistivity structure of reservoir is usually wellestablished prior to time lapse monitoring (Lien and Mannseth, 2008). Hence, the location of flooding front is of particular interest for 4D monitoring, which could provide important information for new injection and production wells. Due to the small differences caused by local changes at flooding front, the accurate identification of flood front directly from time lapse differences is very challenging. However, the analysis of gradient or second-order derivative of time lapse responses makes it possible to accurately locate the flooding front within reservoir (Greer, 2003; Andreis and MacGregor, 2011). The gradient or second-order derivative of responses is corresponding to these areas where the responses changes abruptly. Here, we first normalized the time lapse responses by the reproduction responses, and then calculated second-order derivative of the normalized responses with respect to range (Andreis and MacGregor, 2011). To compare the change behaviour of different MT responses (apparent resistivity and impedance phase), we re-normalized the second-order derivative of the normalized data set of different response types.

Fig. 4 displays the results of 2nd order derivative of time lapse MT responses (including apparent resistivity and impedance phase) compared to responses acquired in the preproduction stage at frequency of 1.0 Hz. The flooding front after production is well mapped at all responses. In particular, the extent of residual oil within the reservoir after production also is highlighted, few changes in the center of reservoir are observed, which could provide information for optimized reservoir management and successive production strategy.

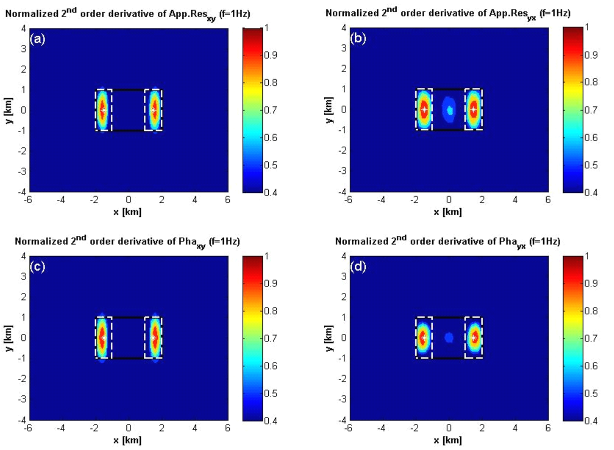

Figure 4. Normalized second order derivative of time lapse MT responses compared to responses acquired in preproduction at frequency of 1 Hz. In each panel, the black solid line plots the horizontal extent of reservoir, the overlaid white dashed line outlines the lateral extent of injected saline water within reservoir.

CONCLUSIONS

We have studied the feasibility of magnetotellurics using for reservoir monitoring through 3D MT numerical simulation. The results show that local changes of subsurface resistivity structure due to oil displacement with saline water during reservoir production can produce small but measurable changes in MT responses which can be distinguished through prior information and careful time lapse analysis of response data. For production monitoring, identification on lateral variations in resistivity structure is useful and required. 4D attribute analysis such as gradient or second order derivate of time lapse MT responses can accurately map the lateral extent of injected saline water and trace the fluid migration during reservoir production. However, we should keep in mind that study on repeatability error (which is not considered in our case) is paramount when attribute analysis is using for practical application. One useful approach to assess repeatability error during production is continuous monitoring such as permanent installation of acquisition instrument. This is practical and cost-effective for MT techniques which employ natural sources. In summary, magnetotelluric technique using for reservoir monitoring is feasible, but considering its practical application, high resolution inversion is required for quantitative analysis, which needs further work.

ACKNOWLEDGMENTS

This work was supported by grant from National Natural Science Foundation of China (NO. 41274077) and National Science and Technology Major Project of China (NO. 2011ZX05019-007), and partly supported by Innovative Group Project of Hubei Province, China (NO. 2011CDA123). We would like to thank Randall L. Makie making his 3D forward serial source code available.

REFERENCES

Andreis D, and MacGregor L., 2011, Using CSEM to monitoring production from a complex 3D gas reservoir—A synthetic case study, *The Leading Edge*, **30**, 1070-1079.

Black N, and Zhdanov M S., 2009, Monitoring of hydrocarbon reservoirs using marine CSEM method, 79th Annual International Meeting, SEG, Expanded Abstracts, 850-854.

Greer, A. A., MacGregor L M., and Weaver R., 2003, Remote mapping of hydrocarbon extent using marine active source EM sounding, 65th Conference and Exhibition, EAGE, Extended Abstracts, F17.

Lien M., and Mannseth T., 2008, Sensitivity study of marine CSEM data for reservoir production monitoring, *Geophysics*, **73**, 151-163.

Li Y., Hu X Y., Yang W C., et al., 2012, A study on parallel computation for 3D magnetotelluric modeling using the staggered-grid finite difference method. Chinese J. Geophys, **55**, 4036-4043.

Mackie R L, Madden T R, and Wannamaker P E., 1993, Three-dimensional magnetotelluric modeling using difference equations-Theory and comparisons to integral equation solutions, *Geophysics*, **58**, 215-226.

Mackie R L, Smith J T, Madden T R., 1994, There-dimensional electromagnetic modeling using difference equations: The magnetotelluric example, *Radio Science*, **29**, 923-935.

Orange A, Key K, Constable S., 2009, The feasibility of reservoir monitoring using time-lapse marine CSEM, *Geophysics*, **74**, 21-29.

Wirianto M, Mulder W A, and Slob E C., 2010, A feasibility study of land CSEM reservoir monitoring in a complex 3-D model, *Geophys. J. Int*, **181**, 741-755.