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Theoretical assessment of 3-D magnetotelluric method for oil and gas exploration: Synthetic examples

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ABSTRACT

In petroleum explorations, seismic reflection technique has been almost always the preferred method for its high exploration depth and resolution. However, with the development of three dimensional (3D) inversion and interpretation schemes, much potential has been shown in MT method dealing with complex geological structures as in oil and gas exploration. In this study, synthetic geophysical models of petroleum reservoir structures are modeled and utilized to demonstrate that feasibility of 3-D MT technique for hydrocarbon exploration. A series of typical reservoir structure models are constructed and used to generate synthetic MT and seismic data to test the capabilities of 2-D/3-D MT and 2-D seismic inversion techniques. According to the inversion comparison, in addition to correctly retrieve the original forward model, the 3-D MT method also has some advantages over the reflective seismology method, which suffered from the lack of reflection wave and multiple wave problems. With the presented 3-D high resolution MT inversion method, MT techniques should be employed as one of the first choices for petroleum explorations.

1. Introduction

In petroleum explorations, the magnetotelluric (MT) technique is often used as a complement method to the primary technique of reflective seismology method (From Wikipedia, the free encyclopedia). With the diffusive nature of electromagnetic (EM) wave propagation, the vertical resolution of EM exploration methods usually cannot match those of reflective seismology in cases such as distinguishing deep strata. Therefore MT is often employed as a backup method where seismic reflection method performs poorly in complex terrain and geological conditions (Constable et al., 1998; Sun et al., 2003), for example, in situations where carbonate outcrops produce strong reflections that interfere with accurate seismic detection.

The MT method, however, possesses several important advantages over other methods: it is unaffected by high-resistivity layers, capable of great exploration depth and low-cost (Chen and Wang, 1990; Wei, 2002). It is also more environment-friendly because of its light-weight equipment and reduced hazards comparing to seismic reflection methods (e.g. no drills, no explosives). In most cases, MT data are collected along 2-D profiles across geoelectrical strikes with 2-D assumptions that the layers and bodies underground extend unlimitedly in strike direction. In some instances, accurate interpretation of 3-D geology can be achieved by careful application of 2-D modeling and inversion (Wannamaker et al., 1984). But, in other cases, 2-D inversion may not get reasonable models, especially in a complex geological environment. Besides the different physical response parameters, the vertical resolution of 2-D MT may be not as good as seismic reflection methods. However, 3-D MT modeling does not require the 2-D underground assumption nor need approximate calculations like strike rotation. Theoretically, 3-D methods can model any 3-D geological body, although might be restricted by the algorithms of forward modeling in reality. And the location and uniform limitation (grids and sites) in 2-D method (Avdeev et al., 2000; Chen and Zhao, 2009) rarely appeared in 3-D (the method used in this paper), because each site corresponds to each grid that contained it which means the relative position of the site in the grid is not critical and the relative size of the grids will not influence the inversion results (Zhang, 2013).

A number of 3-D MT inversion methods have been proposed, including rapid relaxation inversion (Smith and Booker, 1991; Tan et al., 2003), conjugate gradient inversion (Mackie and Madden, 1993; Lin, 2011), quasi-linear approximate inversion (Zhdanov et al., 2000), Bayesian statistical inversion (Spichak, 1995) and nonlinear conjugate gradient (NLCG) inversion (Newman and Alumbaugh, 2000; Mackie et al., 2001; Zhang et al., 2013). Although each of these methods has its own advantages and disadvantages (see comparisons by Zhang et al., 2013), we consider the NLCG method to be the ideal 3-D MT inversion method with the advantage of high resolution, efficiency and precision. There are many applications of crust and ore exploration

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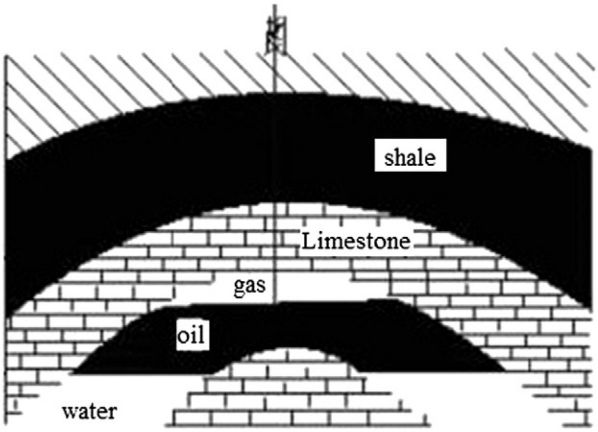

Fig. 1. Typical oil-bearing structure model.

Table 1
Petrophysical properties of materials in oil-bearing structures.

Property	Resistivity, ρ ($\Omega \cdot$ m)	Density, σ ($\times 10^3$ kg/m^3)	S-wave velocity V_S (m/s)	P-wave velocity V_P (m/s)
Shale	10–1000	2.0–2.50	780–2300	1330–3970
Limestone	10–10 000	2.3	1450–3500	2500–6000
Oil	≥10 000	2.93	1400	2600
Gas	≥100 000 000	0.7–0.8	1400	2350
Groundwater	1–100	1–1.02	1450	2700

(Wang, 1988; Wang et al., 1988; Batzle and Wang, 1992; Chave and Jones, 2012; and some data available from http://wenku.baidu.com/view/2bff294ccf84b9d528ea7aea.html and http://www.docin.com/p-52175997.html

using 3-D MT survey and inversion, including Coso field exploration for large geothermal reservoirs (Newman et al., 2005), Xinjiang field AMT exploration for study the electrical structure of Cu-Ni mining (Xiao et al., 2010), Iceland field exploration for understanding the complex geothermal systems of the Hengill and Krafla volcanic complexes (Gasperokova et al., 2011), Gulf of Mexico exploration for demonstrating the capability of imaging a sea-bottom resistivity structure (Zhdanov et al., 2011), Krysuvik exploration in SW Iceland for understanding the electrical structure of the high temperature areas (Hersir et al., 2013), Central California field exploration for studying the electrical conductivity structure of the San Andreas Fault (Tietze and Ritter, 2013) and so on. After effective results and interpretations are obtained from 3-D MT inversion models, the advantages of 3-D inversion are manifested on large real-world data set and resolution of complex structure (Tietze and Ritter, 2013) and so on (Newman et al., 2005; Xiao et al., 2010).

MT sounding can reflect the underground electrical interfaces where conductivity differences exist. An oil reservoir usually requires an impermeable cover, connected reservoir and impermeable base, so the gas, oil or water in reservoir is difficult to escape. The electrical difference between cover and reservoir is usually great and can be easily detected by MT method. In the case of an anticline fold oil trap, which is a strong manifestation, electrical difference between the anticline and background rock can also be great and can be distinguished by MT method. Although there are some successful examples of oil and gas exploration using MT including the Ashili region (Wu, 2012) and Gui Depression (Xia et al., 2012) in China, and some areas of Russia (Berdichevsky et al., 2010) and Japan (Khalil and Ushijima, 2003), MT is still not the usual method in the hydrocarbon exploration. And only 2-D inversion methods are used in those interpretations. So in our opinion, the applications of 3-D MT in petroleum exploration are not well-informed.

Utilizing the 3-D MT inversion code presented by Zhang (2012) and Zhang et al. (2013), our primary goal of this study is to demonstrate the value of 3-D MT technique in oil and gas exploration. A series of 3-D models of typical reservoir structures are constructed and used to generate synthetic data of MT and seismic reflection method. Both 2-D and 3-D modeling and inversion were carried out with the synthetic data, along with 2-D reflective seismology inversions to demonstrate the validity of those methods in oil and gas exploration. The result comparison shows that the 3-D method has a better resolution and accuracy then the 2-D MT method. Accurate 3-D MT inversion may also compensate

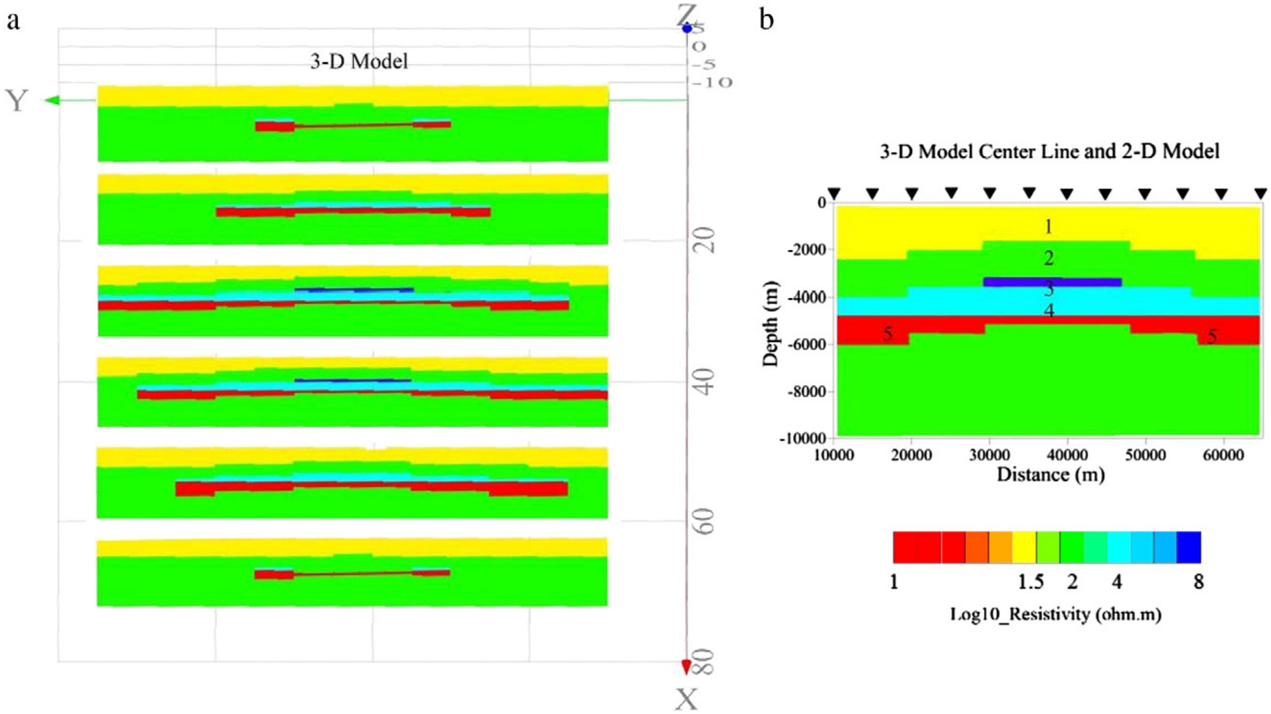

Fig. 2. Synthetic geophysical model (a): 3-D model; (b): central section of 3-D model as 2-D model. 1: shale; 2: limestone; 3: gas; 4: oil; 5: groundwater.