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Direct interpretation of petroleum reservoirs using electromagnetic radiation anomalies

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ABSTRACT

Petroleum exploration using natural source electromagnetic (EM) methods has recently increased due to the economic demand for obtaining high-resolution information about electrical parameter variations related to reservoirs. However, there are challenges present in using traditional EM methods. Regional geo-electrical structures inverted from induced EM signals are insufficient to determine the characteristics of reservoirs. In this study, we propose a natural source prospecting method to directly assess the depths and distributions of oil layers. This is accomplished by deriving electromagnetic radiation (EMR) signals caused by oil flow and reservoir fractures. The method has been validated by theoretical analyses and field measurements in Chepaizi Uplift, China. The modeling results show that Super-Low Frequency (SLF) magnetic amplitudes reveal stationary trends for various types of oil trap models. EMR anomalies, (distinguished from actual SLF magnetic signals) are noise-suppressed and enhanced using the ensemble empirical mode decomposition (EEMD) and the "DB4" wavelet transform. An empirical Frequency-Depth transformation model is developed to directly implement the depth sounding. EMR configurations at the corresponding depths of oil layers are recognized as the target of discovery i.e., reservoirs. The estimated depths of oil layers in producing wells are verified by the actual production, and the depth deviations of reservoirs are generally within a ±10% margin of error. This method is intended to be a viable tool in the accurate identification, delineation and dynamic monitoring of petroleum reservoirs.

1. Introduction

Natural source (passive) electromagnetic techniques, such as Magnetotellurics (MT), have gained prominence in petroleum reservoir analysis, especially in areas where oil deposits are concealed by thick volcanic rocks and seismic techniques do not work well (Mitsuhata et al., 1999; Stanley et al., 1985). Recently, MT seems to be a reasonably accepted tool for imaging oil-bearing sedimentary basins and directly analyzing reservoirs themselves in challenging environments (He et al., 2010a; Meju, 2002). However, the MT response gives an average resistivity from the surface to the skin depth, and it is difficult to identify reservoirs with high resolution (He et al., 2010b; Unsworth, 2005). The feasibility of the natural source induced polarization method is also controversial (Gasperikova and Morrison, 2001). These EM methods use ratios of electric and magnetic fields in order to eliminate stochastic fluctuations of natural EM field, however they possibly overlook subsurface details implied by single electrical or magnetic components. Meanwhile, the aforementioned passive methods only minimally take the electromagnetic radiation (EMR) activity which accompanies petroleum producing operations into account. In fact, EMR signals from rock fracture are subject to numerous field and theoretical investigations dating back for decades (Cress et al., 1987; Frid et al., 2000). Particular focus has been given to EMR phenomena revealing both electrical and mechanical properties of reservoirs (Frid and Vozoff, 2005). EMR signals are normally excited by oscillations of atoms on both sides of openings in small-scale fractures (micro-cracks or nano-cracks). Radiation pulses also occur in the motion of ions in the presence of an electric double layer, which are formed because of oil flow, stress changes or reservoir fractures in the strata (Frid et al., 2003; O'Keefe et al., 2000), especially in producing wells. These phenomena, deemed as seismo-electric and electro-kinetic effects, are fully investigated in experimental observations and field research of oilfields (Hu and Gao, 2011; Revil and Jardani, 2010). Additionally, EMR characteristics, such as amplitudes and frequency ranges are investigated (Liu and He, 2001; O'Keefe et al., 2000; Ren et al., 2012). EMR signals from rock deformations or acoustic propagations in porous mediums are also used to distinguish oil, gas and water (Shi, 2001). Some authors have reported successful application in determining the regional stress field and structural

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geology using natural source EMR signals (Lichtenberger, 2005). Particularly, it yields that the passive EMR magnetic component in the frequencies from 5 Hz to 50 kHz observed at the Earth's surface can help determine stress directions remarkably well (Greiling and Obermeyer, 2010).

This paper is principally devoted to the method of directly interpreting petroleum reservoirs in producing wells using natural source EMR anomalies. A high-resolution prospecting system and the Frequency-Depth transformation have been developed for this process. Four oil trap models were designed to calculate the total magnetic responses on the basis of the MT theory. Subsequently, the ensemble empirical mode decomposition (EEMD) and the wavelet transform were integrated to suppress noise in order to enhance the EMR anomalies. We correlated the EMR anomalies with identifying reservoirs under diverse production circumstances, such as single and multiple deep oil layers, water injection layer and shallow oil layers. Monitoring the spatial distribution of reservoirs was explored using a measuring profile, and the expected accuracies were also evaluated. This method can be appropriate for low-cost efficient identification of reservoir depths and distributions in complicated settings.

2. Passive Super-Low Frequency data acquisition

Super-Low Frequency EM signals have a broad range from 3 Hz to 3000 Hz, and enlarge the earth observation in both range and depth. It necessitates high-resolution acquisition instrumentation, recording control units, thoughtful site layout and data processing. Over the past decade, we have developed a passive Super-Low Frequency prospecting system covering sufficient sensitivity, large dynamic frequency range and filtering capabilities (Wang et al., 2014).

The prospecting system is composed of a high-resolution magnetic detector, control system and power supply in Fig. 1. The magnetic detector is an induction coil sensor which allows the system to record an induction electromotive force with a minimum count of 0.1 μV. The control system contains multi-scale amplifying, filtering, A/D transform, frequency sweep and Frequency-Depth transformation modules. The Frequency-Depth transformation is a key component of the SLF prospecting method, which converts the SLF signal in the frequency domain to that in the depth domain with a prescribed accuracy. In order to derive the Frequency-Depth relationship, interpreted subsurface anomalies in frequency domains need to be in accordance with those in depth distributions which are derived from well log data. Then Frequency-Depth pairs are manually extracted for generating an empirical formula. This formula is also theoretically derived from the Bostick inversion (Chave and Jones, 2012), and can be approximately adjusted in SI units:

$$H = 356^{*}\sqrt{\rho}/f^{c} \tag{1}$$

where ρ (Ω m) is the general resistivity, f is the frequency (Hz), ρ and the index c can be adjusted. This transformation should be examined by a series of field tests, and would be appropriately applied in the study area.

The ultimate “Depth-Relative Amplitude” curve would be visible in real-time. The whole system has power consumption less than 15 W. These lighter power sources enable the continuous performance in long recording durations or in remote recording locations. The detector is portably used in field measurements, and thus it is practical and economical for a few people to accomplish an arduous exploration task.

3. Super-Low Frequency electromagnetic prospecting theory

3.1. Modeling simulation algorithm

In a regional zone where the source is excessively large at a considerable distance above the surface, primary waves are nearly planar and vertically incident at Earth's surface and secondary

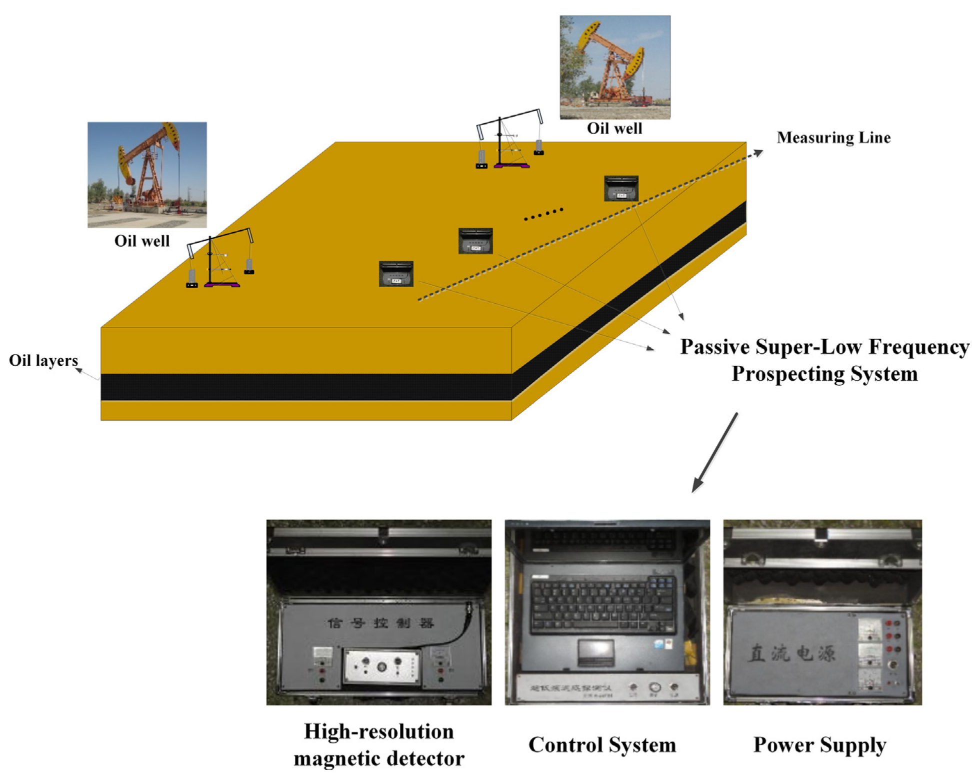

Fig. 1. Passive Super-Low Frequency prospecting system and its deployment in field surveys.