International Journal of Coal Geology 127 (2014) 24–41

Contents lists available at ScienceDirect

International Journal of Coal Geology

journal homepage: www.elsevier.com/locate/ijcoalgeo

Dynamic monitoring of coalbed methane reservoirs using Super-Low Frequency electromagnetic prospecting

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ARTICLE INFO

Article history:
Received 15 December 2013
Received in revised form 8 March 2014
Accepted 9 March 2014
Available online 14 March 2014

Keywords:
Coalbed methane
Dynamic monitoring
Super-Low Frequency
Empirical mode decomposition
Magnetotelluric (MT)
Electromagnetic radiation (EMR)

ABSTRACT

Dynamic monitoring of coalbed methane (CBM) reservoirs plays an important role in reservoir evaluation, production estimation, exploitation and development planning in order to efficiently operate producing wells. This paper proposes a passive Super-Low Frequency (SLF) electromagnetic prospecting and monitoring method, which helps us derive electromagnetic radiation (EMR) anomalies from reservoirs to directly identify and dynamically analyze CBM reservoirs. The modeling study shows that the SLF magnetic responses are sensitive to high resistivity layers. These responses turn out to be approximately stationary and can be seen as simply a component of the background field. This stationary background field can be clearly distinguished and then dynamic anomaly extraction would be completed. In order to suppress cultural noise and high frequency (HF) random noise, the methods of empirical mode decomposition (EMD) and wavelet transform are used in data processing. The reconstructed curves are employed to identify EMR anomalies at corresponding depths of reservoirs, and subsequently help directly interpret and dynamically monitor reservoirs. The SLF prospecting method is validated using the field data observed from CBM wells in the years from 2007 to 2013 in Qinshui Basin, China. The results present that the high EMR "wave packets" contribute conceivably to the CBM reservoir identification. Compared with audio-magnetotelluric (AMT) inversion results, the SLF identification resolution is greatly improved. The dynamic characteristics of producing reservoirs are revealed using EMR anomalies, and agree with production histories and other surveys.

1. Introduction

Coalbed methane (CBM) has contributed significantly to increasing energy resources and triggered the global activity in the exploration and exploitation of CBM reservoirs (Ayers, 2002; Diamond and Schatzel, 1998; Moore, 2012; Yao et al., 2009). In order to enable the commercial production of CBM and allow mining at the least cost to human life, the focus has been on reservoir dynamic monitoring, which stands as a paramount prerequisite for production predictions and has become a new frontier of scientific inquiry (Clarkson, 2013; Gilliland et al., 2013). Methods for dynamically evaluating reservoirs are principally quantitative production analysis (PDA) and empirical methods. In order to generate a forecast, these methods require accurate production data, including flowing pressure, reservoir porosity and other reservoir parameters, which are difficult to be practically appreciated. Additionally, they often yield erroneous results associated with complex reservoir behavior and wellbore fracture geometry (Clarkson, 2013). Other indirect methods, such as core analysis, well-test analysis, and geophysical logs, have subsequently advanced progresses and can be used to locate reservoirs (Chatterjee and Paul, 2013; Fu et al., 2009; Zhou et al., 2012). Despite accurately extracting reservoir parameters, these are not recommended for dynamic monitoring, especially for large numbers of wells due to high cost. Seismic and controlled-source electromagnetic (CSEM) methods for subsurface exploration are widely adopted in reservoir identification (Hordt et al., 2000; Hou, 2002; MacLennan and Li, 2011; Peng et al., 2006; Ramos and Davis, 1997; Xu et al., 2008), but they can be interpreted with uncertainty and are inappropriate in complex subsurface environments.

Recently, passive (natural source) electromagnetic (EM) prospecting methods have been largely developed and provide great potential for economically and efficiently monitoring reservoirs (He et al., 2010a). These techniques are able to determine the regional-scale structures of reservoirs by analyzing natural source EM signals according to magnetotelluric (MT) theory (He et al., 2010b). However, these methods cannot give an adequate resolution of depth and distribution of CBM reservoirs with resistivity, permeability and polarizability inversions. Some unexpected anomalies were often identified because of interpretation uncertainty. Additionally, the impedance in the MT theory, which is the ratio of an electrical component to a magnetic component, represents the general subsurface effects but it neglects the subsurface details implied in single EM components (Wang and Wei, 2006). Meanwhile, they hardly take the electromagnetic radiation (EMR) information into account. In fact, natural source EMR exists because of reservoir fracture, oil and gas

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http://dx.doi.org/10.1016/j.coal.2014.03.002
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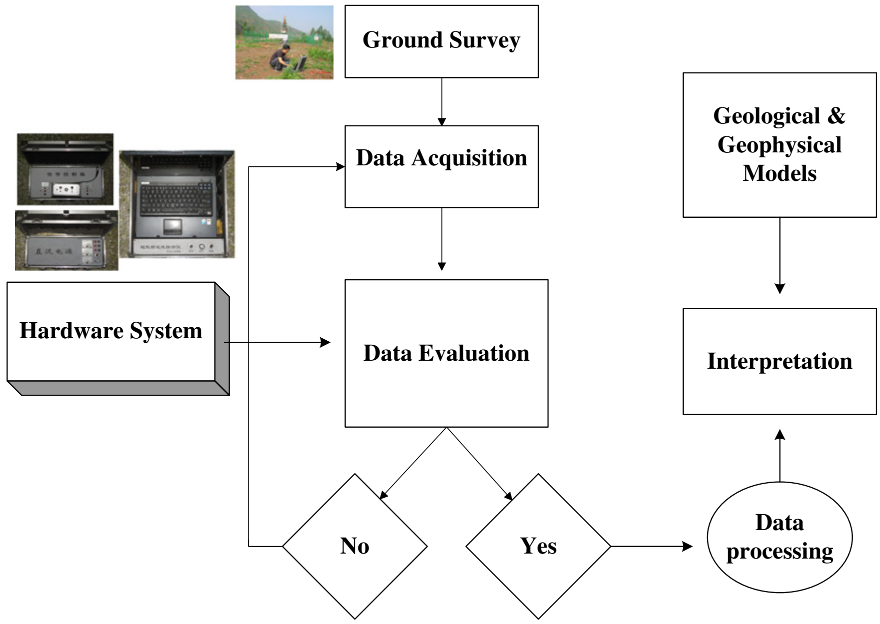

Fig. 1. Overview flowchart of the SLF prospecting system applied in field experiments.

migration, and stress changes in the strata, especially for underground coal mining operations (Frid and Vozoff, 2005; O'Keefe et al., 2000; Paul and Chatterjee, 2011a, b). Some earlier studies have made a series of experimental observations of rock or coal saturated with gas, and critically studied the source origin of electromagnetic radiation signals (Cress et al., 1987; Rabinovitch et al., 2007). Other studies have investigated the EMR responses for rockburst hazard and gas outburst forecast in coal mines (Frid, 1997; Liu and He, 2001). Recently, many researchers have reported the applications of natural EMR signal in determining the regional stress field and structural geology (Greiling and Obermeyer, 2010; Lichtenberger, 2005; Lichtenberger, 2006). Particularly, Greiling and Obermeyer (2010) demonstrated that the EMR magnetic component measured at frequencies from 5 Hz to 50 kHz showed stress directions remarkably well. Meanwhile, EMR signals in the low frequency could also be received at the surface (Hou et al., 2000). However, little interest in EMR geophysical prospecting in hydrocarbon exploration has been completed.

In this paper, a method using natural source Super-Low Frequency (SLF) EMR magnetic signals is proposed for dynamically monitoring CBM reservoirs. In order to enable reliable data acquisition in geological surveys, a reliable high-resolution prospecting system has already been developed. A finite element algorithm for simulating two dimensional models has been validated, and theoretical analyses are conducted for deriving induced SLF magnetic responses. The feasibility that magnetic

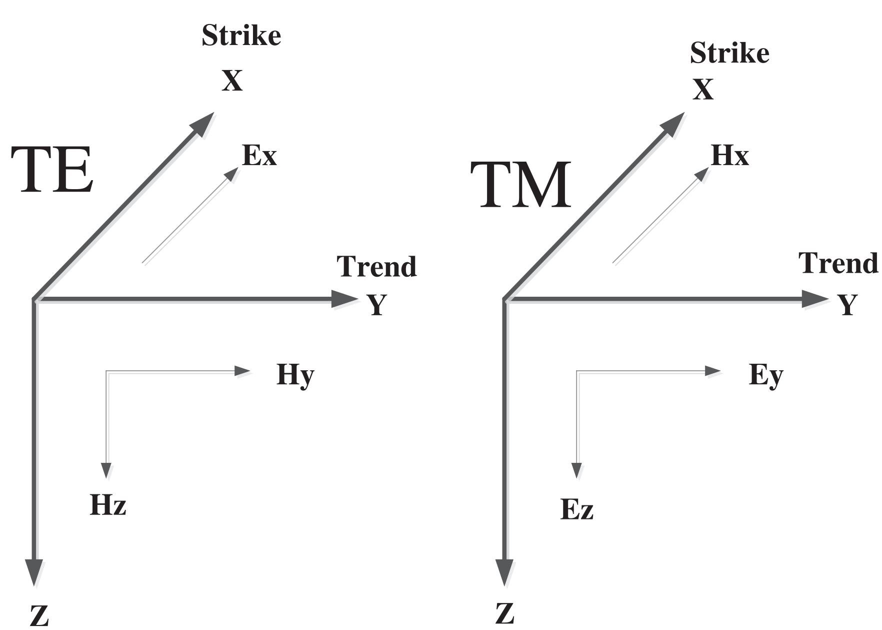

Fig. 2. Diagram of the TE mode and the TM mode: the Ex component is parallel to the strike direction x or perpendicular to the trend direction y, with the Hy and Hz components in the TE mode (left panel). Similarly, the Hx component is parallel to the strike direction x with Ey and Ez for the TM mode. The x–y plane represents the Earth's surface, as well as the y–z plane tangent to the air–Earth interface in each panel.