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Petroleum Electromagnetic Prospecting Advances and Case Studies in China

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Abstract Remarkable progress has been made in electromagnetic (EM) techniques as applied to the petroleum industry in instruments, data acquisition, and processing and interpretation in China. Included here is equipment, such as high-power Controlled Source EM (CSEM) acquisition systems, acquisition methods, such as the three dimensional small-bin Continuous Electromagnetic Array acquisition method, Time and Frequency Domain Controlled Source Electromagnetic, Borehole-to-surface Electromagnetic technique and marine magnetotelluric method. Data processing methods, such as fast three dimensional inversion using nonlinear conjugate gradients, and data interpretation methods, like Induced Polarization and Resistivity anomalies for hydrocarbon detection, are also included. These new techniques have been applied in petroleum survey and many cases are in complicated areas. They have successfully served the investigation of deep igneous rock reservoirs, and prediction of potential hydrocarbon targets. The cases indicate that electromagnetic techniques can help seismic survey to effectively detect hydrocarbon reservoir and remarkably improve drilling successes.

Keywords Petroleum prospecting · Electromagnetic · Equipment · Acquisition technique · Processing technique · Interpretation technique · Case studies · China

1 Introduction

Electromagnetic (EM) techniques have contributed much to petroleum exploration in China, about which many Chinese geophysicists and geologists have ever given comprehensive description in their publications. Wei (2002) and Zhao et al. (2007) summarized and reviewed the development of EM survey techniques in terms of instrument, acquisition,

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processing and interpretation, numerical simulation, and application respectively. Moreover, Wang (2006) also reviewed the development of petroleum EM survey techniques in China, and pointed out that Chinese annual workload of EM acquisition is far higher than other countries. In fact, there are 14,000 magnetotelluric (MT) acquired points and some hundreds of thousands of kilometers in length each year in China. So it is easy to understand why someone said that the capital of MT is China. Continuous Electromagnetic Profile (CEMP), Time and Frequency Electromagnetic (TFEM) and Borehole-surface Electromagnetic (BSEM) acquisition methods show their advantages in complicated areas and in delineation of hydrocarbon reservoirs. Much progress has been made in terms of methodology for static corrections, terrain correction, three dimension modeling and fast 3D inversion of MT data in China. Wang (2006) also pointed out the tendency and challenge of EM methods in China. The author has also published papers on some summary and analysis about the application and tendency of EM and gravity and magnetic methods in hydrocarbon exploration (Wang 2006; Jia et al. 1998; He 2000; He et al. 2001a, b, 2002a, b, 2005). It's clear that non-seismic methods including EM have been growing towards high precision, 3D, and integrated exploration and their objectives have been transferring from regional tectonic reconnaissance to complex structural belts, deep targets, and hydrocarbon reservoirs. These new functions have been popularized in China. Many publications have described the growing course and the status quo. All the opinions and conclusions presented in these publications are not out of date today, so we do not repeat them in the paper.

In recent years, hydrocarbon exploration has been becoming more and more difficult, but a challenge and also an opportunity for EM techniques in China as well as elsewhere in the world (Zonge and Hughes 1988; Keller et al. 1984; Strack 1992; Strack et al. 1990). One of the challenges is that traditional 2D EM cannot satisfy the current hydrocarbon exploration in complex areas, thus 3D acquisition and processing are required and gradually improved. Another challenge is the investigation of deep igneous rocks, which requires the combination of geophysical methods, among which EM technique is one of the most important means. For example, high-power Controlled source EM method (CSEM) is developed for investigation of deep igneous rocks. Another challenge is detecting lithologic reservoirs. Rock geophysical properties of lithologic reservoir are the basis for EM methods to detect hydrocarbons. The study of the geo-electrical anomaly mechanism, identification of the pattern of hydrocarbon reservoirs together with newly developed EM methods have jointly improved the efficiencies of EM methods in the detection and delineation of hydrocarbon reservoirs. The paper introduces some new petroleum EM techniques including instrument, acquisition, processing, interpretation and their applications in China in recent years.

2 Newly Developed EM Methods and Techniques

2.1 EM Instruments Made in China

It is well known that China lagged behind western countries in geo-electric techniques, as well as EM instruments in the last century. So since 1980s, a large amount of EM equipments have been imported including V5, V5-2000, V8, MT-1, MT-24, GMS-06, GMS-07,GDP-32, etc. At the beginning of twentyfirst century, Chinese people began to make EM instruments (Lin and Zhao 2001; Cheng et al. 2004; Zheng et al. 2004a, b; Deng et al. 2003; Wei et al. 2009) by ourselves, and a kind of multi-source EM instrument was produced in China in 2004 (Zheng et al. 2004a, b), which could make use of both natural and controlled sources and acquire both MT and Audio-frequency Magnetotellurics data with frequency range of 0.001–100 kHz. It also can be used for detecting very shallow hydrocarbon targets. Almost at the same time, seabed MT instruments (Deng et al. 2003) were also produced and a field acquisition test (Wei et al. 2009) has been conducted with the instruments in Nanhai, China. Up to now, these kinds of instrument have not been used much in China. On the other hand, the high-power electromagnetic instruments have been greatly developed in China and their results are obvious.

In 1989, a Chinese inspection group visited the former Soviet Union, and realized that EM had contributed much to hydrocarbon exploration in their country, even there was an order that no well was permitted to be drilled without the confirmation of electromagnetic data (Wan and Wang 1991). So the geophysicists decided to import EM technique from the former Soviet Union after returning back to China. In 1990, a long-offset transient EM test was carried out in China with the help of former Soviet geophysicists, and in 1992, a first EM acquisition system was imported. Ever since then, the method has been applied in the hydrocarbon detection in China (He 1993; Lu and He 1994). As time goes by, the system has become outdated, so BGP has decided to develop a new one. It was in 1997 that a new CSEM instrument was successfully developed (Wang and Gao 2001) which was named as GJY-16—the high-power CSEM system was firstly produced by BGP bases on the imported Russia-made CSEM system. The system has shown perfect performances in practical surveys. After further improvement, a new generation, TFEM-1, has been successfully produced (He et al. 2002a, b). Its major specifications are described as follows. Output power: 200 kW. Output current: steady, continuous and optional. Current: Max. 120 A. Turnoff time: <20 μs. Digital receiver: 96 channels, centralized and/or decentralized, among them, 2 centralized acquisition stations with 24 channels for each one, and the rest are 2-channel decentralized digital acquisition stations. Sampling rate (optional): 0.25, 0.5, 1, 2, 4, 8 ms.

The system is a completely domestic instrument granted by patent. Its technical specifications have reached up to the internationally advanced level. In addition, it adopts a more advanced design idea than either EM instrument for CSAMT or LOTEM (Long Offset Transient Electromagnetic). The system adopts domestic controlled source, and can acquire time and frequency domain data simultaneously, in other words, both CSAMT data and LOTEM data, or SIP (Spectrum Induced Polarization) data and TIP (Time Induced Polarization) data are acquired simultaneously with the system. Moreover time and frequency domain data acquired with the system is characterized by good quality.

2.2 Newly Developed EM Methods

2.2.1 3D Small-Bin CEMP Acquisition

MT was studied in 1970's and a book titled "Magnetotellurics Sounding" was complied by three MT groups, including MT group of Institute of geology, CEA; Electric method group for petroleum of Geology College of Wuhan, and Electric method group of BGP, CNPC. MT was firstly used for hydrocarbon exploration in 1980's in China (Yu and Ji 2002). A new acquisition method was introduced to China by Wang (1990) in 1990's. After that, CEMP has been tested and successfully applied (He et al. 2001a, b; Zheng et al. 2004a, b). CEMP is an advanced method of MT technique, similar to Electromagnetic Array Profiling (EMAP) (Bostick 1986). Please refer to Bostick 1986 for details. E field sensor dipoles are placed end-to-end along a survey traverse line to obtain a series of continuous E component measurements along and in the direction of the line; and H field sensors are placed at a fixed location in the survey area to measure the horizontal H components. The method can effectively suppress the influence of near-surface inhomogeneities, as a result, improving exploration effect in China. But for complicated terrain and underground structures, e.g., 3D geologic body, these methods can not provide satisfying results and precision. Under the situation, we put forward 3D small-bin acquisition method which is a patent technique of BGP. It has been applied in hydrocarbon prospecting at some challenging areas like carbonate-covered mountain areas, steep strata, and thick dry sand-mudstone with high velocity which influences reflection of underlying formations, but these kinds of sedimentary caps do not influence signals of 3D CEMP, therefore, 3D CEMP are more satisfying than 2D (Sun et al. 2007).

Figure 1 is the configuration of 3D small-bin CEMP acquisition. The electrodes (M, N) are deployed end to end in form of closed circuit with array of 2 × 2, or 3 × 3… or 5 × 5 (2 × 2:2 channel × 2 channel, 4 receiver sites). The receivers are synchronously controlled by GPS. The size of small-bin depends on the number of receivers and actual topography. When the receiver number is small and topography is poor, the array of a small-bin may be 2 × 2, i.e., four electric receivers and one magnetic receiver (as Fig. 1). Since electric responses are recorded synchronously, electric fields can be re-adjusted according as the principle of closed circuit in the processing indoor. 3D static corrections can be done at space domain simultaneously for all the recorded data of the same small-bin in time domain. Magnetic responses can be processed in the same way. The acquisition presents better anti-noise than CEMP, thereby significantly improving the quality of acquired data (He et al. 2009).

The method is mainly used in complicated areas where seismic exploration is difficult to be conducted. It can provide guiding for seismic survey design, and provides the information about deep structures, thus target areas can be reduced and risk be decreased for seismic survey. The method has been applied in the western China, where the terrain presents complicated mountainous terrain, and in the southern China, where the ground is covered with carbonate rocks. The survey lines are in total several thousands of kilometers in length. Close attention has been paid to this method by oilfield companies (He et al. 2009).

2.2.2 New Surface CSEM Technique

There are several controlled source EM methods developed in China: such as Controlled Source Electromagnetic method with Low-or-Super-Low Frequency (CSEL F/SL F), for

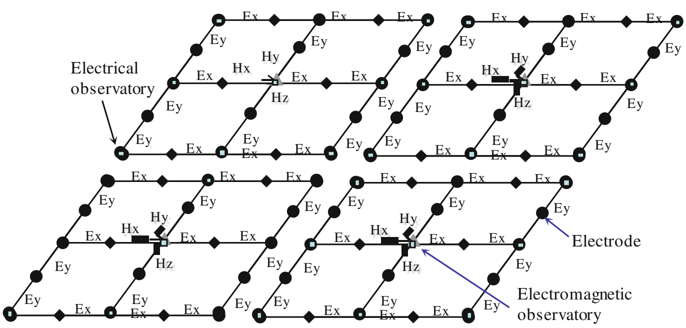

Fig. 1 3D Small-bin acquisition configuration

which scores or hundreds of kilometers transmitting antennas is installed at an area with high resistivity, and electromagnetic fields are measured. This method can be used to study the spatial magnetic field to investigate the underground structures (Zhao et al. 2003; Cai and Zhang 2006) just like MT. But these methods can only be used for studying deep—seated structures, but rarely for hydrocarbon prospecting. For controlled source methods imported from the western countries, such as CSAMT (Goldstein and Strangway 1975; Zonge and Hughes 1988), LOTEM (Keller et al. 1984; Strack 1992; Strack et al. 1990), LOWTEM (Long Offset & Window Transient Electromagnetic Method) and Array TEM (Cai and Zhang 2006; Zhao et al. 2004; Hu et al. 2008), a low power source is usually adopted, so they are unsuitable for hydrocarbon prospecting. LOWTEM and Array TEM have been developed and applied to reservoir monitoring (Hu et al. 2008).

BGP has put forwards a new concept—high power EM technique, which has led the development of CSEM methods for oil exploration in China. SIP, one of these advanced methods, has been applied in hydrocarbon prospecting for the past over 20 years, and now fully developed (Luo and Zhang 1998) and it has contributed much to us in this region (He 2006) But nowadays hydrocarbon prospecting has set foot in the areas with more and more complicated surfaces, these methods can not satisfy our demands anymore; in other words, they work well only in areas with relatively flat terrains. At the same time, a high power CSEM method—TFEM technique, has been greatly and quickly developed.

Presently, almost all CSEM acquisition systems, either CSAMT or LOTEM, or others, can only adopt a single acquisition mode. If a system adopts the CSAMT mode, it can only measure frequency domain data (He 1990), but if a system adopts LOTEM acquisition, the system can only measure time domain data (Zonge et al. 1972). TFEM is a new CSEM technique, for which data at both time domain and frequency domain can be recorded simultaneously (He et al. 2002a, b). Figure 2 shows its acquisition configuration. Theoretically, time-domain data is equivalent to frequency-domain data (He 2006, 1990; Zonge et al. 1972; Kaufman and Keller 1983), since time-domain data and frequency-domain data could be converted mutually by means of forward and inverse Fourier transform (Kaufman and Keller 1983). However, the transform is only from time domain to frequency domain.

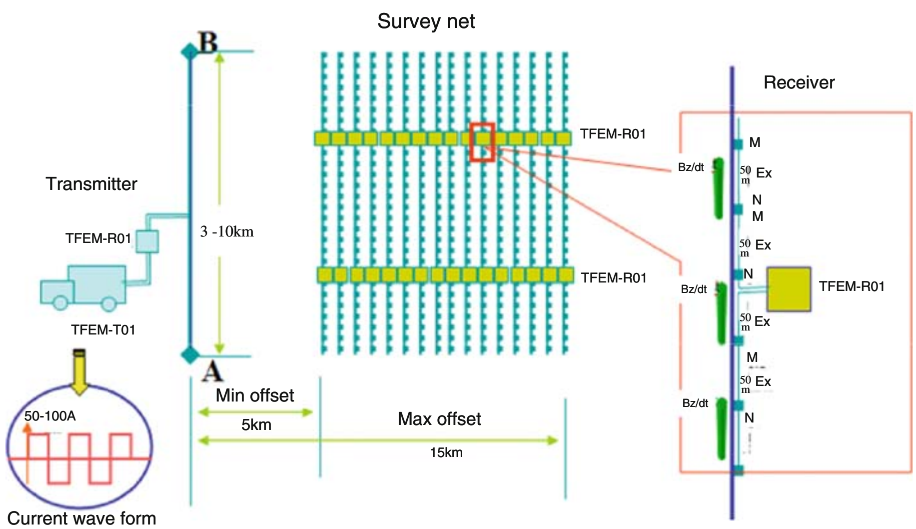

Fig. 2 TFEM Acquisition configuration

There are many differences between the two kinds of data due to narrow-band frequencies and less frequency number used in frequency domain and errors. TFEM system can integrate time-domain and frequency-domain acquisitions (He 2005; Wang and He 2006). The system transmits and records a series of frequency/periodical square wave pulses. Thus, a full spectrum can be analyzed, and its attenuation trend can be concluded. The integration of time-domain data and frequency-domain data can decrease the ambiguity and increase the accuracy, thereby reducing exploration risk.

Electrical and magnetic fields can be simultaneously studied with TFEM method, and their parameters like resistivity (or conductivity), polarization, phases, and dual-frequency phase can be used to describe different physical properties of underground rocks. By means of accurate inversion based on the formation, physical property model like resistivity, polarization, or lithology distribution, can be accurately reconstructed. Having many parameters improves the accuracy of the reconstructed models. So the method presents more advantages than any of the two separate methods since it integrates frequency domain data and time domain data. In the past few decades, it was applied mainly to study and evaluate the hydrocarbon perspectives of seismic traps. Up to now, the method has been applied in dozens of areas for the oil prediction and target evaluation, and all the results are desirable (He 2005; Wang and He 2006; Dong and Zhao 2008).

2.2.3 Borehole-Surface CSEM Techniques

Borehole-surface CSEM method has two trends in China. One is borehole-surface electric potential method, for which casings are adopted as current electrodes and ground electric potential is measured. It is used to monitor the water injection of oil field. The method has been applied in some oilfields (Zhang 2001; Su et al. 2006) in recent years. The method is almost the same as the electric potential methods used in western countries, so there is no need to describe it here.

The other trend is borehole-surface time and frequency domain electromagnetic method (we call it BSEM). It has been developing for about 10 years. It is the extension of ground time and frequency electromagnetic technique. The method was first employed in Russia in 2000 and has been extensively adopted in recent years. We have improved the borehole-surface TFEM method and developed a transmitting and receiving system characterized by up to four square wave forms and 74 frequency points.

Its major feature is that one of two transmitting electrodes is located in a well and the other is on the ground. Its receivers are placed on the ground (Fig. 3). The electrode located in the well needs to be placed at different depth at different time, and the receivers record their ground potential respectively. The method is suitable for the cases that an oil-producing fault block is available and oil-bearing potential of adjacent blocks needs to be determined. The method can reduce risk of exploring wells and can provide a reliable basis for well location design. We have performed trial production at many wells in five oilfields in China and obtained very desirable results (He and Liu 2004, 2005). The success ratio is about 85% more.

2.3 EM Data Processing Techniques and Software Development

In recent years, China has entered the stage of application of processing, modeling and inversion of 2D MT data. Numerous 3D MT modeling and inversion methods have also been developed in China, and now it is coming into the phase of rapid development of 3D processing and inversion (Wang 2006). Staggered mesh method etc. are the major

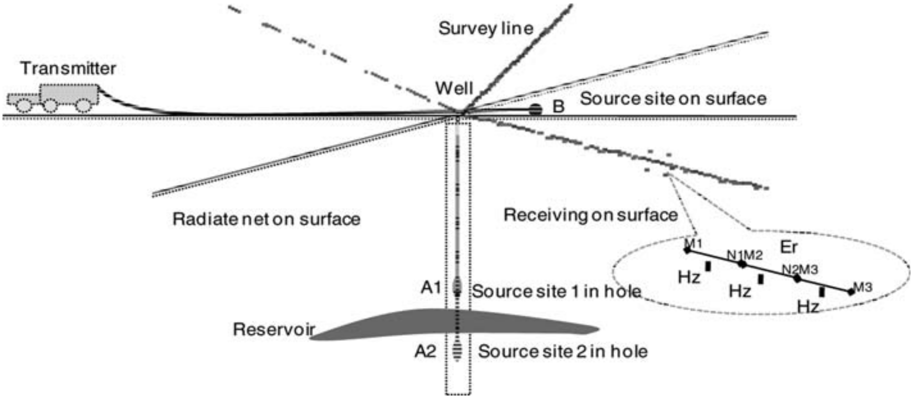

Fig. 3 Acquisition configuration of BSEM system

algorithms for 3D MT modeling (Shen 2003; Tan et al. 2003a, b). The 3D modeling and inversion methods have been greatly developed in their application (Tan et al. 2003a, b; Hu et al. 2005, 2006). It is worth noting that, with the development of large-scale parallel processors and parallel implantation of several algorithms, the computing platform for 3D MT modeling and inversion has been gradually developed from a single computer to PC-clusters and to large-scale parallel computers (Tan et al. 2006; Liu et al. 2006). Forward modeling of controlled source electromagnetic methods has also been developing towards 3D (Wang et al. 2007a, b; Ruan and Wang 2005). 2D modeling and inversion have been developed remarkably (Lei et al. 2004; Yan et al. 2004; Xiong et al. 2004), but there is a long way to go for their application. In fact, pseudo-2D inversion is popularly used nowadays.

Presently, TFEM data is processed with 2D or pseudo-2D modeling and nonlinear conjugate gradient pseudo 2-D Inversion, realizing joint inversion of time and frequency domain data. It includes constrained resistivity inversion and polarization inversion of model's geometric interface. With the development of data processing method, the related software for EM data processing and interpretation has been greatly improved. It is the same with visualization software (Zhang et al. 2002; Chen et al. 2004), which is of full functions and easy operation. A software system has been developed by China University Petroleum (Beijing), which is equipped with functions of data processing, joint inversion and imaging, and comprehensive geological interpretation in an interactive and visualization way, so it realizes the combination of all available geophysical data and information, e.g., EM data, gravity and magnetic data, and seismic data. GMES_V3.1, a subsystem about GME (Gravity, Magnetic, Electric) techniques, is developed on the basis of a seismic data processing and interpretation system GeoEast® by BGP. It provides a platform to share gravity, magnetic, electromagnetic and seismic data and jointly process and interpret them.

2.4 EM Interpretation Method for Hydrocarbon Exploration

In China, electromagnetic techniques for hydrocarbon detecting have been successively developed (Li 1998; Liu 1980; Qian 1985, 1991; Nie and Zhang 1987). The geo-electrical anomaly pattern of a reservoir and the IP mechanism result from a reservoir (Jiang et al.

1995; He 2007) have been concluded with the experiences obtained from a large number of test surveys with Induced Polarization method during 1970s and 1980s. Since 1990s, another method—Complex Resistivity has been conducting in China for oil prospecting since detection depth of IP method is small. After Complex Resistivity survey results were submitted, 65 wells were deployed according to all available geophysical data, among them, 47 wells are within favourable areas predicted with Complex Resistivity results. So success rate is up to 70% (Wu and Cui 1996). Principle of Complex Resistivity is to study the near-surface secondary anomalies which are usually distorted by faults, igneous rocks and ambient noise. Decades' experiences show that the method works not very well and it is difficult to apply it in practice.

In recent years, high power borehole-surface and time–frequency electromagnetic instruments have been produced. The anomaly mode of an oil reservoir—the three-storied electrical anomalies (He 2007)—has been put forward, as well as hydrocarbon detection with multiple electromagnetic parameters. The shallow (top) anomaly zone shows low resistivity and high polarization, which is the basis for traditional methods. The middle one shows relatively high resistivity and polarization. The immigrated hydrocarbon partially stays in formation pores just above the reservoir and gradually forms calcification, which makes the formation show higher resistivity and polarizability than the uncontaminated host. The deep (bottom) anomaly zone corresponds to the reservoir itself. It shows higher resistivity and polarization at the reservoir center than that at the host. Since there exists an electric double layer between the pores filled with water (or/and gas and oil) and the host, high IP effect will occur when a current goes along the electric double layer. We know that water outside the reservoir boundary shows higher infiltration capacity than oil and gas, so stronger polarization effect will appear at the oil–water interface. In addition, since oil reservoir shows high resistivity while water reservoir shows low resistivity, the bottom zone will show ring shaped anomaly, and the actual anomaly is generally monolithic.

IPR method is combination of IP and resistivity (R) method. Parameters for IP method include polarization, time constant, double frequency phase, etc.; parameters for R method include resistivity, electric field amplitude, double frequent amplitude, etc.

IPR method for hydrocarbon reservoir detection is on the basis of three-layered geo-electric anomaly pattern and high-precision TFEM acquisition configuration. 2D or 3D inversion results can describe the spatial distribution of resistivity (R anomaly) and induced polarization (IP) anomalies, based on which hydrocarbon traps can be detected and known reservoir can be mapped. Figure 4 shows IPR anomaly pattern of hydrocarbon reservoirs.

3 Case Studies

3.1 3D CEMP Survey in Challenging Areas

Topography in Western China is characterized by complicated piedmont terrain, where it is difficult to conduct seismic survey, so 3D CEMP survey has been widely applied in this region, like in Kuche and Taxinan of Tarim Basin, western Qudam Basin, northern margin of Qudam Basin, western margin of Erdos Basin, and in the carbonate-covered area in northeastern Sichuan, and the results are satisfying. 3D CEMP survey has three major functions: it can help find potential targets for seismic survey at complicated areas; it can also provide reliable evidences to confirm structures predicted with seismic data but of uncertainty; and for some very important perspectives, integrating gravity, magnetic, 3D

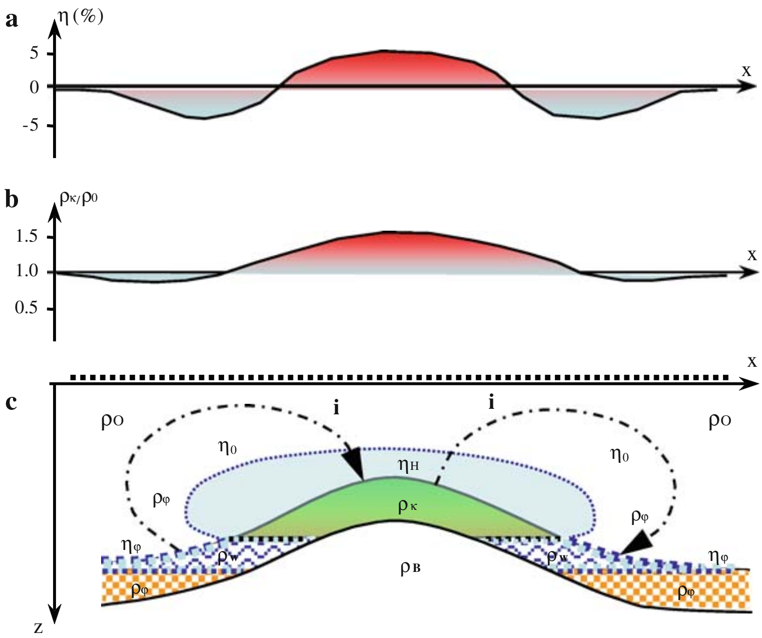

Fig. 4 IPR Anomaly pattern of hydrocarbon reservoir **a** IP anomaly: η is the ratio of secondary to primary potential, **b** Resistivity anomaly: ρ_κ resistivity, ρ_0 is resistivity of background, **c** Reservoir model

CEMP and seismic data can detect and further confirm deep structures. Figure 5 shows the topography relief at Huatg area in Qaidam Basin for following case.

Terrain at Huatg area varies sharply as described in Fig. 5. Within an area of 400 km^2, the elevation difference reaches up to 700 m. Due to complicated topography and complicated underground structures, seismic reflection of deep layers is poor and of low reliability, which limits exploration progress at this area. So the client plans to conduct 3D CEMP survey for the purpose of confirming deep structures predicted with the seismic data. The 3D CEMP observation grid is 500 m × 500 m, and the survey area covers 405 km^2 with geophysical sites of 1,766 in total. The geological objective is to determine depth to the bottom of N_3^1 group over Lower Tertiary and depth to the top Paleozoic system, as well as to predict potential targets for the coming exploration.

3D CEMP inversion is conducted on PC Cluster with quasi-3D parallel nonlinear conjugate gradient algorithm. The actual node number reaches up to 100 × 50 × 50. It can perform 3D inversion with observation points of 1,700 in total each time.

According to 3D inverted result (Fig. 6), there is developed a due northward deep structure at the central of the survey area, and structures at the bottom of Lower Tertiary apparently inheres from those of the top Paleozoic system. Within the northward uplifted structural belt there developed three traps with structural high at well S-25, to the North of well Yh-3, and to the north of Well Jc-1 respectively. It means that local structures are well developed at the deeply-seated northward structural belt. The known data shows the survey area is a part of a hydrocarbon-producing depression, so the northward structural belt is predicted as a potential target, especially the trap marked with black rectangle in Fig. 6. Much attention is paid to this marked trap from the client, so they plan to deploy a seismic

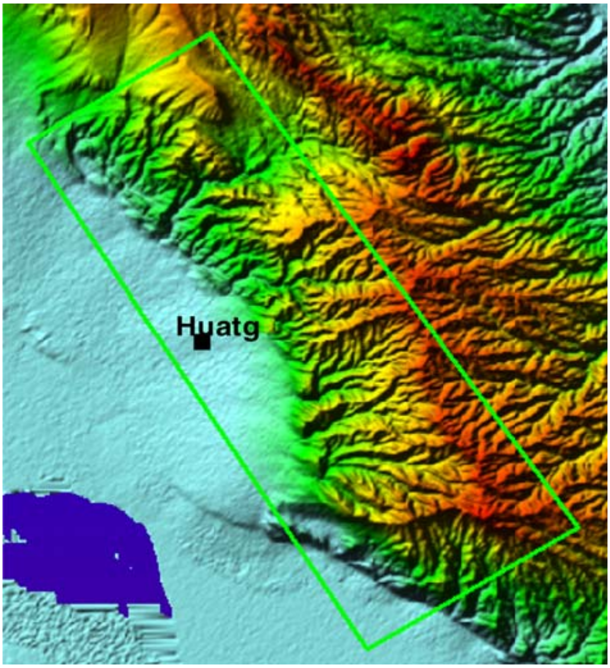

Fig. 5 Topography relief and the location of the survey area

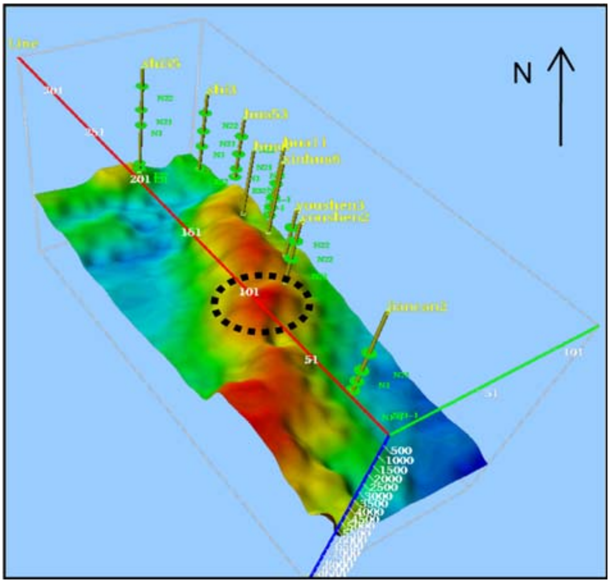

Fig. 6 Iso-resistivity section

line there for the purpose of further confirming the predicted structural high; once it is confirmed, a well location will be designed there for drilling.

3.2 Investigation of Deeply-Seated Igneous Rocks

Figure 7 shows the results of TFEM data obtained from SH Basin, China for the purpose of detecting deep igneous rocks. Since some important hydrocarbon potentials have been discovered within igneous rocks and igneous rocks are well developed in Permian and Carboniferous formations, so, Permian and Carboniferous formations are regarded as potential targets. Due to large burial depth and high velocity of overlying layer, seismic reflection from deeply-seated layers is disordered and unclear, and the distribution of igneous rocks and hydrocarbon cannot be predicted only with seismic data, let alone the details of inner structural belts and traps. So TFEM survey is deployed there and acquired data are processed and interpreted combining with seismic data. Inversion section of TFEM data shown in Fig. 7 clearly describes the lateral and vertical variation of resistivity.

The section shows that resistivity variation at the shallow matches well with that on seismic section. High resistivity of about 150–165 Ωm on the section corresponds to Lower Permian (P1k), presenting continuous lateral variation with thickness of over 600 m. According to the geophysical properties of rock cores collected at the area, it is predicted as intermediate-to-basic igneous rocks mainly characterised by overflow facies.

High resistivity anomalies (155–185 Ωm) with discontinuity between sites 30–70 and 95–110 are predicted as Carboniferous formation. According to the geophysical property

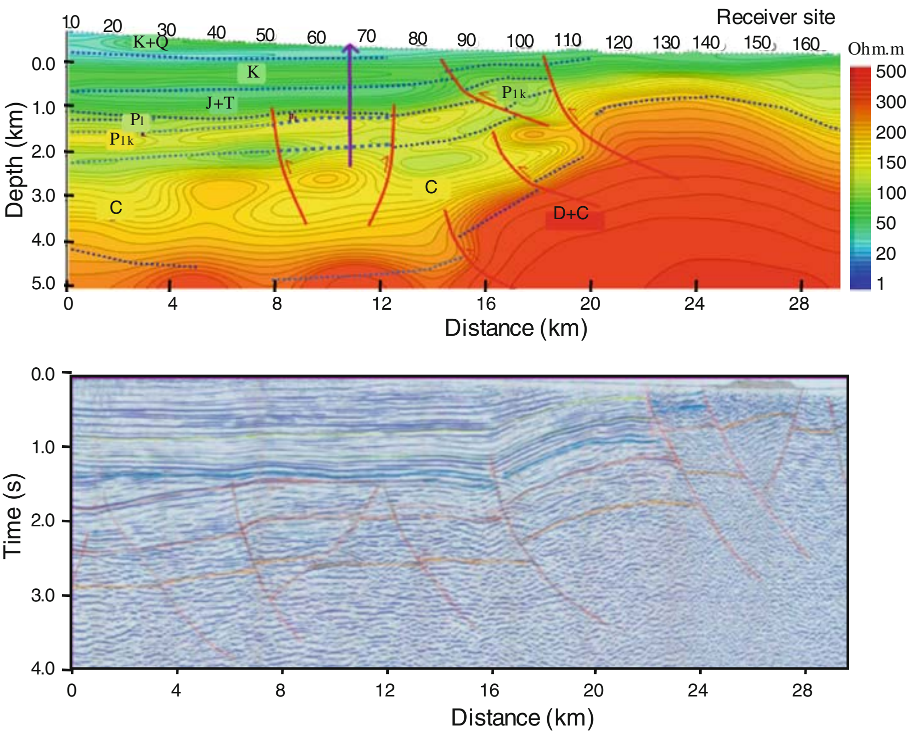

Fig. 7 Inverted resistivity section and seismic section

Table 1 Well Ma-20: drilling results versus predictions

	Formation	Lithology	Lithofacies	Depth to its top	Thickness
Prediction	P1K	Intermediate-to-basic	Overflow	1,400 m	>600 m
	C	Intermediate-to-basic	Overflow	2,200 m	>1,300 m
Drilling results	P1K	Brown basalt (80%) Basalt (20%)	Overflow	1,381 m	634 m
	C	Grey basalt (90%) Andesite/mustone (10%)	Overflow	2,215 m (bottom not penetrated)	385 m (bottom not penetrated)

of rock samples collected at the area, the mass is predicted as intermediate-to-basic igneous rocks with the major facies of overflow.

Well Ma-20 corresponding to point 68, drilled in July, 2007, shows that Lower Permian formation (P1k) is a suite of brown continental basalt, and Carboniferous formation is a suite of deep sea Carboniferous carbonic mudstone and brown basalt deposit. The drilling results fit well with the predicted ones (Table 1).

3.3 Mapping Potential Oil-Bearing Targets

Related study indicates that apparent resistivity and IP anomalies above the reservoir can be detected (Kirichek et al. 1974). In a sedimentary basin, a reservoir presents higher resistivity than that of its host, and there is an electric double layer on the interface between these two mediums which will cause IP effect when a strong current crosses this interface. So the two parameters—resistivity and polarizability—can be used for hydrocarbon detection. Only when the both show high anomalies, the corresponding target can be predicted as potential with top-priority, whereas if only one of these two parameters shows high anomaly the corresponding area will be predicted as secondary potential.

Figure 8 shows resistivity and polarizability inversion sections of TFEM data at YM area, Tarim Basin in western China. Since igneous rocks are well developed at the survey area, seismic reflection is poor and it is difficult to recognize the hydrocarbon reservoir. It is suggested that a TFEM survey should be deployed in order to detect hydrocarbons.

Wells E32, E321 and E33 are the known oil-producing wells. All these wells correspond to structures high of both high resistivity and high polarizability. So these three areas are evaluated as potential areas.

Well E35 corresponds to a geo-electric structure which is of both resistivity high and polarization high, so this area is predicted as a perspective one (Grade I).

Well E38 corresponds to a geo-electric structure which is of resistivity low and polarization high, so this area is predicted as a secondary potential area (Grade II).

Well E44 corresponds to a geo-electric structure which is of resistivity low and polarization high, and there appears another layer with low resistivity, so this area is predicted as secondary potential area (Grade II).

Well E35 was drilled in February 2006 and our predictions have been verified. Commercial oil fluid with daily oil production of 142 m^3 has been obtained at depth between 5550 and 5590 m (corresponding to Silurian System). Well E38, drilled in 2007, has only oil and gas show. Well E44, drilled at the same time and penetrating into siltstone, has only oil and gas show. Results of these wells show that our predictions are reliable.

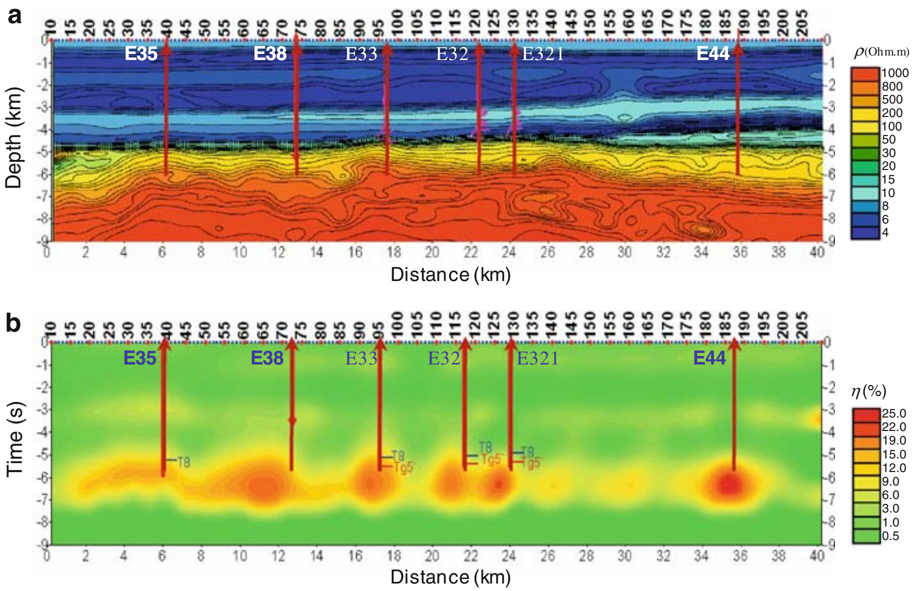

Fig. 8 Resistivity (*above*) and IP (*below*) inversion sections of TFEM data at YM area, Tarim Basin in western China

3.4 Reservoir Monitoring Using Array TEM Sounding

Formation resistivity is closely related to reservoir porosity, pore fluid saturation and properties. In general, the dominant pathway in water or steam-driven reservoir shows distinct resistivity differences between oil-bearing and water-bearing formation. This is the physical foundation for reservoir monitoring by electromagnetic sounding methods. Using seismic methods, it is difficult to detect changes of fluid formation due to the little difference of seismic velocity of oil-bearing or water-bearing formation. Based on their special features, electromagnetic methods with improved resolution should be applied to better mapping the oil–water contact interfaces, monitoring the water or steam-driven front, and dynamically picturing reservoirs and optimizing the developing plans.

Among electromagnetic methods, the time domain or transient electromagnetic method (TEM) is the first choice for hydrocarbon prediction of known structures in exploration and for reservoir dynamic monitoring in a producing field. This is due to its advantages of higher resolution, interference rejection ability and sensitivity to formation resistivity variations. Exploration depth coverage from several meters to several thousand of meters can be achieved by choosing proper observation parameters according to exploration tasks.

A pilot survey of time-lapse array TEM method was carried out at heavy oil reservoir in North West China from 2006 to 2007(Hu et al. 2008). The reservoir bed is braided river delta facies with formation thickness of 20–60 m and thinning gradually westward. The tectonic setting is relatively simple, the substructure is a monocline from the North West toward the South East with small gradient, the formation dip is 4–6° and the average depth of the lower boundary of the reservoir formation is about 400 m. A high power transmitter is used to deliver large current ($\sim$25 A) to the ground through a ground wire of 2 km in length, and offset (transmitter–receiver distance) is 5–10 km. Source waveform is square wave with period of 8–32 s. Distances between survey sites and survey lines are 100–150 m; in total, 13 survey lines and 180 sites were carried out.

Two surveys had been carried out for same sites in same area with possible same survey parameters setup for 4D dynamic monitoring purpose. First survey was carried out in July, and second survey was carried out in November of 2006. In general, the observed field results show good consistency for two surveys, some variations may be the contribution of the steam movements. Detailed interpretation will be given by difference plot of early time resistivity for whole survey area.

Figure 9 shows the time sliced plan plot of early time resistivity at 60 ms derived from data of second observation, which is approximately the depth of 400 m if we take the average resistivity of overburden layer to be 5 Ωm. The production wells are labeled as a blue dot and the steam injection well are red dots. This plot will give a plan view of resistivity distribution of the reservoir layer. Boundary lines are drawn to delineate area of low (<4 Ωm) and high (>4 Ωm) resistivity areas. It can be inferred that the high resistivity areas are the areas of high satuation of oil and contacted with the steam front. And the low resistivity areas are mixed with production and injection wells and are inferred to be water flooded.

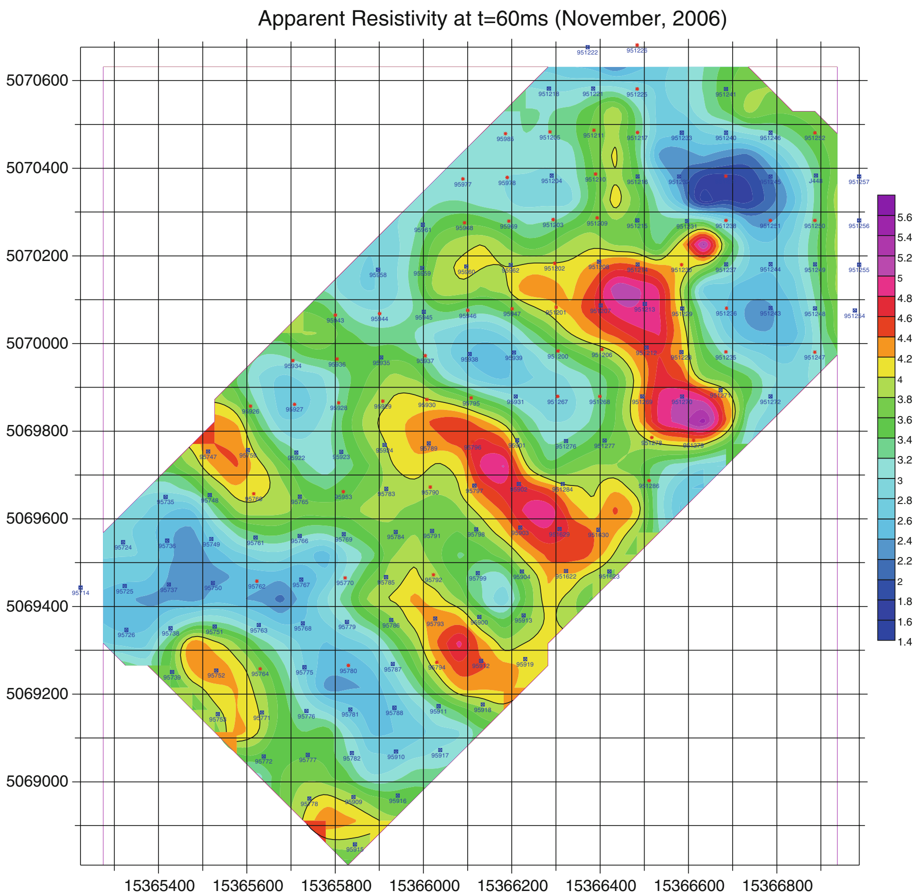

Fig. 9 Apparent resistivity distribution at $t = 60$ ms from second survey (Nov. 2006)

Figure 10 shows the apparent resistivity differences by subtracting the apparent resistivity data of the first survey from that of the second survey. The differences are expressed as percentages, with positive values representing the resistivity increasing from first to second observation and negative values indicate resistivity decreasing.

In general, the maxima and minima of difference of resistivity derived from two time lapped measurements occurred in regions of producing wells except in the channels of steam. Three regions with different speed of steam movement can be classified qualitatively from the residual map. However, more work need to be done for detail interpretation to take into account of complicate relationship between resistivity variation and steam phase change in reservoir. According to this interpretation results, some measures can be taken to optimized the production schedule for enhancing the output ratio.

This study has shown the feasibility of dynamic monitoring of steam or water driven reservoirs by employing TEM method with electric dipole source. Field trials had made successful measurement of electromagnetic field and preliminary processed results show

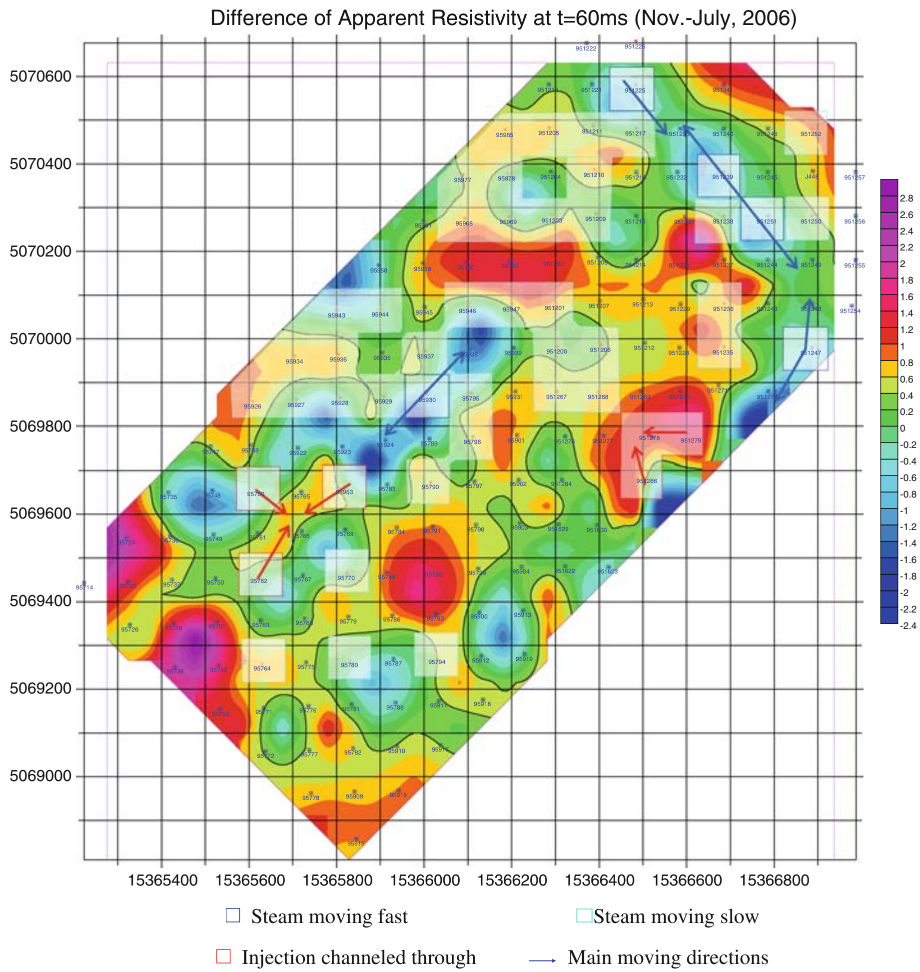

Fig. 10 Apparent resistivity differences at $t = 60$ ms and qualitative inferred interpretation

resistivity anomalies well correlated to the steam front and residual oil. Further detailed interpretation combined with geological and petroleum engineering information is needed for future studies.

4 Conclusions

EM methods have been dramatically developed in China in recent years. With higher and higher requirements on hydrocarbon exploration from oilfields, the integration of EM and seismic surveys has been becoming an effective approach to solve complicated problems, especially 3D EM and higher-precision hydrocarbon detection methods: joint of seismic-EM, which will play more and more important roles in petroleum exploration.

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