High-Precision Magnetic Anomaly and Geological Significance of Shale Gas in Upper Yangtze Region 2018 IFEDC

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Abstract. The accumulation pattern of the marine shale gas in South China is different from that in North America. The former has generally thin reservoirs and complex preservation conditions, so it is difficult to make a fine description of the structural features of shale formations and to reflect accurately the distribution pattern of high-quality shale by using the conventional seismic exploration technology. Based on data processing such as data correction, reduction-to-pole of magnetic data, space transforming, derivative conversion, smoothing filter and regularization filter, the magnetic anomalies were observed and analyzed, and the regional geological structure is divided in detail. The magnetic substrate obtained is the magnetic interface of metamorphic rocks equivalent to the Middle Proterozoic top boundary, with a depth of 2–4 km, reflecting the structural morphology and undulating characteristics of the metamorphic crystalline basement. The low parts on the magnetic basement provide the formation and accumulation of the Late Permian-Early Jurassic shale gas in the basin, in which favourable exploration blocks could be found. The fault structure in the study area has two layers of structure in space. The matching relationship between the sedimentary cap fracture and the basement fault controls the spatial distribution of the dominant reservoir together.

This paper was prepared for presentation at the 2018 International Field Exploration and Development Conference in Xi'an, China, 18–20 September, 2018.

J. Lin (ed.), *Proceedings of the International Field Exploration and Development Conference 2018*, Springer Series in Geomechanics and Geoengineering, https://doi.org/10.1007/978-981-13-7127-1_53

Our research can guide shale gas exploration and development in this area and balance the high upstream exploration cost, and continue to push the efficient shale gas exploration and development process in China.

Keywords: Shale gas · Magnetic exploration · Cap rock · Magnetic basement · Fracture

1 Introduction

Shale gas has caused widespread concern both at home and abroad for its wide distribution and large storage. Compared with developed countries such as the United States, however, China's current investigation and exploration on shale gas resources is relatively low [1–3]. How to overcome various difficulties and vigorously promote the strategic investigation, exploration and development of shale gas resources has become an important and urgent strategic task in the field of oil and gas resources in China [4, 3].

All the time the geophysical methods used in oil and gas exploration is seismic exploration. However, the use of conventional seismic exploration methods are limited for the complex structure and poor seismic data quality, leading to a large difficulty to reservoir interpretation and prediction [2, 5]. The high resistivity carbonate strata block the downward penetration of seismic elastic waves, and thus it is difficult to obtain structural and stratigraphic positions, especially the reliable information in deep part [6, 7]. The two-dimensional seismic exploration in the work area also shows that the quality of the two-dimensional data collected in the field is poor and cannot satisfy the fine interpretation of the formation. In addition, the drilling failure of well TM1 in this area also shows that it is limited to infer the structural characteristics of the target layer only by seismic exploration method. Based on the above facts, it is particularly important to take a variety of geophysical exploration methods to re-understand the structural pattern of the study area.

2 Materials and Methods

2.1 Geological Setting and Samples

The Cen'gong block study area is located in the southwestern part of Tongren city in northeastern Guizhou province, covering a total area of 914 km^2 in the Qianbei area (Fig. 1). The tectonic location of the study area is in the trough-like fold belt of western Hunan-Hubei province on the southeastern margin of the Upper Yangtze plate, where the structural conditions and stress fields are complicated due to multi-stage tectonic movements and deformations. The study area experienced Xuefeng (Neoproterozoic), Caledonian, Yanshanian (Jurassic-Cretaceous) and Himalayan multi-phase tectonic movements, and the Yanshanian movement laid the foundation for the current geological structures and landforms [8]. Complex structures are developed in the study area and are mainly NE and NNE trending. Stratigraphic from Sinian to Quaternary has different levels of development in Cen'gong shale gas block, and from older to younger they are Fanjing Mountain Group, Banxi Group and Sinian, Niutitang Formation($\in_1$n), Bianmachong Formation($\in_1$b), Palang Formation($\in_1$p), Qingxudong Formation($\in_1$q),

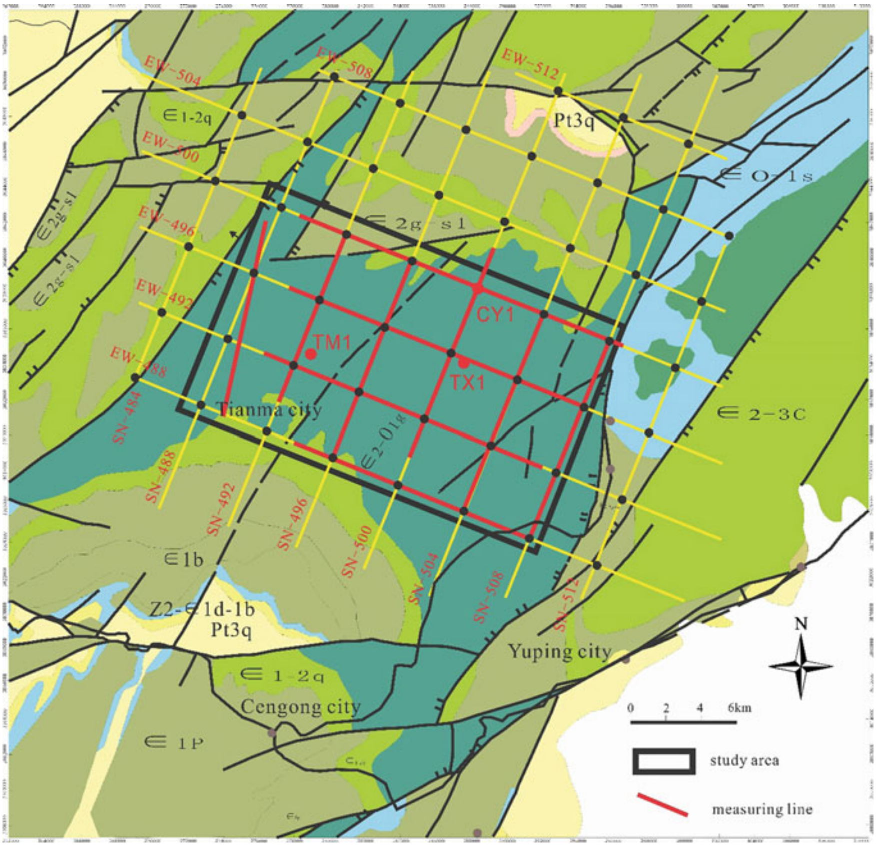

Fig. 1. The formation and magnetic position of the study area

Gaotai Formation($\in_2$g), Loushanguan Formation($\in_3$gls), the lower Ordovician and clay in the Quaternary [8–10] (Fig. 2).

In this paper, we make a statistical study about the magnetic property of metamorphic rocks, carbonate rocks, sandstone in survey area (Table 1).The magnetic susceptibility of sedimentary rock in the Sinian system, Cambrian system, Ordovician System and Quaternary System is very weak, varying between 0 and $25 \times 4\pi \cdot 10^{-6}$ SI. Rock in Upper Proterozoic mostly is shallow metamorphic rock, and magnetic

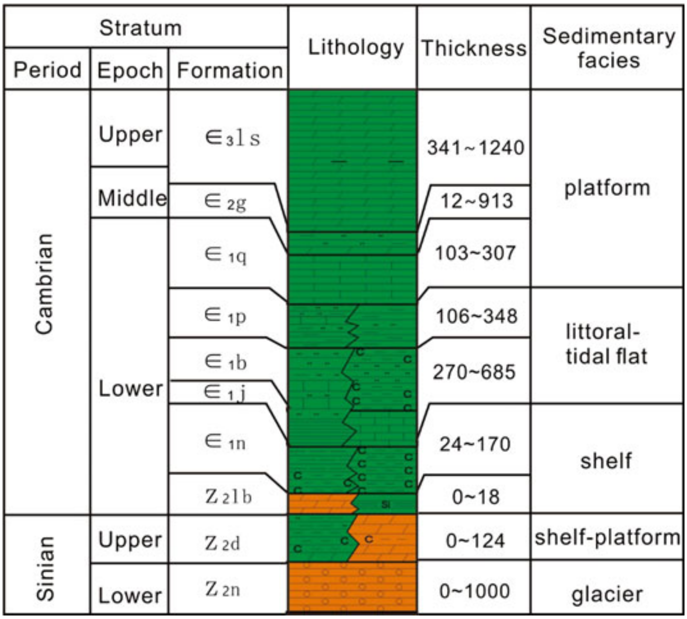

Fig. 2. Columnar section in Cen'gong Shale Gas Block

susceptibility is generally smaller than $25 \times 4\pi \times 10^{-6}$ SI. The Middle Proterozoic consists of palimpsest tuff, diabase and gabbro, and magnetic susceptibility varies between 12 and $1462 \times 4\pi \times 10^{-6}$ SI, with an average value $76 \times 4\pi \times 10^{-6}$ SI. What's more, there is an unconformity between the Middle Proterozoic and its overlying strata. So the magnetic interface in Cen'gong shale gas block is generally considered as the Middle Proterozoic metamorphic top interface.

2.2 Method for Magnetic Field Data Processing

2.2.1 Normal Field Correction

The data taken by the proton magnetometer in the Cen'gong shale gas block are the total magnetic field intensity of the observation point, denoted by $T(x, y, t)$. To obtain the geomagnetic anomaly value ΔT (T) of the measurement point, the first thing to do is to correct the normal field (Fig. 3). In the data consolidation processing, the total magnetic field intensity observed by the observation points is reduced to the normal geomagnetic field $T_0(x, y, t)$, so as to obtain the geomagnetic anomaly value $\Delta T_1(x, y)$ without the diurnal variation correction (Formula 1). This method cannot meet the requirements of modern high-precision magnetic measurement. The method we adopt is to use the international geomagnetic reference field model IGRF (International Geomagnetic Reference Field), and thus there is no need to do a horizontal gradient correction [2, 5, 11]. The mathematical model of normal field correction for magnetic measurement is as follows:

Table 1. The synopsis of rock magnetic properties in survey area

Stratum		Symbol	Lithology	Magnetic susceptibility K ($4\pi \times 10^{-6}$) SI		Magnetic remanence Mr (10^{-3}A/m)	
				Change range	Means	Change range	Means
Quaternary	Cover	Q	Clay	0–5	1		<3
Ordovician		O	Marl, limestone, sandstone, dolomite	1–25	3–5	1–38	<3
Cambrian		∈	Dolomite, limestone, sandstone, shale	0–25	1–6	0–87	<3
Upper proterozoic		Pt3-Z	Siliceous, shale, dolomire	0–25	1–6	0–87	<3
		Pt3-Nh	Shale, carbonate rock	0–25	1–6	0–87	<3
Lower proterozoic	Basement	Pt2	Palimpsest stuff, diabase, gabbro	12–1462	76	1–1000	12

$$\Delta T_1(x, y) = T(x, y, t) - T_0(x, y, t) \tag{1}$$

where (x, y) is the geographical coordinates of the measurement point; T_0 (x, y, t) is the normal magnetic field in time t; T (x, y, t) is the observation value of the field observation time t proton magnetometer; ΔT_1 (x, y) is a geomagnetic anomaly that has not been corrected by diurnal variation correction.

2.2.2 Diurnal Variation Correction

The current system on the earth's upper atmosphere has a short period of influence on the earth's magnetic field, which changes big in the daytime, while is small and relatively at night. This twenty-four hour cycle is called geomagnetic diurnal variation. The result of geomagnetic diurnal variation is that the magnetic field values measured at same point will change with time from several nT to above dozens of nT, and thus the effect of the measured data must be eliminated, which is called diurnal variation correction [2].

The mathematical model of daily variation correction for field magnetic data is as follows:

$$\Delta T(x, y) = \Delta T_1(x, y) - \Delta T_0(T) \tag{2}$$

where ΔT_1 (x, y) is the geomagnetic anomaly without the diurnal variation, and ΔT_0 (T) is the diurnal variation of the t at the observation time, and the ΔT (x, y) is the geomagnetic anomaly after the correction.

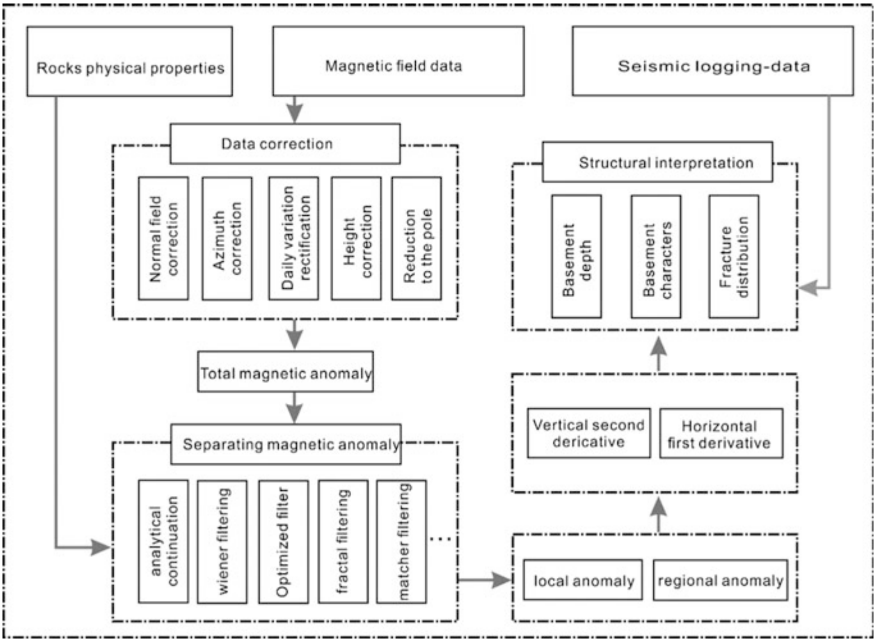

Fig. 3. General thought of inversion of magnetic method

2.2.3 Reduction to the Pole

The magnetic anomaly caused by the underground magnetic body at the earth's magnetic pole is converted to the assumed magnetic body. The magnetic anomaly caused by the earth's magnetic pole is called the magnetic anomaly. This is a theoretical model. In practice, it is often called the polarization of the oblique magnetization. After the underground magnetic body passes through the pole, the projection of its space position on the ground can correspond exactly to the extremum position on the magnetic anomaly contour map, and the form of the magnetic anomaly will become relatively simple [12]. The purpose of this processing is to facilitate qualitative analysis and quantitative calculation, which makes the interpretation of indoor magnetic anomalies more easy (Figs. 4 and 5).

3 Results and Interpretation

3.1 Total Magnetic Anomaly

Through data collation, analysis and interpretation to the high precision magnetic anomalies in the study area are delineated. The mean square error of high precision magnetic survey is 3.19nT, and thus the lower magnetic anomaly in survey area is 10nT (Generally speaking, data greater than 2.5–3 times of the total mean square error of magnetic anomaly is reliable). Magnetic anomaly contour in Cen'gong Shale Gas Block can be mapped in accordance with 0nT, 10nT, 20nT, 30nT… (Fig. 6). In this

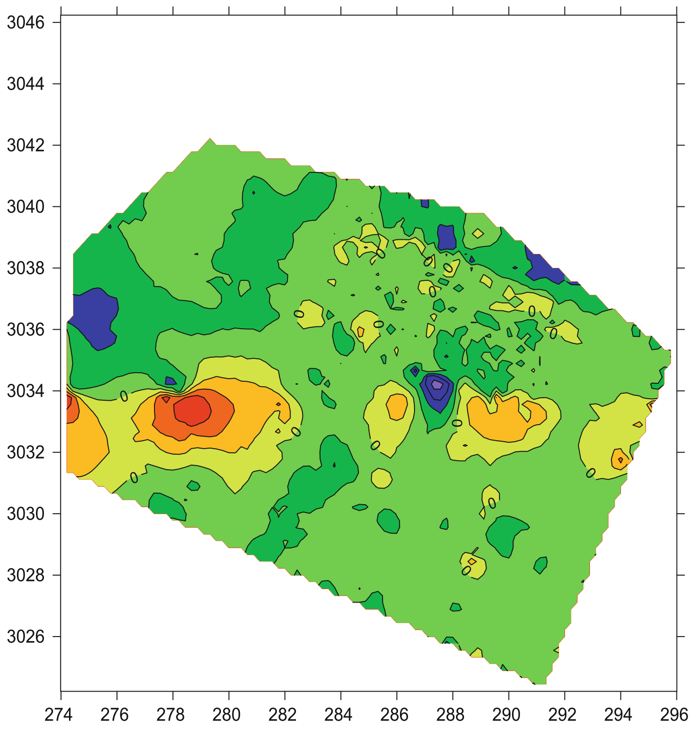

Fig. 4. Magnetic anomaly ΔT before reduction to the pole

study, 10 geophysical anomalies of high precision were collected, including 4 positive anomalies and 6 negative anomalies, and positive anomalies were distributed along East-West into beads, and the negative anomalies were distributed on both sides of the positive anomaly (Fig. 6).

3.2 Depth of Partial Magnetic Bodies

The depth of magnetic bodies is calculated by tangential method (Fig. 7), and the data can be used to govern the inversion when we calculate the depth of basement. This south-west region of well TM1, the magnetic basement depth is ranging from 2000 to 2200 m. The deepest place of magnetic basement is located in the middle near well TX1 and its surrounding, about 4000 meters, and the basement depth in the east is ranging from 2600 ~ 3500 meters [2] (Fig. 8).

Based on the high precision magnetic data of 1:50,000 in the study area, the residual magnetic anomalies of the base are extracted from the optimized filtering, regularized filtering and compensation circular filtering. According to the inversion results of magnetic profile, drilling data and rock physical data in the measured area, the buried depth of magnetic basement and the characteristics of basement undulation can be obtained by inversion calculation (Fig. 3). The magnetic interface in Cen'gong Shale Gas Block is generally considered as the Middle Proterozoic metamorphic top

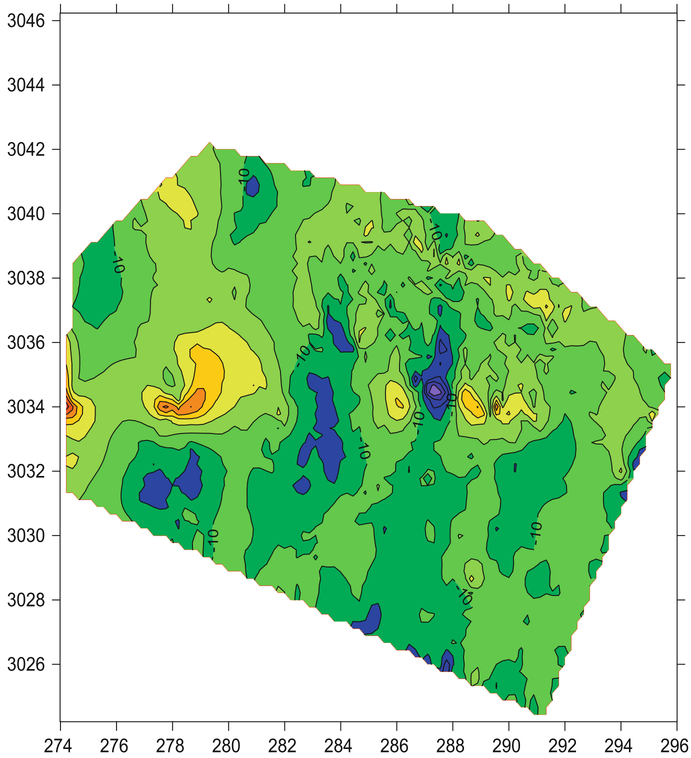

Fig. 5. Magnetic anomaly ΔT after reduction to the pole

interface and its depth ranges from 2 to 4 km. The lower position of the structure in sedimentary basins provides a good condition for the formation and accumulation of the shale gas in period from the Late Permian to early Jurassic favorable exploration and indicates favorable exploration tract of shale gas in search area (Fig. 9).

4 Discussion

4.1 Cause of Magnetic Anomaly and Shale Gas Sweet Spots

It was found that the abnormal high wave velocity existed above the oil and gas reservoirs, and is interpreted as the result of the upward migration of hydrocarbon in the sedimentary strata. The concept of "chimney effect" was proposed to explain the abnormal phenomenon as a result of special and secondary iron bearing mineral in the overlying strata of the oil and gas reservoirs, leading to geophysical and geochemical anomalies in the ground measurement. It was considered that the high frequency magnetic anomaly was closely related to the magnetite formed by diagenesis, and could be used to guide the exploration of oil and gas fields [2, 13, 14, 15, 16]. The stratas exposed are mainly comprised of the Cambrian strata, being characterized by

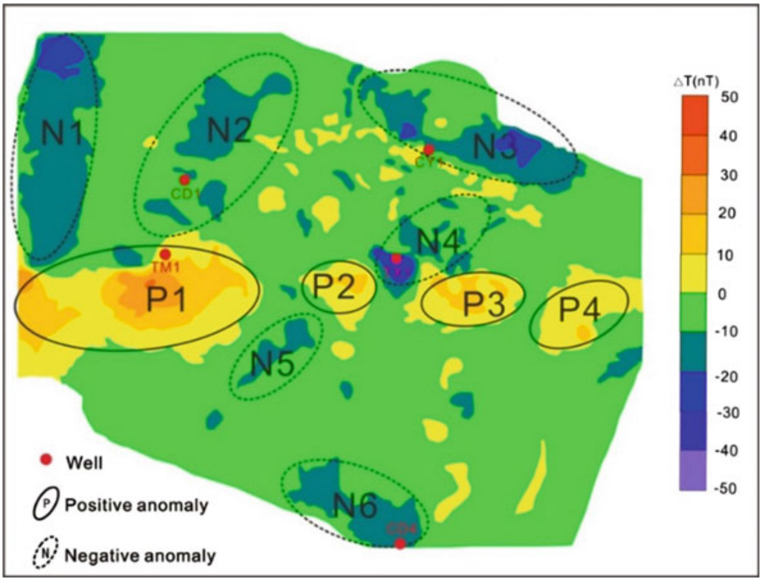

Fig. 6. Magnetic anomaly in Cen'gong shale gas block

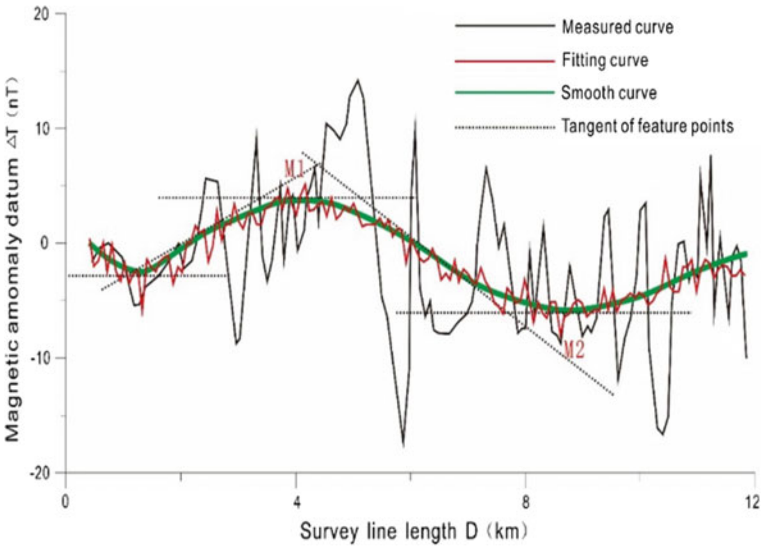

Fig. 7. Magnetic total field (ΔT) profile and tangential method

sedimentary rocks such as limestone and dolostone, which have weak magnetic susceptibility compared with the metamorphic rock in the basement, so the magnetic anomalies in the study area are mainly caused by metamorphic basement.

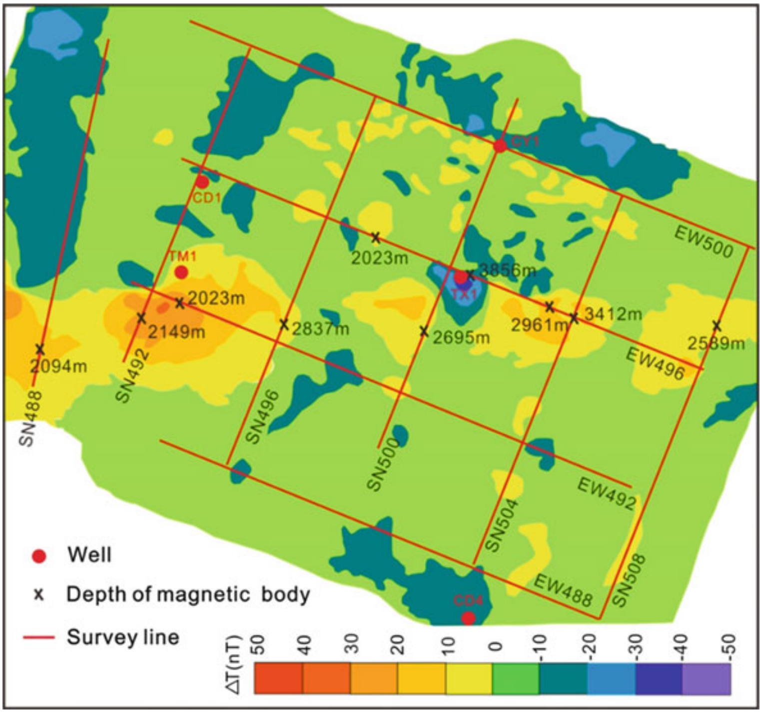

Fig. 8. Depth of magnetic bod

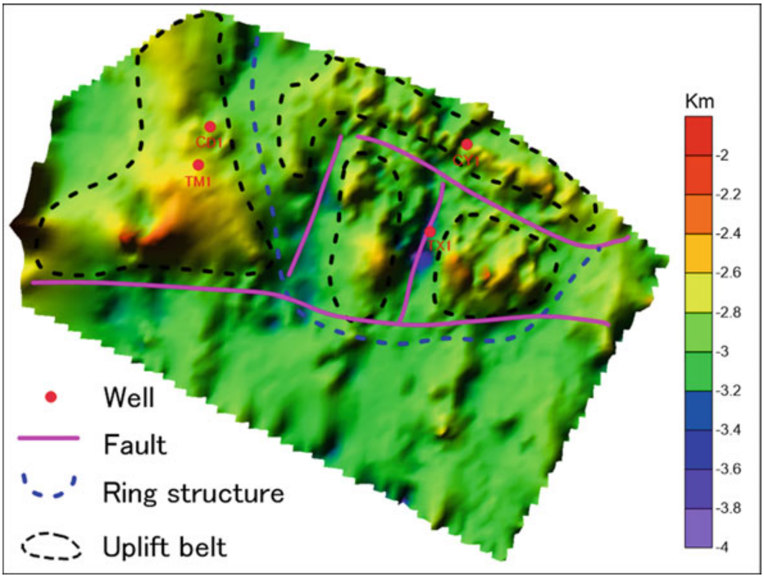

Fig. 9. The magnetic interface in Cen’gong Shale Gas Block and its basement faults

Five exploratory wells including wells CY1, TX1, TM1, CD1, CD4 are drilled in Cen'gong shale gas block, and among them wells CY1, TX1, CD1, CD4 are located in magnetic negative anomaly area while well TM1 is located in magnetic positive anomaly area. Wells CY1, TX1, CD1, CD4 all have different degrees of airflow, especially well TX1 with a length of flame 5–7 m in the gas-fired. But well TM1 is dry hole, which is located in west of TX1 within 10 km. These may indicate that shale gas in the Niutitang Formation may have certain correlation with the near surface magnetic anomalies. Is this correlation accidental or inevitable? If it is inevitable, then what is the nature between geology and geophysics. Is the indirect factor of geological structure or the direct factor of micro leakage diffusion of hydrocarbon? All these need further study.

4.2 Buried Depth of Basement and Its Oil-Gas Geological Significance

Based on the segment of deep seismic reflection migrated profile, the top boundary of the Middle Proterozoic (Pt2) is between 2.5 thousand meters to 4.5 thousand meters in the study area, while the top boundary of the Middle Proterozoic (Pt2) is between 3.0 thousand meters to 4.8 thousand meters based on resistivity profile (Figs. 10 and 11). The result above matches the magnetic base data well, calculated using tangent method and Euler deconvolution method (Figs. 8 and 9).

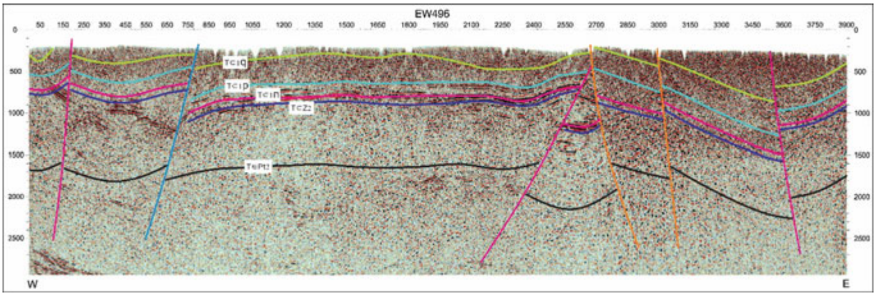

Fig. 10. The segment of deep seismic reflection migrated profile EW496

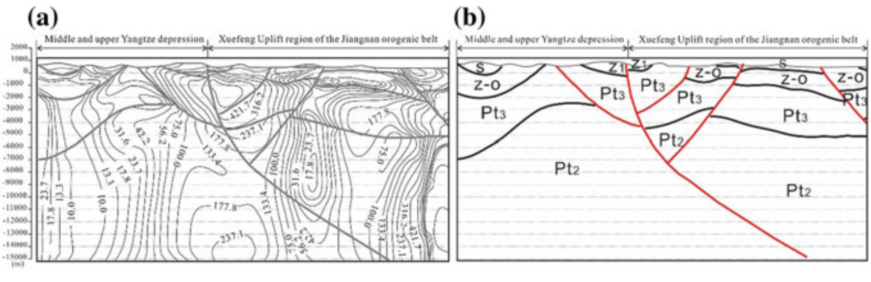

Fig. 11. Geological structure based on resistivity. **a** Resistivity profile in the study area (Hz); **b** Inversion of resistivity profile in two-dimensional continuous medium

The Niutitang formation has a good hydrocarbon generation, but the shale layer have experienced several periods of hydrocarbon and multi-stage tectonic movement, causing varying degrees of destruction of the preservation conditions of shale gas reservoirs. However, shale gas sweet sports may exist in a saddle shaped area with relatively stable structure and better preservation conditions [17, 9].

5 Conclusions

Our fieldwork has accomplished 29 survey lines with 100 m dot pitch of each line, which add up to 286 km and control an area of 240 km^2. The magnetic survey has collected 2034 magnetic data, including 60 checkpoints and 1974 magnetic data. On the basis of geological, geophysical and geochemistry data, this paper summarized the geological characteristics of regional geology and survey area. What's more, this paper introduced field data collection of high precision magnetic survey and the quality of data, and introduced characteristics of magnetic parameters.

By data processing such as data correction, reduction-to-pole of magnetic data, space transforming, derivative conversion, smoothing filter and regularization filter, our work has delineated 10 high accuracy aeromagnetic anomaly zones, and calculated the top depth of buried magnetic body which has a magnetic anomaly in each section through inversion calculation.

Our work was based on high precision magnetic data processing and interpretation in Cen'gong block of shale gas and study area tectonic, including of magnetic basement depth of the block, undulating morphology and the fracture distribution, which can guide shale gas exploration and development in this area.

Acknowledgements. This research work was funded by Major Projects of National Science and Technology "Large Oil and Gas Fields and CBM development" (Grant No. 2016ZX05027). Our grateful thanks are due to Shanghai Branch of CNOOC Ltd. for their help in providing geological data. Thanks are also due to anonymous reviewers for their constructive suggestions.

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