IOP PUBLISHING JOURNAL OF GEOPHYSICS AND ENGINEERING

J. Geophys. Eng. **8** (2011) 74–82 doi:10.1088/1742-2132/8/1/009

Investigation of igneous rocks in Huanghua depression, North China, from magnetic derivative methods

Ya Xu[1,4], Tianyao Hao[1], Baimin Zhao[1,2], Zhou Lihong[3], Lili Zhang[1], Zhiwei Li[1] and Song Huang[1]

[1] Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China
[2] China Aero Geophysical Survey and Remote Sensing Center for Land and Resources, Beijing 100083, People's Republic of China
[3] Research Institute of Exploration and Development, Dagang Oil field, Tianjin 300280, People's Republic of China

E-mail: xuya@mail.iggcas.ac.cn

Received 19 May 2010
Accepted for publication 1 November 2010
Published 9 December 2010
Online at stacks.iop.org/JGE/8/74

Abstract
The igneous rock study plays an important role in understanding the tectonic evolution of sedimentary basins. The distribution of igneous rocks is one of the basic aspects in the igneous rock study. Based on the magnetic susceptibility contrast of igneous and other rocks, magnetic methods are usually used in the igneous rock investigation. In this paper, we delineated the distribution of igneous rocks in Huanghua depression based on the reduction to pole (RTP) magnetic anomaly and its derivative processing results. The main methods used to enhance the anomaly character of igneous rocks include total horizontal derivative, analytic signal modules and the tilt angle. Based on the RTP anomaly and the derivative results, three types of igneous rock distribution areas are predicted in Huanghua depression. The large scale igneous rocks are mainly distributed in the north part of Huanghua depression. The string bead-shaped igneous rocks are mainly located in the north and southwest parts. Some craters are located in the middle-south part. The distribution of igneous rocks is controlled by the deep buried fault along the coastal boundary and the associated tertiary faults. Our study verified the validity of the magnetic derivative methods for the planar distribution study of igneous rocks. The study results of Huanghua depression are the basis of the seismic interpretation of igneous rocks and the tectonic study in this area.

Keywords: magnetic anomaly, igneous rocks, magnetic derivative methods, Huanghua depression

1. Introduction

Igneous rocks are important components of the earth's crust and widely spread in the shallow and deep crust. The igneous rock study is helpful to understand the regional tectonics, their effects on the sedimentary basins and reservoirs. Numerous hydrocarbon occurrences in and around igneous rocks were reported all over the world (Schutter 2003), including in China (Yang *et al* 2006b, 2009). One basic aim of igneous rock study is to delineate their distribution. Based on the high magnetic susceptibility contrast between igneous rocks and metamorphic/sedimentary rocks, magnetic methods are mostly used for the investigation of igneous rocks (Eventov 1997, Yang *et al* 2006a, He *et al* 2008, Jallouli *et al* 2003, Lin *et al* 2008). The dominant magnetic anomaly is associated with magnetic basement (mainly metamorphic and/or igneous rocks). The local variations of magnetic anomalies caused

[4] Author to whom any correspondence should be addressed.

 © 2011 Nanjing Geophysical Research Institute Printed in the UK

by scattered igneous rocks are superposed on the regional anomaly of magnetic basement. Igneous rocks can be identified from the local magnetic anomalies and the magnetic processing results (Sparlin and Lewis 1994, Secomandi *et al* 2003).

In this paper, we introduce magnetic derivative methods for the investigation of igneous rocks and apply them in the igneous rock study of Huanghua depression. The investigation of the igneous rocks of Huanghua depression started from 1964. These rocks are widely spread in Huanghua depression according to the core samples. Up to 400 wells have encountered igneous rocks, and several reservoirs associated with igneous rocks have been discovered in this area (Zhou *et al* 2000). However, the igneous rocks of Huanghua depression have different scales, and their distribution pattern has not been fully recognized. Here we discuss the igneous rock distribution of Huanghua depression based on magnetic data. The distribution pattern of igneous rocks and its geological implications are also discussed in the paper.

2. Methods

Various methods can be used to enhance the anomaly character of igneous rocks and assist in identifying the igneous rocks. One of the important methods is based on the derivative computation (Hsu *et al* 1996, Fedi and Florio 2001, Cooper and Cowan 2006, Wang *et al* 2009, Wijns *et al* 2005). Here we mainly used the methods based on the first-order derivative to study the distribution of igneous rocks.

The reduction to pole (RTP) operation transforms the magnetic anomalies centred over their causative bodies and simplifies the interpretation. All the processing we performed in this paper is based on the RTP magnetic anomaly. The basic derivative methods include the derivatives along the three axis directions, $\partial M/\partial x$, $\partial M/\partial y$, $\partial M/\partial z$, where M stands for the RTP magnetic anomaly.

The vertical derivative (VDR) and the total horizontal derivative (THDR) are two basic derivatives used for data enhancement and source body edge detection. The extreme value of the horizontal derivative and the zero value of the VDR can be used to locate the edge of geological bodies. The definitions of VDR and THDR are given as

$$\mathrm{VDR} = \frac{\partial M}{\partial z}, \tag{1}$$

$$\mathrm{THDR} = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2}. \tag{2}$$

The analytic signal used for edge detection in magnetic anomaly was first developed by Nabighian (1972, 1984) based on the first-order derivative. The analytical signal modulus (ASM),

$$\mathrm{ASM} = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2}, \tag{3}$$

is comonly used in magnetic interpretation. In addition, Miller and Singh (1994) proposed the definition of tilt angle (TA) as the ratio of VDR and THDR. It can balance dynamic anomaly changes and enhance the source edge anomaly features. The TA formula is given by

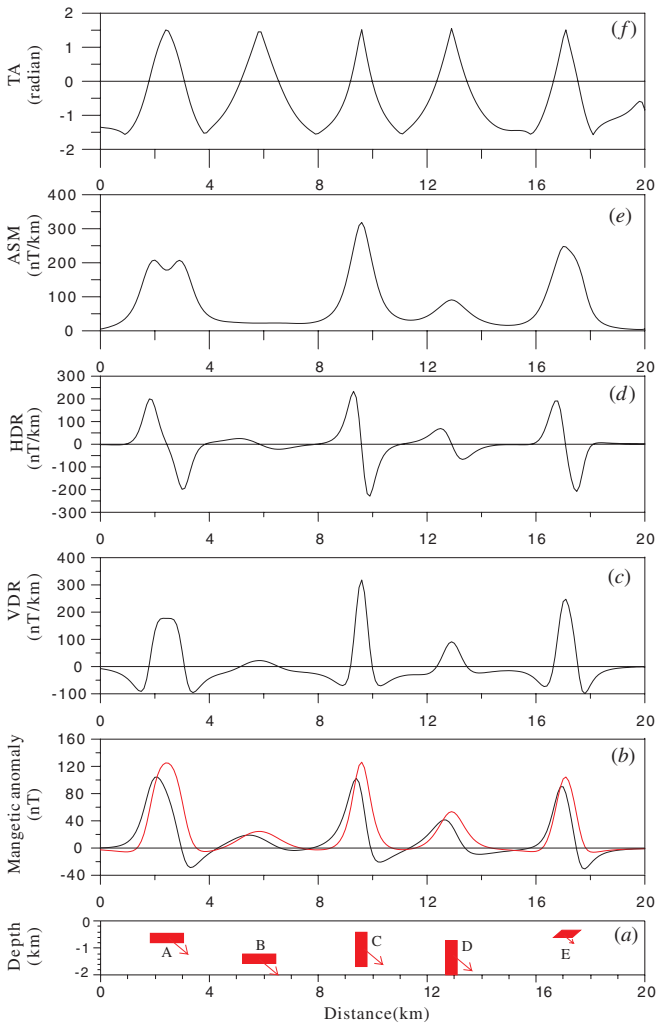


Figure 1. Magnetic anomaly of synthetic profile model and the derivative processing results. (*a*) The profile model; all anomalous bodies have the same susceptibility (1 A m^{-1}) and magnetic inclination (60°). (*b*) The magnetic anomaly (black line) and its RTP magnetic anomaly (grey line, red online). (*c*) Vertical derivative (VDR). (*d*) Horizontal derivative (HDR). (*e*) Analytical signal modulus (ASM). (*f*) Tilt angle (TA).

$$\mathrm{TA} = \arctan\left(\frac{\mathrm{VDR}}{\mathrm{THDR}}\right), \tag{4}$$

and the value of TA is from $-\pi/2$ to $\pi/2$.

3. Synthetic profile experiment

To validate the effect of derivative methods in igneous rock detection from magnetic anomaly, one profile model is established according to the basic igneous rock pattern. Generally, igneous rocks are intrusive or extrusive bodies; hence we use a horizontal sheet and vertical column to represent the basic shapes of igneous rocks. The synthetic model shown in figure 1(*a*) contains five anomalous bodies (A–E). Two horizontal bodies (A and B) and two vertical bodies (C and D) are located at different depths, and one smaller parallelogram body (E) is in the shallow part. All these bodies have finite extension in the Y direction (1 km

Table 1. Magnetic susceptibility of cores in Huanghua and adjacent region (Zhou *et al* 2003)

Stratum	Lithology	Magnetic susceptibility (1×10^{-5} SI)		
		Minimum	Maximum	Average
Q	Unconsolidated sedimentary	5	40	14
Ng	Sand shale	0	120	21
	Sandstone	3	20	12
Es_1	Mudstone, sandstone	0	13	5
	Basalt	200	2500	1600
	Basaltic andesite	2000	4000	2500
Es_{2-4}	Basalt, andesite	300	3500	2200
	Diabase	500	3800	1939
	Mudstone, sandstone	0	25	6.4
	Shaly clastic rock	0	48	4.8
	Sandstone	0	35	8
Ek	Mudstone	10	120	42
	Basalt	600	2200	939
Mz	Pyroclastic rock	40	350	170
	Andesite	45	4500	1500
	Sandstone, mudstone	0	80	13
C-P	Sandstone, mudstone, limestone	20	250	83
	Mudstone	5	180	24
E-O	Limestone	0	13	5
	Limestone	0	0	0
Ar-Pt	Granite gneiss	400	2500	970
	Amphibolite	200	2000	935
	Migmatite	500	4000	1815
	Amphibolite	800	8500	4770
	Biobite gneiss	150	2000	520

extension) and the same magnetic susceptibility (1 A m^{-1}) with the inclination of 60°. The forward magnetic anomaly is the black line in figure 1(*b*), while the RTP magnetic anomaly is plotted as the red line. The derivative processing results of RTP magnetic anomaly are illustrated in figures 1(*c*)–(*f*). Obviously, the anomalies of shallow buried source bodies (A, C and E) have high amplitude, and the deep buried source bodies (B and D) have weaker anomalies. The derivatives of RTP magnetic anomaly are used to enhance the anomaly characters of magnetic source bodies here. The maximum of the VDR and the modulus of the analytical signal can identify the top centre of the source bodies; the extreme values of horizontal derivative can locate the edges of source bodies. As shown in figure 1, for the shallow buried bodies (A, C and E), the derivative results can well locate their source bodies. For deep buried bodies (B and D), the weak anomalies are not so clearly enhanced compared to other high amplitude anomalies. So it is still difficult to identify the deep buried source bodies or other source bodies with weak anomalies. Comparatively, the TA provides a better result to identify such weak anomalies. It has the automatic gain control nature, and has the property of being positive over a source and negative elsewhere (Miller and Singh 1994). From the synthetic test, all the anomalies of source bodies, including the deep buried bodies B and D, can be identified easily with the positive area of the TA.

4. Field example

4.1. Magnetic anomaly data and petrophysical property

Huanghua depression is located in the middle-north part of the Bohaiwan basin, North China. The Dagang area was selected as a research region for igneous rock study (see figure 2(*a*)). It consists of the Cangdong uplift, Huanghua depression, Chengning uplift and Shaleitian uplift. The sub-tectonic frame of Huanghua depression, the deep-seated faults and the Cenozoic fault system are shown in figure 2(*b*).

The aeromagnetic data are compiled from the Bohai Bay aeromagnetic database of Institute of Geology and Geophysics, Chinese Academy of Sciences and China Aero Geophysical Survey & Remote Sensing Center for Land and Resources (Hao *et al* 2008). The data were converted to the grid file with sample distances in the x and y directions of 1 km interval and reduced to the magnetic pole. The regional earth magnetic inclination and declination parameters used in RTP process are 55° and −5.6°, respectively.

The RTP magnetic anomaly map (figure 3) has very good agreement with the main tectonic frame of the Dagang area. The sedimentary basin (Huanghua depression) has low magnetic anomaly, and the uplifts correspond to the high magnetic anomaly area. The local high anomaly in sedimentary basin is mostly related to the strong magnetic sources.

According to the petrophysical study of Huanghua depression (Hao *et al* 2008), the magnetic source bodies are mainly from the Archean to lower-Proterozoic crystalline basement and the igneous rocks in Mesozoic and Cenozoic. The classical magnetic susceptibility characters of different rocks and layers are listed in table 1. The magnetic susceptibility of Archean basement is about 935–4700 $\times 10^{-5}$ SI, the magnetic susceptibility of igneous rocks is generally thousands of 10^{-5} SI, and the sedimentary layer has little or almost no magnetism. The igneous samples from well core

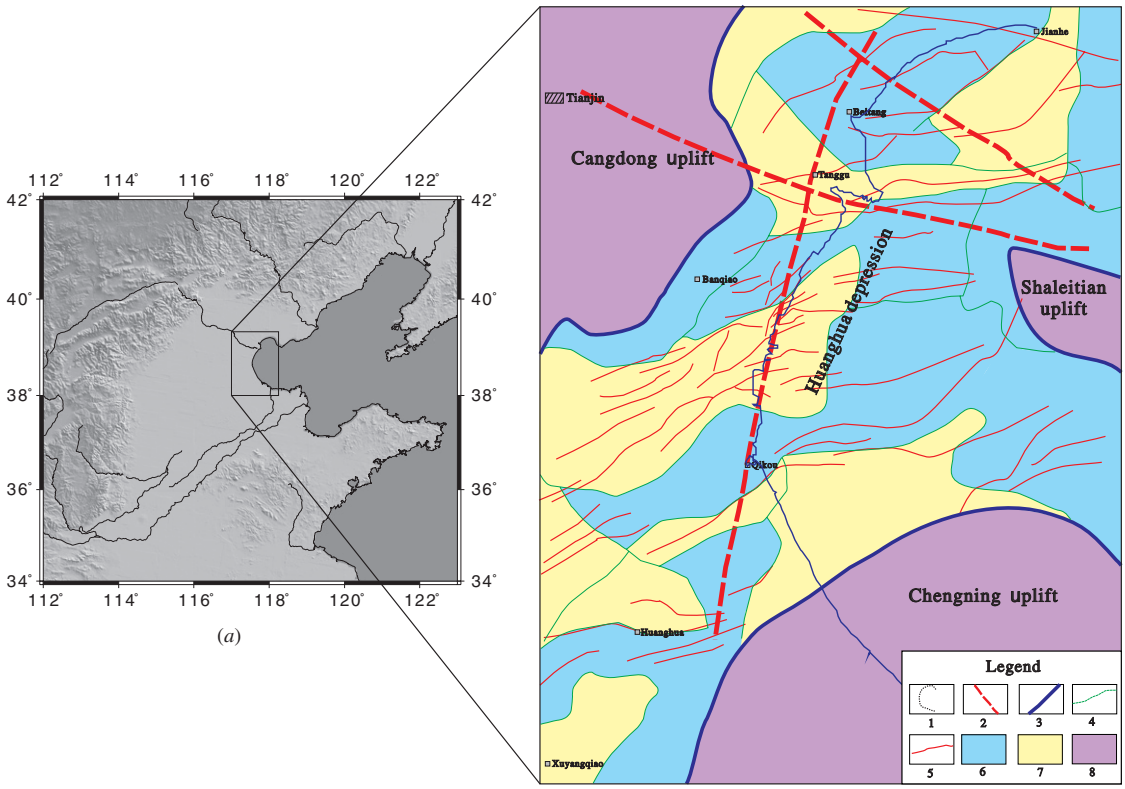


Figure 2. The location and the tectonic frame of the Dagang area. (*a*) The location of the study area; (*b*) the tectonic frame of the study area. Legend stands for: 1, the coastal line; 2, deep-seated fault; 3, tectonic boundary; 4, sub-tectonic boundary; 5, Cenzoic faults from seismic interpretation; 6, the positive sub-tectonic units in Huanghua depression (salients and buried mount); 7, the negative sub-tectonic units in Huanghua depression (sags); 8, the uplifts.

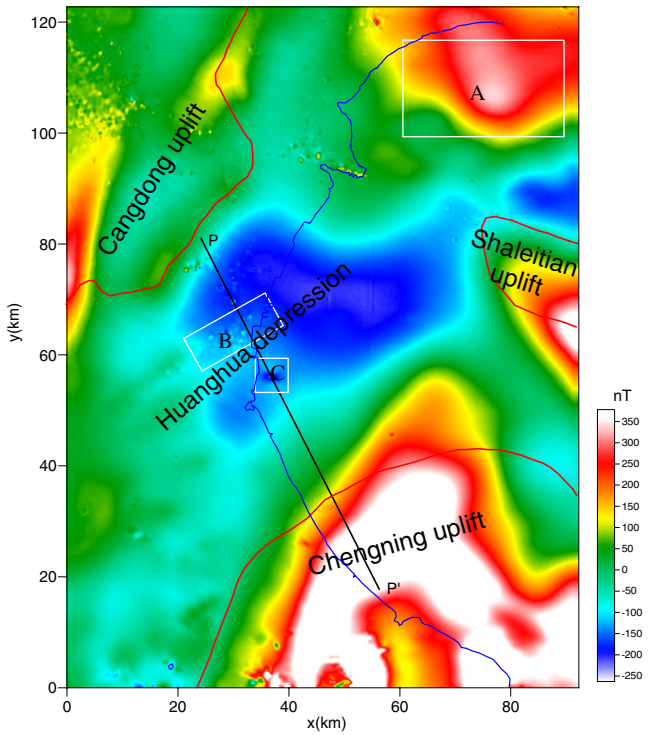


Figure 3. The RTP magnetic anomaly of the Dagang area. PP′ is the location of the seismic profile in figure 4. The red line is the tectonic boundary and the blue line is the sea boundary. The rectangles A, B and C indicate the typical anomaly zones for igneous rock investigation.

show that igneous rocks are mainly diabases and basalts; the susceptibility of basalts can reach 132–2933 $\times$ 10^{-5} SI and that of diabases 279–4885 $\times$ 10^{-5} SI (Xu *et al* 2008). In conclusion, the magnetic susceptibility of igneous rocks is high and the igneous rocks are the main magnetic anomaly sources in the Dagang area.

4.2. Magnetic profile analysis

In practice, the seismic reflection of igneous rocks is complex and cannot be easily identified with other reflection features. In this case, the magnetic anomaly data can be used to assist the interpretation of igneous rocks. We choose one seismic profile (figure 4(*a*)) in the Dagang area, North China, for magnetic data analysis and igneous rock detection. The seismic reflection characteristics clearly indicate the existence of craters and conduits in area C. However, the intrusive igneous rocks in area B cannot be identified easily from the seismic reflection. We extract the magnetic anomaly data (black line in figure 4(*b*)) of the profile (the location of this profile is shown in figure 3), and compute the RTP magnetic anomaly (red line in figure 4(*b*)) and its derivative results (figures 4(*c*)–(*f*)) for igneous rock investigation. From the derivative results, the anomaly features of intrusive igneous rocks in area B and crater in area C are clearly illustrated. Our experiment illustrates that the derivative methods can locate the edges of igneous rocks very well, which provides useful assistance for the seismic interpretation.

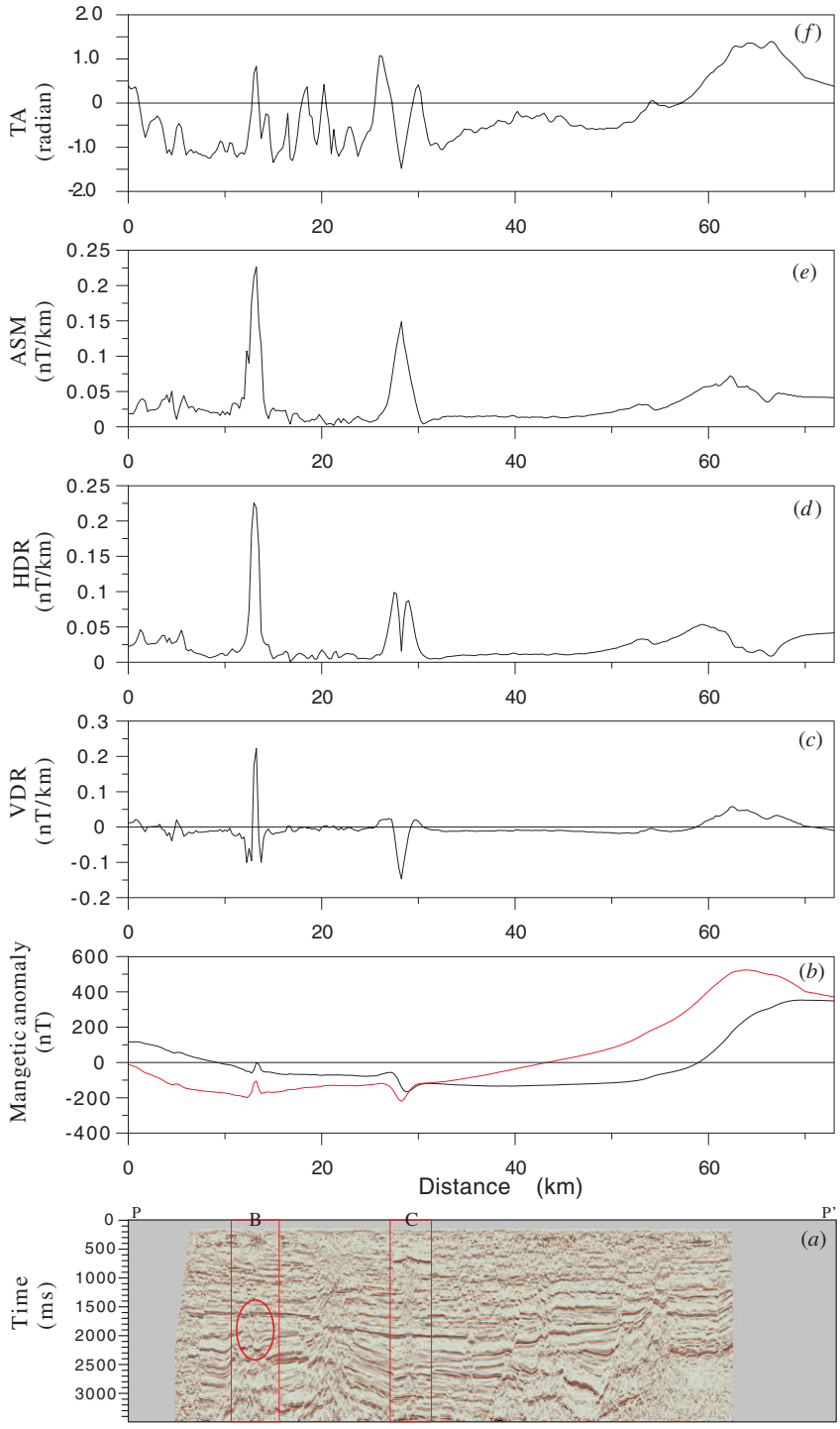


Figure 4. Magnetic anomaly and the derivative computation results of the seismic profile. The profile location can be seen in figure 3. (*a*) The seismic profile, B and C areas are intrusive igneous rocks and crater, respectively. (*b*) Magnetic anomaly (black line) and the RTP magnetic anomaly (red line). (*c*) Vertical derivative (VDR). (*d*) Horizontal derivative (HDR). (*e*) Analytical signal modules (ASM). (*f*) Tilt angle (TA).

4.3. Data processing results

In order to enhance/extract the magnetic anomaly related to igneous rocks, the derivative processing method is applied to the RTP magnetic anomaly.

Figure 5 illustrates the VDR of the RTP magnetic anomaly of the Dagang area. The black line indicates the zero value of the VDR which can be used as the signature of edges of igneous rocks. Figures 6 and 7 show the THDR and the ASM, respectively. The local anomaly features related to igneous

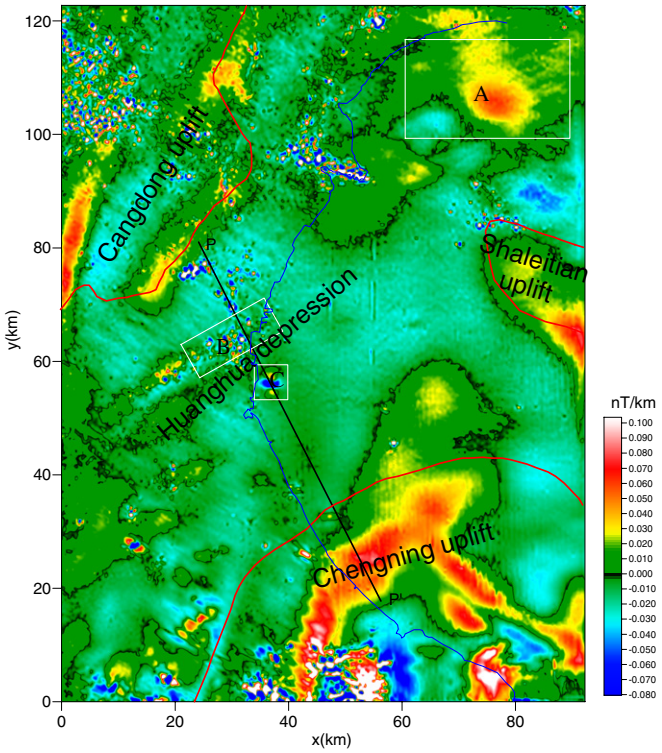


Figure 5. The VDR of the RTP magnetic anomaly of the Dagang area. Black colour indicates the zero value zones.

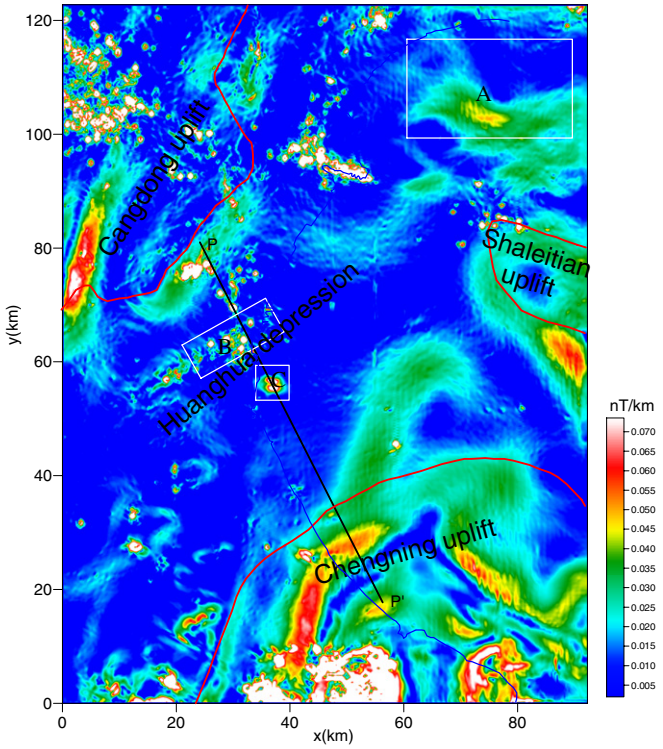


Figure 6. The THDR of the RTP magnetic anomaly of the Dagang area.

rocks are highlighted by the extreme value of the THDR and ASM. The TA is one important method to balance the high and low amplitude anomaly; the zero values or near-zero zones can be taken as the edges of source bodies. The zero zones (radian range from -0.4 to 0.4) of the TA of RTP magnetic anomaly in the Dagang area are displayed in figure 8. It indicates the edges of igneous rocks in this area.

4.4. Geological interpretation of igneous rocks

According to the anomaly feature of RTP magnetic map and the derivative results, we classify the typical igneous magnetic anomalies of the Huanghua depression into three types for interpretation, as illustrated in areas A, B and C in figure 3.

(1) Large scale high magnetic anomaly in sedimentary basin (area A in figure 3).

Because of the thick but small magnetism sedimentary layer, the magnetic anomaly in sedimentary basin is lower than in uplift areas. The high magnetic anomalies in sedimentary basin are mainly associated with strong magnetic geological bodies in the sedimentary basin. The area A in figure 3 is located in the Beitang Sag; the RTP magnetic anomaly is 250 nT higher than the adjacent region. The high amplitude anomaly indicates the existence of highly magnetic geological bodies in the sedimentary layer. The reasonable interpretation is that the anomaly is caused by the igneous rocks based on the rock magnetic susceptibility analysis in this area. The drilling wells in this area have revealed about 40 m igneous rock layer in tertiary stratum. Integrated with the petrophysical property analysis, the high anomaly area corresponds to the widely spread igneous rocks in the Beitang sag. The maximum value

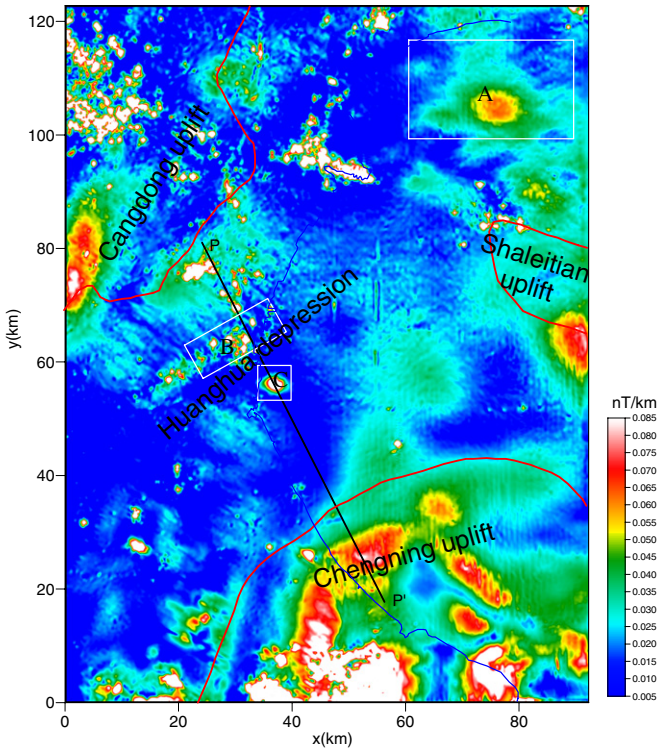


Figure 7. The ASM of the RTP magnetic anomaly of the Dagang area.

of the ASM indicates the centre of the igneous rocks. The zero zones of VDR and TA well delineate the edge of the area of igneous rocks.

(2) String bead-shaped magnetic anomaly (area B in figure 3).

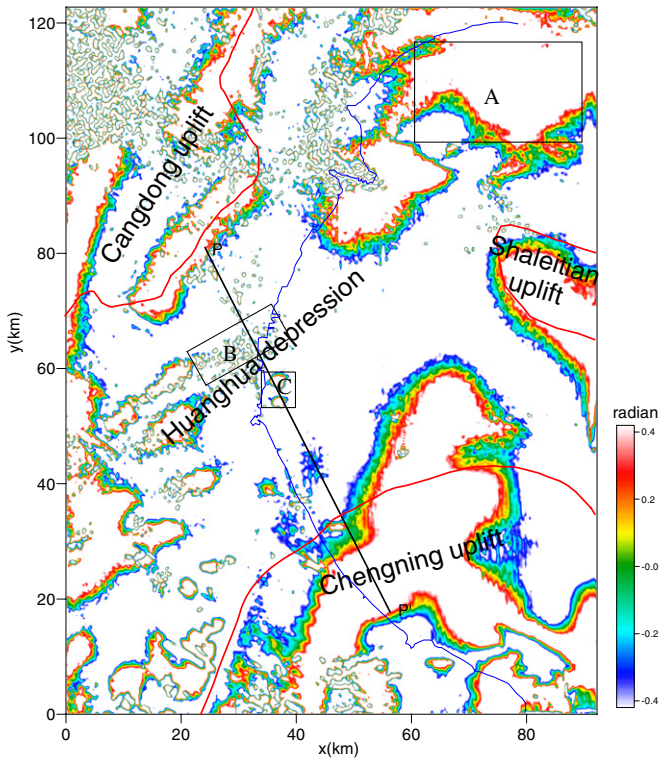


Figure 8. The TA of the RTP magnetic anomaly of the Dagang area.

The bead-shaped high magnetic anomalies are typical features for igneous rock investigation. They are mainly related to the scatter distributed igneous rocks along the fault system. There are many string bead-shaped magnetic zones in the RTP magnetic anomaly map. The anomaly of area B illustrates the typical style of this kind of anomaly. The bright spots indicate the high anomaly caused by igneous rocks. The derivative processing results greatly enhance the anomaly features. The seismic profile (figure 4(*a*)) also reveals the relationship between anomaly characteristics and igneous rocks. The string bead-shaped anomaly in area B along the southwest–northeast direction is consistent with the fault in this area.

(3) Circular and high–low associated magnetic anomaly (area C in figure 3).

Another type of magnetic anomaly is related to the craters and volcanic conduits. The profile test has illustrated the magnetic anomaly feature of the crater (part C in figure 4). The planar magnetic anomaly and the RTP magnetic anomaly of the crater are characterized with circular anomaly or positive and negative associated anomaly (or high–low associated anomaly). The anomaly of area C illustrates one typical magnetic anomaly of the crater. It has low value circular anomaly at the centre and associated high value on both sides (figure 9). The low value anomaly is mainly caused by the volcanic extrusion, and the magnetic material is around the crater. Other craters also were identified from the RTP magnetic anomaly and its derivatives. They are represented by the red filled circles in figure 10.

4.5. Igneous rock distribution in sedimentary basin

Based on the analysis of three types of magnetic anomaly characters and the derivative processing results, we delineate

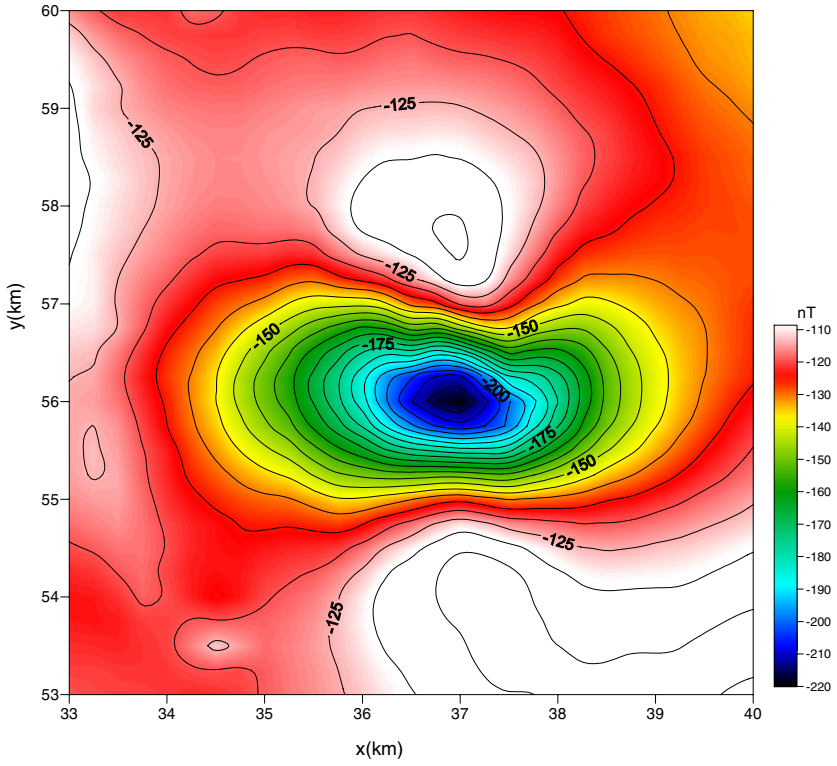


Figure 9. The RTP magnetic anomaly of the crater of area C in figure 3.

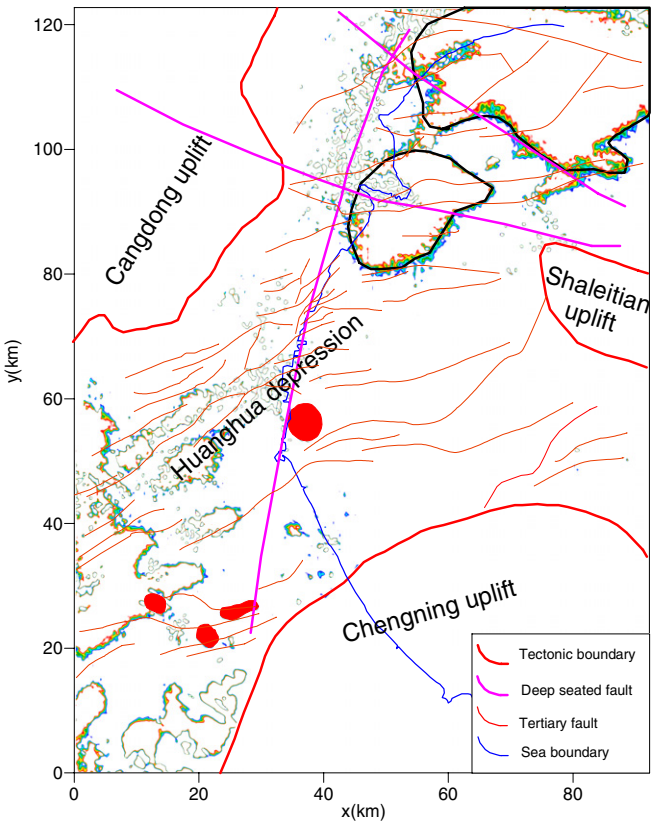


Figure 10. The distribution of igneous rocks in sedimentary basin of the Dagang area. The black circle is the large scale igneous rock distribution area. The coloured area is the zero zones of the TA; it is used to represent the scattered igneous rock distribution in the Dagang area. The red filled circle is the craters identified by magnetic anomaly analysis.

the distribution of igneous rocks in the sedimentary basin of the Dagang area (figure 10).

The widely spread igneous rocks are mainly distributed in the north part of the sedimentary basin. The VDR and the TA results well locate the boundary of igneous rocks related to large scale high magnetic anomaly. Especially for the southwest area A, the middle-high amplitude anomaly is well enhanced by the TA analysis. We use the black line to represent the area of large scale igneous rock distribution.

The four derivative processing results also enhance the local high amplitude anomaly related to scattered igneous rocks. The bead-shaped anomalies in derivative processing results mainly illustrate the distribution of the igneous rocks. We use the near-zero zones of the TA in the sedimentary basin (coloured area in figure 10) to represent the bead-shaped igneous rock distribution area. It has great agreement with the prediction results from the other three derivative results in this paper.

Four crater distribution areas are studied based on the anomaly feature. They are represented by red filled circles in figure 10.

The igneous rocks are mainly distributed in the north and southwest part of the Huanghua depression. From the deep-seated faults and Tertiary fault system of the Dagang area in figure 10, the scattered igneous rock distribution is mainly controlled by the fault system. The deep-seated fault along the coastal boundary (nearly north–south trend) may be the main factor to control the distribution of the igneous rocks in the Dagang area.

5. Conclusion and discussion

The investigation of igneous rocks is the primary step to find reservoirs associated with igneous rocks. The magnetic method is one of the useful geophysical methods for investigation of highly magnetic igneous rocks. The igneous rocks are mainly related to the local high amplitude anomaly superposed on the regional magnetic field background. The derivative methods can be used for the enhancement of anomalies caused by igneous rocks.

The experiments of the synthetic profile model and the seismic profile in this paper have illustrated the effects of derivative methods for edge detection of igneous rocks. The edges of magnetic source bodies (igneous rocks) can be well located by the zero zones of the VDR and the TA, the extreme value of the horizontal derivative and the ASM. For the weak anomaly caused by the weakly magnetic igneous rocks or deep buried igneous rocks, the TA can well balance the high–low amplitude anomaly and give clear signature of the edges.

From the petrophysical study, the igneous rocks are highly magnetic and the main magnetic anomaly sources in Huanghua depression. It is the primary reason to detect igneous rocks by magnetic methods in this area. The RTP magnetic anomaly and its derivative processing results are used to investigate the distribution of igneous rocks. The zero zones of VDR and the TA can well locate the edges of igneous rocks. Integrated with the extreme value analysis of THDR and the analytic signal modules, we delineated the distribution area of igneous rocks in the Huanghua depression. In the north part, there mainly exist large scale igneous rocks with regional high amplitude magnetic anomaly. Several spot-scattered igneous rocks are related to string bead-shaped anomalies and widely spread in the north and southwest part of Huanghua depression. Some craters in this area are detected according to the circular and high–low associated magnetic anomaly.

Combined with knowledge of the fault system of Huanghua depression, the distribution of igneous rocks is mainly controlled by the fault along the sea boundary (north–south trend) and associated tertiary faults. Most scattered igneous rocks are distributed on the west side of the deep-seated fault along the sea boundary.

The petrophysical study of igneous rocks is the basement of the usage of magnetic anomaly for igneous rock detection. The derivative methods based on the first-order derivative, including VDR, THDR, ASM and the TA, can be successfully used to detect highly magnetic igneous rocks. The application in the Dagang area has outlined the distribution of the igneous rocks, and the results are partly confirmed by the seismic profile. The magnetic methods can well assist the further exploration of igneous rocks and the seismic interpretation.

From our analysis, the magnetic derivative methods can enhance the local anomaly well and delineate the edges

of igneous rocks. However, we should note that all the interpretation of derivative results is based on the magnetic susceptibility analysis of igneous rocks. In practice, the selection of the investigation method for the igneous rock study should refer to the petrophysical study and the geological background. The magnetic methods can be used to locate the igneous rocks with high magnetic susceptibility within low regional magnetic background.

Acknowledgments

The authors thank Professors Liu Guangding, Liu Yike, Duan Zhenhao, Wang Yanfei, Chen Ling, Dr Su Liping and Yuan Shuqin for their constructive comments and suggestions. They also thank the anonymous reviewer and the editors for their useful advices, which helped them improve the manuscript. This work was jointly supported by National Natural Science Foundation (40804016, 90814011 and 4062014035), National High Technology Research and Development Program of China (2009AA093401), National Major Project of China (2008ZX05008-006) and the Knowledge Innovation Program of the Chinese Academy of Sciences.

References

Cooper G R J and Cowan D R 2006 Enhancing potential field data using filters based on the local phase *Comput. Geosci.* **32** 1585–91

Eventov L 1997 Applications of magnetic methods in oil and gas exploration *Leading Edge* **33** 489–92

Fedi M and Florio G 2001 Detection of potential fields source boundaries by enhanced horizontal derivative method *Geophys. Prospect.* **49** 40–58

Hao T Y *et al* 2008 Integrated geophysical research on macroscopic distribution of Pre-Cenozoic residual basins—a case in Dagang area *China J. Geophys.* **51** 491–502 (in Chinese with English abstract)

He Z, Liu Y, Suo X and Dong W 2008 Application of magnetic prospecting in recognition of volcanic reservoirs *CSEG Recorder* **33** 45–8

Hsu S K, Sibuet J C and Shuy C T 1996 High-resolution detection of geologic boundaries from potential-field anomalies: an enhanced analytic signal technique *Geophysics* **61** 373–86

Jallouli C, Mickus K, Turki M M and Rihane C 2003 Gravity and aeromagnetic constraints on the extent of Cenozoic volcanic rocks within the Nefza-Tabarka region, northwestern Tunisia *J. Volcanol. Geotherm. Res.* **122** 51–68

Lin S H, Xie Z A, Lin J W, Fu X S and Zhang W L 2008 Application of pre-stack multi-attribute inversion technology on igneous rock investigation in Nanpu oilfield *Geophys. Prospect. Pet.* **47** 83–8

Miller H G and Singh V 1994 Potential field tilt—a new concept for location of potential field sources *J. Appl. Geophys.* **32** 213–7

Nabighian M N 1972 The analytic signal of two dimensional magnetic bodies with polygonal cross section: its properties and use for automated anomaly interpretation *Geophysics* **37** 507–17

Nabighian M N 1984 Toward a three dimensional automatic interpretation of potential field data via generalized Hilbert transforms: fundamental relations *Geophysics* **49** 780–6

Schutter S R 2003 Occurrences of hydrocarbons in and around igneous rocks *Geol. Soc., Lond.* **214** 35–68 Special Publications

Secomandi M, Paoletti V, Aiello G, Fedi M, Marsella E, Ruggieri S, D'Argenio B and Rapolla A 2003 Analysis of the magnetic anomaly field of the volcanic district of the Bay of Naples, Italy *Mar. Geophys. Res.* **24** 207–21

Sparlin A M and Lewis R D 1994 Interpretation of magnetic anomaly over theOmaha Oil Field, Gallatin, Illinois *Geophysics* **59** 1092–9

Wang W Y, Pan Y and Qiu Z Y 2009 A new edge recognition technology based on the normalized vertical derivative of the total horizontal derivative for potential field data *Appl. Geophys.* **6** 226–33

Wijns C, Perez C and Kowalczyk P 2005 Theta map: edge detection in magnetic data *Geophysics* **70** L39–43

Xu Y, Zhang L L, Duan Q L, Li Z W, Huang S, Wang B B and Qin J X 2008 Igneous rock distribution study in Dagang area based on aeromagnetic data *Progress of Geology and Geophysics in China—Celebrate the 80th Birthday of Academician Liu Guangding* ed X L Jin, Y S Qin, R X Zhu and J B Li (Beijing: Ocean Press) pp 217–24 (in Chinese with English abstract)

Yang H, Wen B H, Zhang Y, Zhang G Y, Liu Z Z, Wu F C, Wei Y Z, Dai X F and Hu Q H 2009 Distribution of hydrocarbon traps in volcanic rocks and optimization for selecting exploration prospects and targets in Junggar Basin: case study in Ludong-Wucaiwan area, NW China *Pet. Explor. Dev.* **36** 419–27

Yang H, Zhang Y, Liu X, Wen B and Xu D 2006a Aeromagnetic anomalous feature of Xujiaweizi fault depression in north part of SongliaoBasin and geologic meaning for oil/gas exploration *Oil Geophys. Prospect.* **41** 97–9 (in Chinese with English abstract)

Yang H, Zhang Y, Zou C, Wen B and Li M 2006b Volcanic rock distribution and gas abundance regularity in Xujiaweizi fault depression, Songliao basin *China J. Geophys.* **49** 1136–43 (in Chinese with English abstract)

Zhou L H, Li S Z and Liu J Z 2003 *Pre-Tertiary Tectonic Evolution and Buried Hill-Type Oil–Gas Development and Reservation Under the Bohai Bay Basin* (Beijing: Science & Technology Press) p 28 (in Chinese)

Zhou L H, Wu Y P, Xiao D Q, Wei A J and Wang G Z 2000 Character of the Tertiary igneous rocks and investigation of their relationships with hydrocarbon in Huanghua depression *Acta Pet. Sin.* **21** 29–34