The existence of underground gas storage causes geomagnetic anomaly in this area?

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Abstract. When the stress state of the rock changes, its permeability will also change accordingly, which is the so-called piezomagnetic effect. The piezomagnetic characteristics of rocks are an important and reliable physical basis for the seismomagnetic effect. Based on the experiments of rock magnetism, many scholars have carried out targeted experiments on the relationship between stress and rock magnetism, and achieved many important experimental understandings. As the largest underground gas storage (UGS) in operation in China, the Hutubi UGS has a design storage capacity of 10 billion cubic meters. It is operated periodically every year by gas injecting in summer and gas extracting in winter. During the process of gas injection and gas extraction in Hutubi UGS, the gas well pressure changes up to more than 10 MPa. Periodic injection and extraction operations will induce variations in the in-situ stress field in local areas. Whether these variations can cause local crustal magnetic anomalies is the focus of this paper. An observation network composed of 63 total geomagnetic intensity measuring stations was established in the Hutubi UGS and its surrounding areas, and the geomagnetic anomalies have been systematically observed. Based on the two phases of field observation data in October 2016 and October 2018, a polynomial fitting method was used to obtain the crustal magnetic anomalies in the UGS area. Results show that the existence of the Hutubi UGS has indeed caused the geomagnetic anomaly changes in this areas, the maximum value of the magnetic anomaly is 19 nT. The results of this field observation further confirmed the existence of the piezomagnetic effect in the laboratory and established the internal connection between the meso-scale crustal magnetic anomalies and the underground stress variations.

1. Introduction

Geomagnetic field is one of the most important geophysical fields [1]. It is composed of different magnetic field components and has complex spatial structure and time evolution [2]. Lithospheric magnetic field (or crustal magnetic field), as a basic component of the geomagnetic field, originated from magnetic rocks in the crust and upper mantle [3]. Although its energy accounts for only 4% of the Earth's total magnetic field energy, the magnetization environment, pressure temperature conditions of the rock are different from the magnetic carrier and its structural evolution, which leads to the complexity of its distribution far more than the main magnetic field accounting for about 95% of the total magnetic field [4]. It is precisely because of this that the lithospheric magnetic field carries a wealth of information on geological structures and geodynamics, which provides us with favorable conditions for detecting the internal structure of the Earth and understanding the physical processes within the Earth [5-6].

The lithospheric magnetic field is very stable, and the time scale of its variation is calculated by the geological age of millions of years, which indicates that the source of the lithospheric magnetic field is
very stable [7]. But during some severe tectonic activities, the lithospheric magnetic field in some areas will change rapidly, such as earthquakes, volcanic eruptions, creeping faults, and water storage in reservoirs and so on [8-10]. These changes are related to the loading and rupture of crustal rocks. Piezomagnetic effect represents the change of the magnetization of ferromagnetic minerals under mechanical stress [11]. The magnetic minerals in the lithosphere above curie show the characteristics of magnetic induction and remanence [12]. In the tectonic area, the piezomagnetic changes of these magnetic minerals caused by stress will produce local magnetic anomalies [13-15].

Previous studies have shown that the tectonic movement in the crust is closely related to the crustal stress [16-18]. The pressure difference produced by the injection and extraction operation of the ultra-large UGS will cause periodic deformation of the surface of the gas storage cap layer, leading to fluctuations in the pore pressure of the underground medium, and changing the media properties and stress state of the faults inside and near the gas storage [19-20]. Therefore, whether the process of gas injection and gas extraction in the ultra-large UGS can cause magnetic anomalies in this local area is the research content of this paper.

In this paper, the lithospheric magnetic anomalies in Hutubi UGS and its surrounding areas are obtained by using the high-precision intensive observation of the total geomagnetic intensity, and the corresponding relationship between the magnetic anomalies and the gas injection and gas extraction process of the UGS area and its structure is analyzed.

2. Data and Method

We conducted intensive observations of the total geomagnetic intensity above the gas storage and surrounding areas. The measuring instrument used was the proton precession magnetometer GSM-19T (https://www.gemsys.ca). Forty stations were measured in October 2016, including twenty-five stations directly above the gas storage (as shown by the circles in figure 1) and fifteen stations on the periphery of the gas storage (as shown by the solid triangles in figure 1). In October 2018, sixty-three stations were measured. In addition to the measurement stations in October 2016, we added another twenty-three stations in the core area of the gas storage (as shown by the solid circles in figure 1). The measurement data of each period uses the continuous recorded data of the WMQ observatory to eliminate the external field component of the geomagnetic field.

![Figure 1: Hutubi UGS study area. The gray polygon indicates the surface projection of the Hutubi UGS. Hollow star delineates the WMQ geomagnetic observatory. Triangles represent the locations of the 15 stations on the periphery. Circles represent the distributions of the 25 internal stations in 2016. Solid circles show the locations of the 23 internal stations in 2018.](image)

The calculation method used in this paper is as follows: firstly, based on the data of the measuring stations on the periphery of the UGS area, the fitting results of the stations directly above the gas
storage are obtained by using the Taylor polynomial fitting method [21]. That is the distribution of the geomagnetic field in the area when the gas storage does not exist. Then, the fitting results are subtracted from the actual observation results of the measuring stations directly above the gas storage. It can be considered that the geomagnetic field changes in the area caused by the existence of the gas storage. Finally, the surface spline fitting method is used to obtain the spatial distribution numerical model of the local magnetic anomaly in the core area of the gas storage, and the spatial distribution characteristics of the local magnetic anomaly caused by the existence of the gas storage are analyzed.

The fitting formula of the surface spline function is as follows [22]:

\[
\begin{align*}
F(x, y) &= a_0 + a_1x + a_2y + \sum_{n=1}^{N} B_n r_n^2 \ln(r_n^2 + \varepsilon) \\
\sum_{n=1}^{N} B_n &= \sum_{n=1}^{N} x_n B_n = \sum_{n=1}^{N} y_n B_n = 0
\end{align*}
\]

(1)

where \(x\) and \(y\) are the abscissa and ordinate coordinates of the fitting stations; \(F(x, y)\) is the physical quantity calculated at \((x, y)\); \(x_n\) and \(y_n\) are the abscissa and ordinate coordinates of the \(n\)th original measuring point, respectively; \(a_0\), \(a_1\), \(a_2\) and \(B\) are the fitting coefficients of the surface spline functions; \(N\) is the number of center points; \(\varepsilon\) is the curvature factor; and \(r_n\) is the distance between the fitting station and the \(n\)th original measuring station. \(r_n\) is expressed as follows:

\[
r_n^2 = (x - x_n)^2 + (y - y_n)^2
\]

(2)

3. Results and Discussion

3.1. Results of the Taylor polynomial fitting

According to the data of fifteen measurement stations on the periphery of the Hutubi UGS area, the Taylor polynomial model of the geomagnetic field in the UGS and its surrounding area is calculated using polynomial fitting method. After comparison, it is found that the second order is more suitable for the truncation order of the geomagnetic field model. Figure 2 shows the second-order Taylor polynomial model in 2016 and 2018, respectively. We found that the spatial distribution of the model obtained from the two measurements is basically the same. The spatial distribution of the geomagnetic field in the area above the UGS is obtained by fitting the data of external measuring stations. Due to the existence of geomagnetic secular variation, the amplitude difference of the magnetic field through the center of the UGS is about 160 nT.

![Figure 2](image_url)

Figure 2. The second-order Taylor polynomial model of geomagnetic field. (a) Result of October 2016, (b) Result of October 2018. The contour intervals of fine and coarse lines are 20 nT and 10 nT, respectively. Triangles delineate the locations of the 15 stations on the periphery of the Hutubi UGS.
3.2. Results of the local geomagnetic anomalies

The geomagnetic anomalies in the Hutubi UGS area is obtained by subtracting the fitting data at the stations above the UGS area from the actual measured data of the stations, as shown in figure 3. It can be clearly seen from the two figures that the change of the geomagnetic field gradually increases from the northeast corner to the southwest, and an obvious turn has taken place in the area above the surface projection the UGS field. The geomagnetic field changes are more obvious in the areas covered by measuring stations, but the distribution of the geomagnetic field is more uniform in the areas without measuring stations, which is mainly because the areas without stations are all interpolated from the model space. This is the reason why the spatial range of the magnetic anomalies in figure 3 (b) is larger than that in figure 3 (a). On the basis of figure 3 (a), figure 3 (b) adds another 23 measuring stations in the peripheral circle.

![Figure 3](image_url)

**Figure 3.** Local geomagnetic anomalies in the Hutubi UGS area in 2016 (a) and in 2018 (b). The contour intervals is 2 nT. Hollow circles show the distributions of the 25 internal stations in 2016. Solid circles represent the locations of the 23 internal stations in 2018.

Comparing the two figures in figure 3, it is also found that the amplitude of the local geomagnetic anomalies above the surface projection the UGS field is roughly the same, which is mainly related to the specific time of the two measurements observed at the peak of gas injection. However, the spatial distribution of the geomagnetic anomalies in the UGS structure area obtained by these two measurements is obviously different. The reason for this phenomenon may be the difference of injection and extraction pressure changes, the diffusion and elimination process of the gas in the internal space of UGS. However, the error in observation and model calculation is not excluded (although the error generated is small).
3.3. Relative variations of the local geomagnetic anomalies

We calculated the relative changes of the geomagnetic anomalies at the measuring stations directly above the UGS area, are shown in figure 4. There were 25 stations in October 2016 and 48 stations in 2018. Among them, one of the 48 stations in October 2018 was problematic, so it was deleted in the calculation.

![Figure 4](image_url)

**Figure 4.** Relative changes of the local geomagnetic anomalies at each station in different surveys.

The minimum value of relative change in 2016 was 0.003%, the maximum value was 0.032%, and the average relative change of 25 stations was 0.019%. In 2018, the minimum and maximum values were 0.002% and 0.031%, respectively, and the average relative change of 47 stations was 0.016%. It can be seen from figure 4 that for the measurement stations 1-25, the relative change trends obtained in 2016 and 2018 are basically the same, which further proves the reliability of this result.

4. Conclusion

Previous studies have shown that tectonic activities within the crust can cause geomagnetic anomalies in local areas [16]. These changes are related to the loading and rupture of crustal rocks. For rocks with stress sensitivities and magnetizations of $10^{-3}$ MPa$^{-1}$ and 1 Am$^{-1}$, volcanic eruptions or moderate to large earthquakes are expected to be accompanied by several nT of moderate-scale magnetic anomalies [13]. Along with the change of underground stress or temperature, the abnormal change of the total intensity of the surface magnetic field may reach 2-10 nT [12].

The pressure change of gas injection and gas extraction wells in Hutubi UGS reaches more than ten MPa. These pressure changes will cause periodic deformation of the surface of the UGS cap layer, leading to fluctuations in the pore pressure of the underground medium, and changing the medium properties and stress states of the faults inside and near the UGS [23]. Relevant GPS and InSAR measurements show that a decrease or an increase in the gas pressure produces 2.11 mm/MPa of subsidence or 2.63 mm/MPa of uplift [24]. Internal stress state variations of the Hutubi UGS in turn lead to changes in the magnetic properties of underground rocks, and finally causes to the magnetic anomalies in local areas.

The geomagnetic anomalies of Hutubi UGS and its adjacent areas were obtained through two field surveys. The maximum amplitude of geomagnetic anomaly is 19 nT, and the largest anomaly in the surface projection the UGS field is 12 nT. The acquisition of these geomagnetic anomalies proves that the process of gas injection and gas extraction in large UGS area can produce certain local geomagnetic anomalies just like other tectonic movements.
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References
[1] Witze A 2019 Nature 565 143-4
[2] McLeod MG and Coleman PC 1980 Phys. Earth Planet. Inter. 23 5-19
[3] Counil J, Cohen Y and Achache J 1991 Earth Planet. Sci. Lett. 103 354-64
[4] Thébault E et al. 2010 Space Sci. Rev. 155 95-127
[5] Hulot G, Olsen N and Thébault E 2009 Geophys. J. Int. 177 361-6
[6] Finlay CC, Olsen N, Kotsiaros S, Gillet N and Tøffner-Clausen L 2016 Earth Planets Space 68 112
[7] Maus S 2010 Geochem. Geophy. Geosy. 11 Q06015
[8] Breiner S 1964 Nature 202 790-1
[9] Johnston MJS and Stacey FD 1969 Nature 224 1289-90
[10] Davis PM and Stacey FD 1972 Nature 240 348-9
[11] Gorev RV and Udalov OG 2019 Phys. Solid State 61 1563-71
[12] Hao J, Hastie LM and Stacey FD 1982 Phys. Earth Plant. Inter. 28 129-40
[13] Johnston MJS 1989 Phys. Earth Planet. Inter. 57 47-63
[14] Zhan Z 1989 Phys. Earth Planet. Inter. 75 11-22
[15] Gu Z, Zhan Z, Gao J, Yao T and Chen B 2006 Phys. Chem. Earth 31 258-67
[16] Mueller RJ and Johnston MJS 1998 Phys. Earth Planet. Inter. 105 131-44
[17] Meng L, Fu X, Lv Y, Li X, Cheng Y, Li T and Jin Y 2016 Petrol. Geosci. 23 2016-031
[18] Villasenor A, Herrmann RB, Gaite B and Ugalde A 2019 Solid Earth 11 63-74
[19] Tang L, Lu Z, Zhang M, Sun L and Wen L 2018 J. Geophys. Res. Solid Earth 123 5929-44
[20] Zhou P, Yang H, Wang B and Zhuang J 2019 J. Geophys. Res. Solid Earth 124 8753-70
[21] Wang Z, Chen B and Yuan J 2020 Geomagn. Aeronomy 60 373-80
[22] Harder RL and Desmarais RN 1972 J. Aircr. 9 189-91
[23] Jiang G, Qiao X, Wang X, Lu R, Liu L, Yang H, Su Y, Song L, Wang B and Wong T 2020 Earth Planet. Sci. Lett. 530 115943
[24] Qiao X, Chen W, Wang D, Nie Z, Chen Z, Li J, Wang X, Li Y, Wang T and Feng G 2018 Seismol. Res. Lett. 89 1467-77