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Connectivity Analysis of Magnetic Mineral Veins based on Multi-boreholes Image

(Analisis Kesambungan Vena Mineral Magnet berdasarkan Imej Pelbagai Lubang Gerek)

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ABSTRACT

There are a large number of primary structural planes of deep rock ore such as rhyolite, and bedding, which are well preserved and are often the geological interfaces of mineralization. Study on the occurrence of these structural planes is helpful to understand the extension direction of deep veins. Using borehole imaging technology as the means of acquiring information of structural plane, the magnetic angle of the borehole is obtained by using the gyroscope and the magnetic instrument and the structural plane occurrence is modified to obtain the accurate information. According to the depth effect of the deep structural plane, the concept of the feature point pair is proposed. In this paper, the mathematical description method of the structural plane in the space coordinate system is established and the information of the shape and depth of the structure plane is transformed into the 3D point coordinates in the space coordinate system. Based on the feature points, the connectivity analysis method of structural plane is established and the connectivity of the structural planes such as the interface of the vein and rhyolite is analyzed. According to the stratigraphic information in the borehole image, the extension direction of the whole field is determined. The feasibility of the method is verified by the application in a magnetite in Anhui Province, China. The results are in good agreement with the actual drilling results and the error of traditional drilling analysis is corrected. The main conclusions of this paper include: The use of gyroscopes and magnetic instrument can obtain the magnetic effect angle, to modify the structural plane information; and multi borehole structural planes connectivity analysis can provide a reference for the extension of the deep veins.

Keywords: Borehole image; connectivity analysis; magnetic effect angle; magnetic mineral vein; structural plane

ABSTRAK

Terdapat sejumlah besar struktur satah utama dalam bijih batuan dalam seperti riolit dan perlapisan yang terpelihara dan merupakan antara muka geologi untuk pemineralan. Kajian tentang kejadian struktur satah ini sangat membantu untuk memahami arah perluasan vena dalam. Menggunakan teknologi pengimejan lubang gerek sebagai cara mendapatkan maklumat struktur satah, sudut magnet lubang gerek diperoleh dengan menggunakan giroskop dan alatan magnet dan kejadian struktur satah diubah suai untuk mendapatkan maklumat yang tepat. Menurut kesan kedalaman struktur satah dalam, konsep ciri butiran pasangan dicadangkan. Dalam kertas ini, kaedah penerangan matematik struktur satah dalam sistem koordinat ruang ditubuhkan dan maklumat bentuk dan kedalaman struktur satah ditukar menjadi koordinat butiran 3D dalam sistem koordinat ruang. Berdasarkan ciri butiran ini, kaedah analisis kesambungan struktur satah ditubuhkan dan kesambungan struktur satah seperti antara muka vena dan riolit dianalisis. Menurut maklumat stratigrafi dalam imej lubang gerek, arah perluasan keseluruhan bidang ditentukan. Kebolehlaksanaan kaedah ini disahkan dengan kegunaannya dalam magnetit di Wilayah Anhui, China. Keputusan ini bersetuju dengan keputusan sebenar penggerudian dan ralat analisis penggerudian tradisi diperbetulkan. Kesimpulan utama kertas ialah penggunaan giroskop dan alatan magnet boleh mendapatkan sudut kesan magnet untuk mengubah suai maklumat struktur satah dan analisis kesambungan pelbagai lubang gerek struktur satah boleh memberikan rujukan untuk perluasan vena dalam.

Kata kunci: Analisis kesambungan; imej lubang gerek; struktur satah; sudut kesan magnet; vena mineral magnet

Introduction

As shallow mineral resources are gradually depleted, undiscovered reserves in deep strata are becoming a main source of minerals and their discovery has become an important concern for prospectors over the world. Despite the varied prospecting methods, some key issues remain to be solved, one of which being the accurate determination of a deep magnetic vein's direction. The structural planes of rock bodies can be divided into two categories: Macroscopic interfaces, such as faults and foliation planes; and various primary and structural fissures. Compared to the first category, these interfaces occurred with tremendous high frequency and display considerable randomness and uncertainty in their distribution and occurrence. Among these fissures, the primary structural planes in particular are a good indication for a vein's direction. A statistical analysis of the structural planes within a magnetic vein, such as igneous patterns, interlayers and joints, may help us accurately assert the vein's direction and determine the locations of prospecting boreholes and the mine's reserve volume (Anees et al. 2017; Deere 1964; Huang et al. 2004; ISRM 1978; Jia et al. 2008).

The Digital Panoramic Borehole Camera System (DPBCS) as shown in Figure 1 is a combination of electronic, video and digital computer technology (Han et al. 2015, 2013; Haq et al. 2016; Wang et al. 2009). It captures real image of borehole rock wall, which is post-processed by analysis software to create virtual rock core model and 360° unfolded image as shown in Figure 2, as well as describe the structural plane dip, dip direction and other occurrence elements. Deep prospecting generally involves veins at depths over 500 m which have well-preserved primary features that can be acquired by borehole camera systems. However, borehole camera systems rely on magnetic compasses to determine their directions, making them vulnerable to disturbances from magnetic veins. Moreover, the effects of magnetic minerals can vary between boreholes as well as different depths within the same borehole. To study the extension directions of magnetic veins, it is necessary to utilize gyroscopes which are not affected by magnetic fields, in addition to magnetometers in order to acquire accurate information on their deep structural planes.

FIGURE 1. The digital panoramic borehole camera system

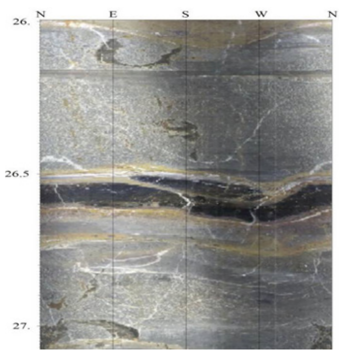

FIGURE 2. 360° borehole wall plane image

Taking the deep prospecting for magnetite veins at Zhongxinji, Anhui Province in China as an example, this paper provides an introduction to the utilization of borehole camera systems in studying the extension directions of veins. By using a combination of gyroscopes and magnetometers, the angles of magnetic influences can be calculated, which allows the correction of structural plane occurrence data. The results indicated that the digital rock cores and borehole images thus generated are consistent with the actual results obtained through drilling and the vein directions calculated using the occurrence data of structural planes are accurate (Jafar Ahmad & Loganathan 2017).

Methods

ANGLE OF MAGNETIC INFLUENCE

Gyroscopes allow precise determination of a moving object's position and directions. They are based on the principle that the direction of a rapidly spinning object's axis of spin is stable without an external force. While not affected by magnetic fields, gyroscopes tend to be influenced by the temperature of electronic components and additional moments from the testing process, which causes gyro drifts, i.e. Variations ('drift') that may occur when measuring the same object under the same conditions at different times. Hence it is necessary to correct for drifts on inertial directions measured by a gyroscope. The fact that gyros are not in-built in our panoramic borehole camera systems means we cannot directly position the camera using gyro data. In practical use, we also need to correct gyro data using magnetometers, which functions similarly to the camera systems' compasses and allows us to calculate the angles of magnetic influences.

First, we establish a central frame of reference using the inclination of a given spot on the borehole walls. As the inclination of the shaft does not change over time, having both the gyroscope and magnetometer lean along the shaft at the same spot would give them the same inclination. We made cylindrical probes approximately 2.5 m in length for both the gyro and the magnetometer, which allows them to cling to the shaft closely and ensure they have the same horizontal projection along the same inclination. By comparing the differences between both instruments' readings with said horizontal projection, the difference between their readings, i.e. the angle of magnetic influence can be obtained.

As shown in Figure 3, the direction of AO is the inclination of the borehole, where α is the apical angle of the shaft. The included angle between the inclination and the vertical direction; AA' is the vertical line from A to the horizontal plane oxy; A' is the projection of A on the horizontal frame OXY; OA' is the projection of OA on said horizontal frame.

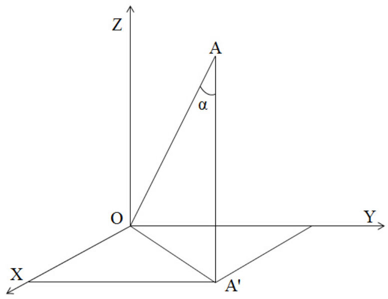

FIGURE 3. The inclination of the shaft

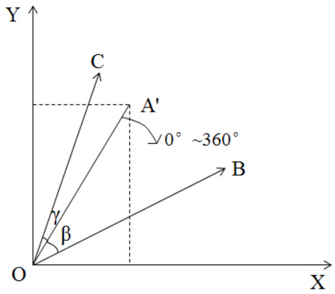

FIGURE 4. Determination of the angle of magnetic influence

Figure 4 shows the projections of the system on a horizontal plane. The AO segment of the borehole has only one horizontal projection OA'. Using OA' as the reference and clockwise as the positive rotation, a polar coordinate system from 0° to 360° can be established on horizontal plane OXY. Suppose OB is the direction of the gyroscope pointer at point A and OC is the direction of the magnetometer pointer at the same point A, the angle measured from the gyro is the value of ∠A'OB and the reading of the magnetometer is the rotation angle from OA' around point O to OC. The value of ∠BOC will be the angle of magnetic influence, which should be greater than negative 180° and smaller than or equal to 180°.

Suppose for a given A, the reading of magnetometer is X, the gyro reading is Y and the angle of magnetic influence is Z, then we have:

$$Z = \begin{cases} X - Y + 360 & X - Y \le 180 \\ X - Y & -180 \le X - Y \le 180 \\ X - Y - 360 & X - Y \ge 180 \end{cases} . \qquad (1)$$

CORRECTING OCCURRENCE DATA USING ANGLES OF MAGNETIC INFLUENCE

Detailed occurrence data of structural planes within a borehole can be acquired using a panoramic camera system. While the influences of magnetic minerals on the magnetic compass prevents the camera system from acquiring the full occurrence data from structural planes, the determination of their dips is not affected and correction for magnetic influences is only required for dip directions.

Suppose the camera obtains the dip direction ω of a structural plane at point A in Figure 3:

$$0° \le \boldsymbol{\omega} < 360°, \qquad (2)$$

where ω is the 0 means true north; and clockwise is the positive rotation.

As this dip direction value is obtained using a magnetic compass, correction for influence is needed. Suppose the corrected dip direction is ω′, which also must satisfy the basic requirements, thus:

$$\omega' = \begin{cases} \omega + Z + 360 & \omega + Z \le 0 \\ \omega + Z & 0 \le \omega + Z \le 360 \\ \omega + Z - 360 & \omega + Z \ge 360 \end{cases} . \qquad (3)$$

This method allows correcting the dip direction at the testing point A. It is impossible to acquire angles of magnetic influence in all locations; values for locations beyond the gyroscope/magnetometer testing points can be obtained by linear interpolation.

Suppose testing point A has a depth of H and the next point A_1 following it has a depth of H_1, the correction value Z_1 at A_1 can also be obtained by the same method. However, for a point A_i between A and A_1 at the depth of H_i, its value Z_i must be interpolated using the following equations.

From $\frac{Z_i - Z}{H_i - H} = \frac{Z_1 - Z}{H_1 - H}$,

We get the following:

$$Z_i = \frac{H_i - H}{H_1 - H}(Z_1 - Z) + Z \ , \qquad (3)$$

Using the angle of magnetic influence Z_i, the dip direction of the structural plane at A_i can be corrected

CONNECTIVITY OF STRUCTURAL PLANES IN A MAGNETIC OREBODY

Structural planes, especially primary vein planes of ore bodies are large enough to cover a sizable area. During a survey, one vein plane may be penetrated by multiple adjacent boreholes and its cross-sectional trajectories in the boreholes can be detected through their similarity in morphology and occurrence. This property is called the connectivity of a structural plane. With limited survey data, the connectivity of structural planes can be used to analyze the sizes and ranges of structural planes and help determine the strikes of veins (Baecher et al. 1977; Huang et al. 2012; Liu et al. 2007; Lu et al. 2007; Shi & Dai 2007; Song 2009; Wu 1993).

FEATURE POINT-BASED DESCRIPTION OF STRUCTURAL PLANES

A structural plane, abstracted as a flat plane in a three-dimensional space, can be described by a 'feature point' P_C, defined as the intersection point between the structural plane and its normal vector passing through the origin point (i.e. point O). Each feature point uniquely corresponds to a structural plane and provides a good description of its occurrence and position.

First, the coordinate system is established by using a point near the borehole opening P as the origin, the true north as the x-axis and the true east as the y-axis, vertical down as the z-axis, so that the center of the opening has the coordinates $P_O(X_O, Y_O, Z_O)$. Suppose a structural plane N exists at depth H_z, with dip direction α, and dip angle β. Draw a perpendicular line from the center of the opening to the structural plane, with the foot at $P_{LC}(X_{LC}, Y_{LC}, Z_{LC})$, then the following conversions exist between the foot coordinates and the structural plane occurrence:

$$
\begin{aligned}
X_{LC} &= X_O + H_Z \bullet \cos\beta \bullet \sin\beta \bullet \cos\alpha \\
Y_{LC} &= Y_O + H_Z \bullet \cos\beta \bullet \sin\beta \bullet \sin\alpha \\
Z_{LC} &= Z_O + H_Z \bullet \cos\beta \bullet \cos\beta
\end{aligned} \quad . \tag{4}
$$

Draw a perpendicular line from the origin to the structural plane, with the foot at $P_C(X_C, Y_C, Z_C)$. This is the plane's feature point, which has the following conversions with known data:

$$
\begin{aligned}
X_C &= X_{LC}' \bullet (1 + \frac{X_{LC}' \bullet X_O + Y_{LC}' \bullet Y_O + Z_{LC}' \bullet Z_O}{X_{LC}'^2 + Y_{LC}'^2 + Z_{LC}'^2}) \\
Y_C &= Y_{LC}' \bullet (1 + \frac{X_{LC}' \bullet X_O + Y_{LC}' \bullet Y_O + Z_{LC}' \bullet Z_O}{X_{LC}'^2 + Y_{LC}'^2 + Z_{LC}'^2}) \\
Z_C &= Z_{LC}' \bullet (1 + \frac{X_{LC}' \bullet X_O + Y_{LC}' \bullet Y_O + Z_{LC}' \bullet Z_O}{X_{LC}'^2 + Y_{LC}'^2 + Z_{LC}'^2})
\end{aligned} \quad . \tag{5}
$$

$$
\begin{aligned}
X_{LC}' &= X_{LC} - X_O \\
Y_{LC}' &= Y_{LC} - Y_O \\
Z_{LC}' &= Z_{LC} - Z_O
\end{aligned} \quad . \tag{6}
$$

THEORY OF CONNECTIVITY ANALYSIS FOR STRUCTURAL PLANES

Prior to the connectivity analysis, the following assumptions are made: The planes are assumed to be infinitely extending planes in early analysis, before further assessments are made based on geological features of borehole walls; and a borehole is assumed to be vertical as long as its apical angle is not sufficiently large.

Engineering geological surveys frequently utilize multiple boreholes. Due to their sizes, it is possible for the same structural plane to be penetrated by more than one borehole. Using borehole cameras, a structural plane can be detected through analyzing its cross-sectional trajectories in several adjacent boreholes. This is the theory behind the connectivity analysis.

Under a global coordinate system, two fractures P1 and P2, respectively from two adjacent boreholes can be represented by the coordinates of their feature points as $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$. Thus the distance between them is:

$$
|P_1P_2| = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \ . \tag{7}
$$

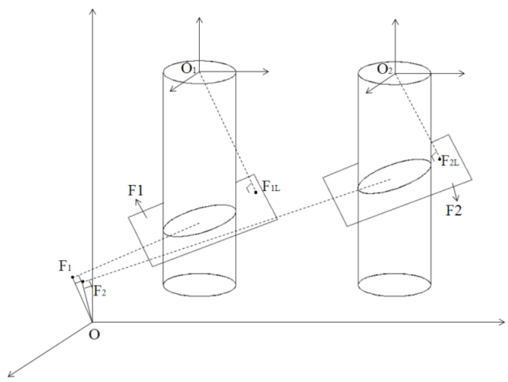

FIGURE 5. Schema of connectivity analysis

Each fracture corresponds to a unique feature point in the global coordinate system. In the ideal state, two fractures can be proven to be connected if their feature points overlap, i.e. the distance between them is zero (shown in Figure 5). But this may not be the case in practice, due to limitations such as accuracy of measurement. A minimum value ε is then designated as the threshold for connectedness, as follow:

$$
\begin{cases}
|P_1P_2| \le \varepsilon & P_1 \text{ and } P_2 \text{ are connected} \\
|P_1P_2| > \varepsilon & P_1 \text{ and } P_2 \text{ are not connected}
\end{cases} \ . \tag{8}
$$

The value of ε can be determined by the precision needed by the data.

$|P_1P_2|$ is the distance between two fractures' feature points. If $|P_1P_2|$ is below the threshold ε, two fractures may be connected, i.e. they exist on the same structural plane; if it is above ε, they are not connected by the same plane.

It is possible for the process above to detect false positives, i.e. different structural planes with similar parameters. Therefore, further assessments must be performed on these potentially connected fractures based on the geological features of rock bodies around them.

A CASE STUDY AND DISCUSSION

The example test is performed at the quartz-magnetite deposit of Zhongxinji, Huoqiu County, Anhui Province. Magnetic influence correction is necessary for using borehole camera systems in this region. Rock cores obtained by drilling show that the primary components of veins in the region are quartz-magnetite and dolomite-marble. Both minerals have well-preserved primary structural planes (or rock textures). The textures have strong contrasts with their background colours, making them simple to identify through optical imaging.

The following are partial screen captures from the borehole camera image of ZK13 borehole in the region, showing clear structural planes with obvious colour differences.

FIGURE 6. Magnetite

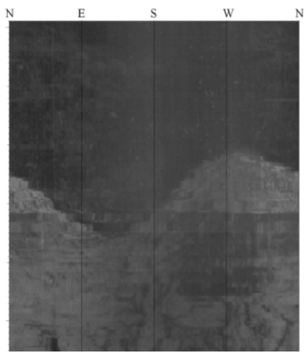

FIGURE 7. Interface

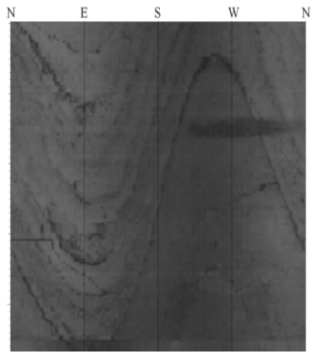

FIGURE 8. Dolomite-marble

TABLE 1. Borehole record by Geological Survey Team 313 of Anhui Province

Deposit	Zhongxinji, Huoqiu, borehole ZK13 (total depth: 550m)				
Instrument	STI-IGW digital gyroscope		KSP-1-2 digital magnetometer		
Depth (m)	Apical (°)	Azimuth Y (°)	Apical (°)	Azimuth X (°)	Correction
-120	1.15	41.9	0.7	51.7	9.8
-140	1.75	65	1.3	58.6	-6.4

TABLE 2. ZK13 -120~-125m segment structural plane dip direction correction

Depth (m)	Dip direction (º)	Dip angle (º)	Corrected dip direction (º)
-121.775	287.8	44	296
-121.945	286.3	13.8	295
-122.357	288.1	46.6	296
-123.936	281	40.6	288
-123.996	267.3	29	274

Figure 6 shows an image from the quartz-magnetite orebody. Figure 7 shows the interface between the magnetic orebody and white marble. Figure 8 shows an image from the dolomite-marble orebody. We can see significant differences between the ore-vein and background colours, which makes statistical analysis of the textures possible.

Table 1 shows the magnetic influences measured using gyroscopes and magnetometers. The gyro readings have already been corrected for drift. The example comes from the -120 ~ -140 m segment:

It can be seen that the magnetic influence correction is 9.8º at depth -120m (i.e. 51.7º-41.9º=9.8º) and -6.4º at -140m (i.e. 58.6º-65º=-6.4º). For textures located between -120 ~ -140 m, the correction value is obtained via linear interpolation. Table 2 shows the structural plane occurrence data in ZK13's -120 ~ -125 m segment obtained by digital borehole camera and the dip directions corrected for magnetic influences.

The following shows the calculation process. For example, in the correction of dip direction at -121.775 m, suppose the magnetic influence at said point is Zj and the dip direction post-correction is ωj, the interpolation of (3) gives:

$$Z_j = \frac{-121.775+120}{-140+120}(-6.4-9.8)+9.8 = 8.36. \quad (9)$$

The dip direction correction of (2) gives:

$$\omega + Z = 287.8 + 8.36 = 296.16. \quad (10)$$

This satisfies:

$$0 \le \omega + Z < 360 \,. \tag{11}$$

Hence we assume,

$$\omega_j' = 296 \,. \tag{12}$$

All structural planes discovered by the camera system have been corrected, resulting in more accurate dip directions for the textures.

The location of borehole ZK13 and ZK14 is shown in Figure 9. A coordinate system can be established with the center of ZK13's opening as the origin, the true east as the x-axis, the true north as the y-axis and vertical up as the z-axis. The feature point coordinates can be calculated based on the corrected occurrence data from Table 2, with results shown in Tables 3 and 4.

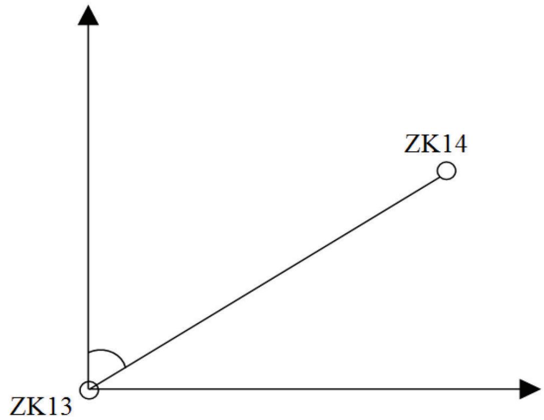

FIGURE 9. Sketch map of boreholes location

TABLE 3. Feature point coordinates of structural planes in ZK13

Depth (m)	Dip direction (°)	Dip angle (°)	Feature point coordinates		
			X	Y	Z
-33.891	86.7	74.2	-0.408331243	7.081751856	-2.007262193
-33.985	80.3	75.6	-1.157598413	6.772229645	-1.764032582
-34.336	86.4	78.7	-0.299272742	4.756804023	-0.952382546
-34.679	80.4	79.1	-0.847005491	5.007797169	-0.978046258
-35.132	87.8	77.7	-0.206796957	5.383076952	-1.174566339
…					

TABLE 4. Feature point coordinates of structural planes in ZK14

Depth (m)	Dip direction (°)	Dip angle (°)	Feature point coordinates		
			X	Y	Z
-37.054	80.7	82.9	-0.709690569	4.333821996	-0.546995935
-37.909	124.3	52	9.863506538	14.45935985	-13.67499497
-38.186	172.5	49.5	17.60449938	2.317676312	-15.16540504
-38.631	37.1	25.8	-12.33971749	-9.332455042	-32.0040697
-39.286	73.3	80.3	-1.900545542	6.334848202	-1.130517856
…					

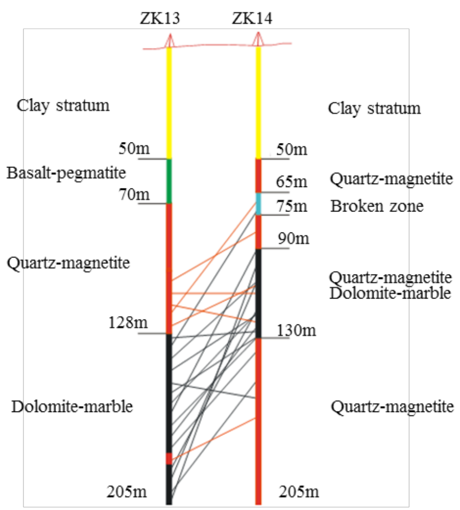

FIGURE 10. Analysis results of connectivity between two boreholes

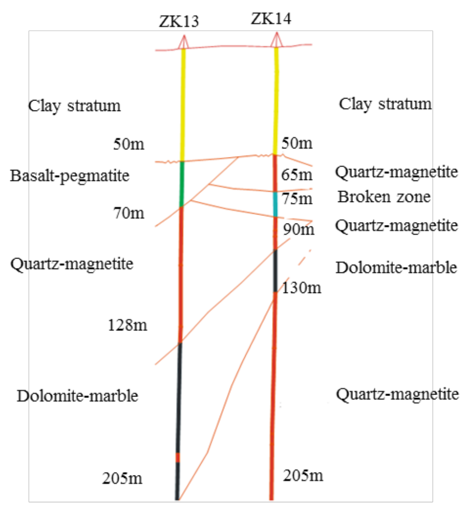

FIGURE 11. Prediction of vein extension based on drilling result

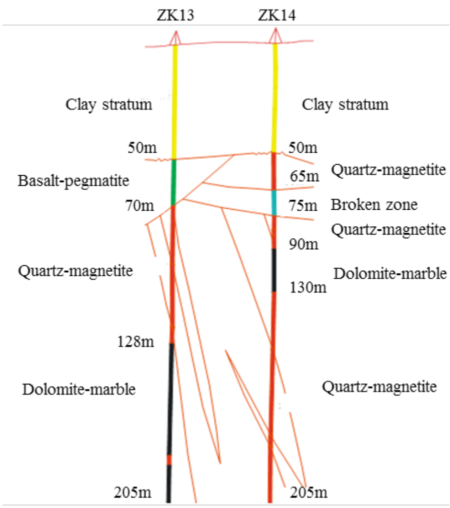

FIGURE 12. Prediction of vein extension based on multi-boreholes connectivity analysis result

The connected fractures between ZK13 and ZK14 in the 0~205 m range can be identified using the connected analysis. The structural plane schema in Figure 10 can be obtained by drawing a line between each pair of connected fractures. The results can be used as a basis to analyze the ranges of mineral veins in rock bodies between boreholes. Compared to cross-sectional diagrams drawn with the traditional approach, the results in Figures 11 and 12 show more details and provide a more accurate way to determine the extension of mineral veins, while eliminating the human errors from the traditional process.

Conclusion

This paper presents a method using borehole camera systems to obtain high-definition digital borehole images from a magnetic deposit, which contains the occurrence data of the mineral veins' primary structural planes (i.e. textures). The dip directions of the structural planes are then corrected using angles of magnetic influences obtained by gyroscopes and magnetometers. The corrected occurrence data can be used to analyze the vein extensions between two boreholes. Through comparison with the predictions of traditional methods, it is shown that this method provides a more accurate description of structural planes. The following conclusions can be reached: The digital borehole camera technology can be an important and effective method in deep prospecting; and the flow patterns of veins can provide information on directions of their extensions.

Acknowledgements

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