Acoustic Borehole Images for Fracture Extraction and Analysis in Second Pre-pilot Drillhole of CCSD*

Zou Changchun
Geodetection Laboratory, China University of Geosciences, Ministry of Education, Beijing 100083, China; School of Earth and Space Sciences, Peking University, Beijing 100871, China

Shi Ge
School of Earth and Space Sciences, Peking University, Beijing 100871, China

Pan Lingzhi
Geodetection Laboratory, China University of Geosciences, Ministry of Education, Beijing 100083, China

ABSTRACT: Ultrasonic imaging logging provides continuous and oriented images of structures vs. depth. In the Chinese Continental Scientific Drilling (CCSD) Project, acoustic borehole images were recorded in the second pre-pilot drillhole which penetrates the metamorphic rocks. This paper focuses on fracture evaluation of the drillhole with these images. Both least square fit and a modified Hough transform are used for fracture extraction, and 269 fractures were mapped in the interval from 69.5 to 1020 m. Most fractures dip steeply, with an average angle of 54°. Fracture dip directions are dominantly in the range of 220°—280° above the depth of 267 m, but 80°—120° in the lower zones. These observations may indicate the differences in structural movements or in-situ stress fields between the upper and lower zones in the drillhole.

KEY WORDS: Chinese Continental Scientific Drilling (CCSD), acoustic borehole image, fracture, analysis.

INTRODUCTION

The second pre-pilot drillhole of Chinese Continental Scientific Drilling (CCSD-PP II) Project is located in the east of Dabie-Sulu ultra-high pressure metamorphic (UHPM) belt, and the south of Sulu area in the north of Maobei Village, Donghai County, Jiangsu Province, China. PP II was drilled down to 1028, 68 m depth with 75.5 cm bits, and cased at a depth of 69.5 m. The investigation into drill cores reveals that PP II penetrates metamorphic formations. Five major lithological units are identified as follows: paragneiss, orthogneiss, amphibolite, eclogite and fault breccia. The percentages of main units, paragneiss and orthogneiss, are about 63 % and 20 %, respectively (Liu et al., 2001). Acoustic borehole images along with conventional logs were recorded after the completion of the drillhole, but dipmeter log and electric imaging log did not run since the slim hole (Niu and Pan, 2000).

Core analysis for structural features is limited because the cores are not oriented, and core recovery is often incomplete. Ultrasonic imaging logging provides continuous and oriented images of structures vs. depth, and is considered as an essential method to analyze and understand the structural features in PP II.

The early ultrasonic imaging logging tool is borehole televiewer (BHTV), Mobil Oil, Inc. introduced the first BHTV device in the late 1960s and obtained a patent (Zemanek and Caldwell, 1969). Great improvements have been made on BHTV due to the development of electronics and computers (Rambow, 1986, 1984; Georgi, 1985; Heard, 1981; Wiley, 1980). During the 1990s, new ultrasonic imaging logging tools have been developed, such as UltraSonic Imager (USI, Schlumberger) and UltraSon-
ic Borehole Imager (UBI, Schlumberger), Circumferential Borehole Imaging Log (CBIL, Baker Atlas) and Circumferential Acoustic Scanning Tool (CAST, Halliburton). Some of them are universally used in oil, natural gas and coal explorations, Continental Scientific Drilling Program (CSDP) and Ocean Drilling Program (ODP).

The ultrasonic imaging logging survey was conducted in PP∥ with a small calibre imaging logger supplied by the well-logging station of Shandong Coal Geology Bureau. The sonde is 3.6 m in length and 55 mm in diameter. Acoustic pulses (about 1.0 MHz) are transmitted from an acoustic transducer to the borehole wall and back at a rate of 300 times per rotation around the borehole. The rotation rate of the transducer is 5 revolutions per second, and the vertical sampling interval is 1 mm. The amplitude and travel time of each acoustic pulse reflected from the borehole wall are recorded, and then assembled into high-resolution images of the borehole wall.

Both the amplitude and transit time images are obtained from the depth of 69.5 to 1,020 m in PP∥. The repeat measurements in the section between 500 and 550 m demonstrate that the tool has been in a good quality state. The aim of this study is to extract and analyze fractures from acoustic borehole images in PP∥.

**APPROACHES TO FRACTURE EXTRACTION**

When a fracture plane intersects with a cylindrical borehole, the fracture trace will have a sinusoidal shape on the unwrapped image (Fig. 1). Fracture dip and dip direction can be determined according to the sinusoidal trace. In our investigation, fractures will be picked up from acoustic borehole images by the use of least square fit and modified Hough transform.

**Least Square Fit (LSF)**

Least square fit can be used to extract fracture and bed features from borehole images. It is usually done interactively on a computer screen (Barton et al., 1991).

On the unwrapped borehole wall image, a fracture trace in \((z, \varphi)\) coordinates satisfies an equation of the form

\[
z = A_0 \sin (\varphi - \theta_0) + z_0
\]

where \(A_0\) is amplitude; \(\theta_0\) is original phase and \(z_0\) is depth of the fracture.

The acoustic borehole image is displayed on a computer screen with a suitable depth scale. Move the mouse over the image, and select \(N\) points of interest \((N \geq 3)\) along the trace. The values of each point \((z_i, \varphi_i)\) \((i = 1, 2, \cdots, N)\) are recorded, from which three characteristic parameters of the sinusoid, \(A_0, \theta_0\) and \(z_0\), can be computed according to equation (1). Then, fracture dip and dip direction can be determined by the following equation

\[
a = \arctg \left( \frac{2A_0}{D} \right), \quad \beta = \frac{\pi}{2} + \theta_0
\]

where \(a\) is fracture dip and \(\beta\) is dip direction.

Least square fit is a simple and fast approach for fracture extraction. The main disadvantage of this approach is that some random errors may be created due to the manually selecting process.

**Modified Hough Transform (MHT)**

Hough transform, a powerful method for extraction of any analytic patterns in images (Hough, 1962), can map a sinusoidal curve in an image space into sets of points in a parameter space, and then determine the amplitude and phase of the curve according to the relative features in the parameter space. Therefore, Hough transform can be used to detect fractures from borehole wall images (Glossop et al., 1999; Torres et al., 1990).

Let \((z, \varphi)\) as image space, and \((A_0, \theta_0)\) as parameter space. Each point on a sinusoidal curve in the image space maps onto a curve in the parameter space. On the contrary, the cross point of each curve in the parameter space corresponds to the amplitude and the phase of the sinusoid in the image space. In actual implementation, a voting process is introduced to search the coordinate of the cross point. Because

![Figure 1. Intersection of a fracture plane with a cylindrical borehole and effect on 2-D unwrapped cylindrical surface.](image-url)
$z_0$ is an unknown parameter. Hough transform must be carried out for each depth of $z$ to find the optimal $A_o$, $\theta_o$ and $z_0$. And then, the dip and dip direction of the fracture can be calculated by equation (2).

The acoustic borehole image should be binarized before the Hough transform, with 1 representing the pixel of object features and 0 the pixel of backgrounds.

Hough transform can eliminate manual errors with a reference to the least square fit, and allow the traces of fracture uncontinuity. However, large computation and huge storage space are required for the standard Hough transform.

If the pixels of the object features in the acoustic borehole image are excessive, the efficiency of the standard Hough transform will decrease. For this reason, a modified Hough transform method is suggested with the combination of least square fit. First, fracture detection is conducted by the use of least square fit. Then, the results from least square fit are used to define the searching range of $A_o$, $\theta_o$ and $z_0$ of the parameter space. Finally, the optimum of $A_o$, $\theta_o$ and $z_0$ is determined by Hough transform. Since the parameter range is limited, the pixels for Hough transform decrease, resulting in a significant save in computing time.

**RESULTS AND ANALYSES**

Opening fractures manifest themselves as sinuroids on both amplitude and transit-time images, but closed fractures can be identified only from amplitude images. Therefore, it is easy to distinguish the opening and closed fractures from the images. Most of fractures, detected in PP II appearing on both amplitude and transit-time images, are opening fractures. With the approaches mentioned above, fractures were extracted from acoustic borehole images in PP II. The results show that the modified Hough transform is more accurate for fracture extraction, while least square fit is more suitable for the detection of irregular fractures. 269 fractures are mapped in the interval from 69.5 to 1 020 m, and their dips and dip directions are computed. The dips and dip directions are corrected for borehole deviation.

![Figure 2. Histograms of dips (a) and dip directions (b) of fractures in PP II.](image)

Histograms are drawn for fracture dip and dip direction over the interval from 69.5 to 1 020 m (Fig. 2). In Fig. 2a, where the horizontal coordinate represents the dip, and the vertical one is the number of fractures, a very large percentage of fractures are high angle fractures with an average dip of 54° except a few with a dip less than 20°. In Fig. 2b, where the horizontal coordinate represents the dip direction, and the vertical one is the number of fractures, the fractures are concentrated in two major dip directions; one is from 80° to 120°, and the other from 220° to 280°.

The changes in the fracture dip directions with the depth are also analyzed. Five fracture zones (FZs) are determined: FZ1 (69.5–267 m), FZ2 (298–470 m), FZ3 (490–580 m), FZ4 (650–690 m) and FZ5 (795–840 m), probably resulting from structural movements. The fractures appear in almost all rocks except eclogite. Rose plots of the fracture dip directions are drawn for the different fracture zones (Fig. 3). The depth interval in Fig. 3a is 69.5–1 020 m. Fig. 3b to Fig. 3f represent FZ1 to FZ5, respectively. The fractures in FZ1 dip dominantly southwestward, while those in the other four FZs dip eastward or southeastward, indicating the differences in structural movements or in-situ stress fields between FZ1 and the lower zones in the drill-hole.

In comparison of the acoustic borehole images with the conventional logs, the responses of some conventional logs are abnormal on the fracture and fault zone. The readings of resistivity logs are espe-
cially lower for the low-resistivity fluids filled in the fractures. The high-resistivity readings are in excellent agreement with the rocks which are hard and homogeneous, with few fractures within. Therefore, the conventional logs can be used as a reference to indicate the extent of fracture and fault growth. As shown in Fig. 4, LL3 is strongly affected by fractures for the shallow depth of investigation and high vertical resolution, so that the LL3 readings are lower in the location of fracture and fault section.

![Figure 3. Rose plots of dip direction of several selected depths.](image)

Most of fractures manifest themselves, as shown in Fig. 5, on both the acoustic borehole images and the core images. The left in Fig. 5 is the acoustic borehole image, and the right is the core image, both indicating that there are two fractures in the depth interval of 102–103 m. For the different coordinate systems, the fractures in the two images present different geometrical characteristics. The fractures observed in cores are usually more than those on the acoustic borehole images. One main reason for this difference is that the resolution is lower to find the fine fractures on acoustic borehole images. Another probable reason is that fractures are induced in drill cores during drilling the hole or transporting the cores.

![Figure 4. Comparison of acoustic borehole image and conventional logs.](image)

![Figure 5. Comparison of acoustic borehole image and core image.](image)

There is lack of structural information in the several intervals of acoustic borehole images due to cement seal operation. The borehole deviation also affects the analytical results in some intervals.
CONCLUSIONS

The fractures in PP II are successfully extracted from the acoustic borehole images obtained with both least square fit and a modified Hough transform. The results show that the modified Hough transform is more accurate for fracture extraction, while least square fit is more suitable for the recognition of irregular fractures.

In our analyses, 269 traces of fractures are extracted in the interval from 69.5 to 1.020 m, most of which are steep ones with an average dip of 54° except a few with the dip less than 20°. The fractures are concentrated in two major dip directions; one is from 80° to 120°, and the other from 220° to 280°. Five fracture zones are determined: FZ1 (69.5–267 m), FZ2 (298–470 m), FZ3 (490–580 m), FZ4 (650–690 m) and FZ5 (795–840 m). The fractures in FZ1 dip dominantly southwestward, while those in the other four FZs dip eastward or southeastward, indicating the differences in structural movements or in-situ stress fields between FZ1 and the lower zones in the drillhole.

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