Fracture analysis and determination of in-situ stress direction from resistivity and acoustic image logs and core data in the Wenchuan Earthquake Fault Scientific Drilling Borehole-2 (50–1370 m)

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A B S T R A C T

After the Wenchuan Earthquake on May 12th, 2008, the Wenchuan Earthquake Fault Scientific Drilling Project (WFSD) was initiated in order to investigate the structure of the fault zones and the mechanism of the earthquake. The WFSD contains four boreholes (WFSD-1, WFSD-2, WFSD-3 and WFSD-4) lying at the maximum displacement locations along the Yingxiu-Beichuan fault zone and the Guanxian-Anxian fault zone, and WFSD-2 is the second borehole and is still being drilled. Core samples, resistivity and acoustic image logging data were acquired from 50 to 1370 m. The natural fractures, borehole breakouts, drilling-induced fractures and drilling-enhanced natural fractures were identified from the cores and the image logs and were statistically analyzed. The strikes of the natural fractures systematically vary and can be sorted into four groups according to depth: (1) above 637 m, mainly striking ENE–WSW; (2) in the interval of 637–932.6 m, striking NNE–SSW; (3) in the interval of 932.6–1200 m, directed ENE–WSW then to NW–ESE, while striking NE–SW from 1030 m to 1150 m; (4) from 1200 m to 1370 m, maintaining a strike of NW–ESE. The natural fractures from 50 m to 637 m seem to be reverse faults which strike approximately parallelly to the main fault. Two sets of conjugate fractures around 1002.4 m indicating subvertical maximum principal paleo-stress direction may be a subordinate structure of the main fault caused by a local stress field, and it reveals the complex stress field of Yingxiu-Beichuan fault zone when the fractures formed. A total of 12 BOs, 2 sets of DIFs and one set of DEFs with an overall length of 30.4 m were interpreted from 960 m to 1370 m in WFSD-2. The average $S_{max}$ Orientation interpreted for WFSD-2 (960–1370 m) is 120.7°–300.7°N (i.e. NW–ESE) with the standard deviation of 9.2° and it is consistent with the stress status of Yingxiu-Beichuan fault zone which is one of the main fault zones in the 2008 Wenchuan Earthquake.

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1. Introduction

May 12th, 2008, the Wenchuan Earthquake (Mw 7.9) ruptured the Longmenshan margin of Tibet Plateau (Burchfiel et al., 2008). In order to investigate the structure of the fault zones and the seismic mechanism, the project of Wenchuan Earthquake Fault Scientific Drilling (WFSD) which contains four boreholes (i.e. WFSD-1, WFSD-2, WFSD-3 and WFSD-4) located in the Yingxiu-Beichuan and Guanxian-Anxian fault zones was initiated in China (Z.Q. Xu et al., 2008; Zou et al., 2012). Both WFSD-1 and WFSD-2 are located in the Hongkou village. Dujiangyan City, WFSD-3 was drilled in the Jiulong town, Mianzhu City and WFSD-4 will be drilled in Nanba town, Pingwu county (Fig. 1). The NE striking fault zone of Yingxiu-Beichuan is the main fault zone in Wenchuan Earthquake (Z.Q. Xu et al., 2008), which was characterized by thrust and right-lateral strike-slip. The vertical displacement, which was longer than 6 m and nearby WFSD-1 and WFSD-2, was observed in Shenxigou, Hongkou village (Lin et al., 2009; X.W. Xu et al., 2008; Xu et al., 2009). As a pilot hole of WFSD-2, WFSD-1 has been drilled to 1201.15 m (in this study, all the depths are given as measured depth). The core spatial position restoring has been achieved (Nie et al., 2012) and the in-situ stress has been studied (Peng et al., 2011). WFSD-2 is designed to drill to 3000 m to penetrate the main Yingxiu-Beichuan fault zone of which the depth is uncertain yet, and the core samples will be acquired continuously. At present, WFSD-2 has been drilled to 1370 m and cores have been continuously recovered. Image logs (including resistivity and acoustic image log), which are of great importance in fracture analysis, have been acquired in the interval from 50 m to 1370 m. The borehole deviation of WFSD-2 from 50 m to 637 m is 0°–6° with an approximate average azimuth of 220°, and from 637 m to 1370 m, the borehole deviation is 0–7.4° and the average azimuth is close to 150°.

Identification of geological structures from only image logs is difficult and may sometimes yield incorrect results (Lin et al., 2010).
Combined with core data sets, the natural fractures and borehole failure structures can be identified, extracted and analyzed effectively. Several studies have shown that for dip slip faults, the strike directions of natural fractures always closely associated with the directions of the maximum horizontal stress (SHmax) when the fractures formed (e.g. Anderson, 1951; Angelier, 1994; Lacazette, 2009). Conjugate fracture sets can be used to analyze the paleo-stress field, for the acute angle bisector of conjugate pair is equivalent to the direction of the maximum principal paleo-stress (Anderson, 1951; Lorenz, 1997; Muchlberger, 1961).

The borehole breakouts (BOs), drilling-induced tensile fractures (DIFs) and drilling-enhanced natural fractures (DEFs) visible in image logs reveal the present-day stress orientation (Barton and Zoback, 2002; Barton et al., 1998; Gough and Bell, 1982; Hickman et al., 1985; Morin, 2005; Rajabi et al., 2010; Shamar and Zoback, 1992; Trautwein-Bruns et al., 2010; Zoback et al., 1985). In a vertical borehole, the long axis of BOs corresponds to the orientation of the minimum horizontal stress (Smint), whereas the direction of DIFs and DEFs corresponds to the orientation of SHmax (Bell, 1996; Bell and Gough, 1979; Hickman et al., 1985; Trautwein-Bruns et al., 2010; Zoback et al., 1985, 1993). This technique has been used widely in the scientific drilling projects of Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland (KTB), Taiwan Chelongpu Drilling Project (TCDP), Chinese Continental Scientific Drilling (CCSD), the San Andreas Fault Observatory at Depth (SAFOD), and so on (Brudy and Zoback, 1993, 1999; Cui et al., 2009; Haimson et al., 2010; Lei et al., 2007; Lin et al., 2006, 2010; Wang et al., 2005, 2007; Wu et al., 2007; Zoback et al., 1993). Zoback et al. (1993), Brudy and Zoback (1993, 1999) used BOs and DIFs to investigate the stress state in the KTB drilling project in Germany. Lin et al. (2006, 2010) and Wu et al. (2007) defined the stress orientations of TCDP hole A and TCDP hole B respectively by analyzing BOs. Haimson et al. (2010) extrapolated the stress state of Chelongpu fault by using BOs along with other information. BOs were also used to define the present stress state of the main borehole of CCSD (Cui et al., 2009; Wang et al., 2005). Hickman and Zoback (2004) researched the stress orientations and magnitudes in the SAFOD Pilot Hole by using the BOs. Lei et al. (2007) determined the present stress field of Xujiaweizi rift in Daqing Oilfield by integrating DIFs.

2. Methodology

2.1. Resistivity and acoustic image logs

Images of the borehole wall in WFSD-2, measured by the electrical resistivity and acoustic reflections, were analyzed to identify the natural fractures, BOs, DIFs and DEFs. Geophysical logging tools used in this study were Halliburton’s EXCELL-2000 Series logging tools, which contain the Electrical Micro Imaging (EMI) and Circumferential Acoustic Scanning Tools (CAST).
The EMI tool contains 150 microelectrodes on 6 pads spaced 60° apart. The diameter of each electrode is 0.5 cm, and the spacing between electrodes is 0.25 cm. While logging, the pads are pressed against the borehole wall under a constant electrical potential. The variation of current of each electrode reflects the change of micro resistivity near the borehole wall as the tool passes through the borehole. The dense sampling is used to convert into color- or gray-scale resistivity images. In the common color-scale images, the lighter the color is, the higher the resistivity is. The cylindrical image of the borehole wall is unwrapped as if cut along the north; the resulting image represents the orientation as N–E–S–W–N from left to right.

In the CAST tool, a high-frequency transducer is used to rotate azimuthally to transmit 200 pulses ultrasonic wave per rotation towards the borehole wall. Both the travel time and the amplitude of the acoustic pulse reflected by the borehole wall are recorded, and the travel-time image and the amplitude image can be obtained. This amplitude is primarily controlled by the acoustic impedance and the roughness of the borehole surface. The images cover 100% of the borehole wall, and are presented in the same way as the images obtained from EMI (Fig. 2). In the color-scale amplitude image, the lighter the color is, the higher the amplitude is. So the images can be used to reveal the geological features such as the fractures, beddings and karst caves.

![Fig. 2. Examples of core spatial position restoring of WFSD-2: EMI, CAST, circumferential scan and front scan. Then geologic characteristics on the images are one to one correspondence after core spatial position restoring. The wathet sinusoidal curves, black curves and the red slips show layers, fractures and breakouts respectively. And because the core diameter is smaller, the heights of features such as fractures are less on the core image.](image-url)
etc. Since the travel time corresponds to a high resolution caliper log, the images can also be useful in showing the geometric shape of the borehole.

2.2. Core spatial position restoring

Cores are directly sampled from the subsurface and they are the most direct and accurate data sets that indicate the information of formation. However, the depth of cores always diverge the true value due to the excess errors introduced by the operators and equipments and the orientation is uncertain, the depth and orientation of cores need to be calibrated to make it match with the formation (Nie et al., 2012; Zou et al., 2007). Continuous cores of WFSD-2 have been obtained and digitally scanned. There are two types of core scan images. The less fragmentized cores are scanned circumferentially and from the front face; more fragmentized core individuals are only scanned from the front face. The depth shift of scanned images of the core is calibrated and matched with the image logs by using the software of CCSDLogCore (Fig. 2) (Nie et al., 2012; Zou et al., 2007). This correction allows unequivocal interpretation of natural fractures, including whether they might be open, and sedimentary structures that can be problematic in image logs alone (Davatzes and Hickman, 2010; Genter et al., 1997).

2.3. Identification of geologic features

Natural fractures and drilling-induced structures typically appear in the regions of enhanced conductivity primarily due to the increasing of the brine-filled porosity in the few centimeters of rocks adjacent to the borehole in EMI logs and in the regions of low amplitude due to the scatter of the acoustic pulse caused by the coarse surface in CAST logs (Blake and Davatzes, 2012). Because the images obtained from EMI or CAST tools are unwrapped cylindrical images, planar structures appear as sinusoidal curves in the images. In case there are natural fractures in the borehole wall, the corresponding resistivity and amplitude of reflected sonic wave are low because the fractures are filled with

![Fig. 3. Statistical graph of fractures by depth of WFSD-2 (50–1370 m): the left one shows frequency of fractures by depth; the middle one shows dips; the right one shows dip directions. According to the dip direction variation, the fractures can be divided into 4 depth intervals.](image-url)
mud. The natural fractures are black sinusoidal curves in the image logs whereas the fractures can be observed on the core samples (Fig. 2). After the fracture extraction and the borehole deviation correction, true attitudes of the fractures can be obtained. If these structures represent dip slip faults, the strike directions of the natural fractures are closely associated with the directions of $S_{\text{Hmax}}$ (Anderson, 1951; Angelier, 1994; Lacazette, 2009). This interpretation is further supported if (1) two conjugate sets of fractures are present and (2) their line of intersection corresponds to the strike.

Three types of drilling-induced structures were also identified in this study: BOs, DIFs and DEFs. These structures are important indicators of horizontal stress orientation (Barton and Zoback, 2002; Barton et al., 1998; Morin, 2005; Rajabi et al., 2010; Shamir and Zoback, 1992; Trautwein-Brunz et al., 2010; Zoback et al., 1985) and they result from the concentration of normal stress acting tangentially to the borehole wall that enhances compression or achieves tension respectively (Blake and Davatzes, 2012). BOs are compressive shear failures which are usually not very clear in resistivity images but can be seen clearly as two vertical black stripes separated by 180° in acoustic images. DIFs are most clearly revealed in resistivity logs and are less evident in acoustic image logs (Davatzes and Hickman, 2010). Near-vertical fractures at opposite sides of the borehole are interpreted as DIFs, while inclined, partly open, sinusoidal fractures are interpreted as DEFs (Trautwein-Brunz et al., 2010). BOs and DIFs occur only in the borehole wall due to concentration of the in-situ stresses, and do not propagate away from the borehole (Peška and Zoback, 1995), thus there are no corresponding features on the cores. However, there are always fractures corresponding to DEFs on the cores. The long axis of the BOs is consistent with the orientation of $S_{\text{Hmin}}$ and the strike directions of the DIFs or DEFs always correspond to the orientation of $S_{\text{Hmax}}$ (Barton and Zoback, 2002; Barton et al., 1998; Morin, 2005; Rajabi et al., 2010; Shamir and Zoback, 1992; Trautwein-Brunz et al., 2010; Zoback et al., 1985). The BOs, DIFs and DEFs observed in boreholes are used to determine an average orientation of $S_{\text{Hmax}}$ using standard circular statistical methods (Mardia, 1972). The quality of average orientation of $S_{\text{Hmax}}$ is ranked according to the World Stress Map (WSM) criteria that take into account the standard deviation of the orientations of drilling-induced structures in addition the total length and number of drilling-induced structures observed (Heidbach et al., 2010).

Fig. 4. The schematic diagram of the fault breccia of 932.6 m in WFSD-2: because of fault breccia, and the borehole enlargement, there is little useful information in acoustic imaging data in this interval, but the strike change of the fractures can be observed clearly in the EMI image. The cores are not continuous at this depth because of the fragment.
3. Results and discussion

3.1. Fracture analysis

The distribution of the natural fractures intersecting WFSD-2 from 50 m to 1370 m is sorted into four groups in depth, as shown in Fig. 3: (1) in the interval of 50–637 m, the strike direction of the natural fractures is mainly ENE–WSW; (2) from 637 m to 932.6 m, it is mainly NNE–SSW; (3) in the interval of 932.6–1200 m, the strikes gradually rotate from ENE–WSW to WNW–ESE, and from 1030 m to 1150 m, a group of natural fractures strike mainly NE–SW; (4) in the interval of 1200–1370 m, natural fractures generally strike WNW–ESE. Most of the natural fractures have moderate dip angles, while in several intervals, there are also fractures with high dip angles and low dip angles. The respective transitions between Zone A to B and B to C are associated with fault breccias evident in core and image logs (e.g., Fig. 4). Additionally, the contoured stereograms (lower hemisphere equal-area) and the rose diagrams of the natural fractures in the intervals of 50–637 m, 637–932.6 m, 932.6–1200 m and 1200–1370 m separately are shown in Fig. 5.

Two sets of conjugate fractures, which formed by shear action, are two groups of cross fractures with an angle of ~60°. They appear in the image logs as crossed black sinusoidal curves, which correspond to the cross fractures on the cores. The direction of the acute angular bisector of the conjugate fractures indicates the maximum principal stress orientation when the conjugate fractures formed (Anderson, 1951; Lorenz, 1997; Muchlberger, 1961).

From the stereogram of the fractures from 50 m to 637 m, two sets of conjugate fractures which strikes ~60° and dips at ~45° to NW and ~25° to SE respectively can be defined (Fig. 5A). According to Anderson (1951), the dips of these fractures lie in the expected range for reverse faults.

Around 1002.4 m in WFSD-2, two small sets of conjugate fractures with much less population were observed (Fig. 6A). The dips and dip directions are listed in Table 1, and it indicates that they strike ~100° and dips ~65° to NNE and ~55° to SSW respectively (Fig. 6B).

That means the maximum principal paleo-stress direction was subvertical when the set of conjugate fractures formed. Thus they seem to be normal faults (according to Anderson, 1951).

DIFs and DEFs are found below 1270 m in the image logs of WFSD-2. Two pairs of vertical DIFs are found at 1271 m and 1323 m and one set of DEFs are found at 1274 m. Fig. 7 shows the DIFs and DEFs at depth of 1270–1275 m in WFSD-2.

3.2. Horizontal in-situ stress orientation

BOs were observed below 960 m in WFSD-2 near following depths: 960 m, 963 m, 979 m, 1010 m, 1011 m, 1015 m, 1043 m, 1049 m, 1164 m and 1358 m (e.g. Fig. 8). The azimuth of BOs in WFSD-2 (960–1370 m) is between 22°N and 44°N. The borehole deviation azimuth of WFSD-2 below 637 m is about 150° and is not in the same direction of the long axis of BOs, and the borehole deviation is much less than 15°. Thus the data sets obtained from the BOs can be used to indicate the state of the horizontal stress (see Peška and Zoback, 1995).

The strike directions of the vertical DIFs at 1271 m and 1323 m are 122°–302° and 105°–285° respectively. The set of DEFs at 1274 m, strike 122°–302°.

A total of 12 BOs, 2 sets of DIFs and one set of DEFs with an overall length of 30.4 m were interpreted in WFSD-2 (960–1370 m). The average SHmax orientation interpreted for WFSD-2 is 120.7°–300.7°N (i.e. WNW–ESE) with the standard deviation of 9.2°. Thus the SHmax orientation interpreted for WFSD-2 is ranked as C-quality according to the WSM criteria. Fig. 9 displays the diagram of the SHmax directions derived from BOs, DIFs and DEFs, and it reveals that the SHmax directions derived from BOs, DIFs and DEFs are consistent with each other.

3.3. Discussion

With the strong collision and extrusion of Indian Ocean plate towards Eurasia plate for 45 Ma, the Qinghai-Tibet Plateau uplifts, with

A

B

C

D

Fig. 5. Dip and strike distribution of natural fractures in WFSD-2 (50–1370 m): A (50–637.0 m), B (637–932.6 m), C (932.6–1200 m), D (1200–1370 m). The left ones are the contoured stereograms (lower hemisphere equal-area) while the right ones are the strike direction contribution rose diagram.
Fig. 6. (A) Two sets of conjugate fractures around 1002.4 m in WPSD-2 (sinusoidal lines). (B) The lower hemisphere equal-area projection diagram of the conjugate fractures. Their attitudes are around 10°–65°–190°–55°, means that the maximal principal stress orientation was 190°–85° when the set of conjugate fractures formulate.
The coseismic deformation is almost pure thrusting on the southern end of Sichuan Basin and the Basin is forced glide to the right direction owing eastward (Tapponnier and Molnar, 1977). The Longmenshan fault zones to the east margin of Qinghai-Tibet Plateau were formed when Qinghai-Tibet Plateau moves eastward and encounters the rigid block of Sichuan Basin (Royden et al., 1997, 2008).

The 5.12 Wenchuan Earthquake probably reflected the long-term uplift of Qinghai-Tibet Plateau, as well as its squeezing power towards Sichuan Basin and the Basin is forced glide to the right direction (Burchfiel et al., 2008). Among the Longmenshan fault zones, the most relevant one to Wenchuan Earthquake, Yingxiu-Beichuan fault zone is directed N35°–45° E, towards NW. It consists of several separate reverse faults arranged in the form of shingles, appearing to be a right-lateral strike-slip fault (X.W. Xu et al., 2008; Xu et al., 2009). The coseismic deformation is almost pure thrusting on the southern segment compatible with a nearly average NW–SE shortening and with field evidence of active thrusting and oblique thrusting deformation indicated by the aftershock distribution and their focal mechanisms (e.g. Ji, 2008; U.S. Geological Survey, 2008; Zheng et al., 2009; Zhu et al., 2008) and by field investigations (e.g. Fu et al., 2008; Li et al., 2008; Lin et al., 2009; X.W. Xu et al., 2008; Xu et al., 2009). Former studies have shown that the principal compressive stress in the Longmenshan fault zone is directed 110°–290° (i.e. NW–ESE) (Hu et al., 2008; Zhong and Cheng, 2006). And in Yingxiu-Beichuan fault zone, the southwest end of Longmenshan fault zone, the principal compressive stress is directed near NW–SE (Shi et al., 2009). The orientation of present-day $S_{\text{max}}$ derived from BOS, DIFs and DEFs in WFSD-2 is consistent with the regional stress state.

There are no BOSs, DIFs or DEFs found from the image logs in WFSD-1, but by using differential strain analysis method (DSA) to analyze cores after the spatial position restoring, the in-situ stress of WFSD-1 has been researched by Peng et al. (2011). The results show that from shallow to deep in WFSD-1, the direction of maximum horizontal principle stress progressively rotate from 325.2° to 298.5°. The analyzed stress orientation result of WFSD-2 (960–1370 m) is consistent with the direction of $S_{\text{max}}$ of the deeper intervals of WFSD-1.

The fractures from 50 m to 637 m seem to be reverse faults which strike approximately parallelly to the main fault. When the fractures formed, the direction of $S_{\text{max}}$ was ~330°. It is a little difference from the direction of present-day $S_{\text{max}}$ of 960–1370 m in WFSD-2, but it is consistent with the stress orientation of the shallower interval of WFSD-1. According to the stress rotation along with depth in WFSD-1, it would make sense that there is a stress rotation between the intervals of 50–637 m and 960–1370 m in WFSD-2.

It is known that faults and joints occur at different scales in a hierarchical fashion, as a consequence of progressive shearing, and shearing along bedding planes created subvertical splay joints that induced the formation of conjugate normal faults. Hence, in the thrust belt, subordinate strike-slip and normal faults can be produced by the compressive deformation (Florez-Niño et al., 2005). Thus, the set of conjugate fractures around 1002.4 m can be interpreted as a subordinate structure of the main fault zones. The difference between the local paleo-stress and the long term regional stress might reveal a local stress rotation when the conjugate fractures formed.

### 4. Conclusion

The $S_{\text{max}}$ evident from drilling-induced structures in the interval between 960 and 1370 m is directed at NW–ESE and is consistent to the stress state derived from WFSD-1. The directions of $S_{\text{max}}$ in both WFSD-1 and WFSD-2 are consistent with the stress state of Yingxiu-Beichuan fault zone.

Results of fracture analysis show that the natural fractures in WFSD-2 can be sorted into four groups with strikes of: (1) ENE–WSW (50–637 m), (2) NNE–SSW (637–932.6 m), (3) ENE–WSW to NW–ESE (932.6–1200 m), NE–SW (1030–1150 m), (4) NW–ESE (1200–1370 m). The fractures from 50 m to 637 m seem to be reverse faults which do not strike accurately parallelly to the main fault. That reveals the possibility of stress rotations along with depth in WFSD-2. The two sets of conjugate fractures around 1002.4 m which indicates a stress rotation are likely a secondary structure as the result of a local stress field. It reveals that the Yingxiu-Beichuan fault zone has the typical structure of a thrust fault zone with complex local stress fields.

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### References


Fig. 7. DIFs and DEFs at 1270.0–1275.0 m in WFSD-2: the DIFs are near vertical fractures parallel to the borehole axis while the DEFs are similar to natural fractures in the logging images. The DIFs cannot be found on the corresponding cores.
Fig. 8. The schematic diagram of the BOs at the depth of 1010.0 m in WFSD-2: there are obvious stripped breakouts on the image logs; the core image at the same depth is smooth and featureless, and that shows these BOs happened after the drilling.
Fig. 9. The schematic diagram of the direction of $S_{\text{max}}$ indicated from BOs, DIFs and DEFs in WFSD-2 (50–1370 m): the main directions of $S_{\text{max}}$ indicated from BOs, DIFs and DEFs are consistent. It shows that the direction of $S_{\text{max}}$ derived from the data is convincible.


