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Fracture patterns in successive folding in the western Sichuan basin, China

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A B S T R A C T

A detailed field survey of fractures was carried out in the Pingluoba and adjacent anticlines in the western Sichuan basin to discuss fracture development during progressive folding, including the relative timing of fracture formation, the successive deformation in a rock layer, the distribution of fracture sets in folds, and the variation of fractures along with the subsequent deformation of rock layers. Based on a comparison of the diverse fracture patterns in folded strata at different stages of fold growth (horizontal, low-angle dipping, high-angle dipping, and vertical layers), a model of fracture development related to fold evolution was built up. It is suggested that the strata were initially under uniform compression, and two sets of planar conjugate shear fractures were formed, the orientations of which would vary along with the subsequent folding of strata. Then, during progressive folding, the deformation of rheologically hard layers was controlled by tangential longitudinal strain, inducing the development of a set of tensile fractures that struck parallel to the fold axis. Layer parallel shear was predominant in the soft layers, and two sets of bedding-oblique dextral shear fractures intersecting with the bedding at angles of 25–40° and 160° were developed. In the progressive folding process, the shear fractures were developed later than the tensile fractures. A polar stereonet of fractures was generated and applied to improve the efficiency and accuracy of fracture identification in the field, providing precise evidence for the exact analysis of fracture patterns and rock deformation.

1. Introduction

Fractures broadly developed in folded strata are a direct consequence of stress applied during fold development. The stress status and deformation mode during folding can be reconstructed based on the fracture patterns preserved in rocks. It is also possible to predict the distribution of fractures based on investigations of the relationships between fractures and folds, which are important in the discovery and evaluation of hydrocarbon and mineral resources (e.g., Schultz-Ela and Yeh, 1992; Fischer and Wilkerson, 2000).

Each fracture set developed in folded strata is always correlated to a specific deformation mode during folding (e.g., Groshong, 1975; Nickelsen, 1979; Gray and Mitra, 1993; Cooke et al., 2000), except for the pre- and post-folding fractures. In buckling folds, three modes of deformation are predominant according to previous studies (e.g., Ramsay, 1967; Ragan and Deng, 1984; Ramsay and Huber, 1987; Price and Cosgrove, 1990; Fischer and Wilkerson, 2000; Bellahsen et al., 2006; Ismat, 2008; Casini et al., 2011), and a unique fracture pattern is developed in each mode. The modes can be described as follows. (i) Layer parallel shortening. When the strata are still horizontal, two sets of planar conjugate shear fractures and a set of tensile fractures parallel to the stress strike develop under the horizontal compression. (ii) Tangential longitudinal strain. During the progressive folding of the strata, the extensional stress caused by the bending of the strata induces bedding-perpendicular tensile fractures, while in the inner arc of the strata bedding-perpendicular cleavage and conjugate shear fractures are mainly developed due to compression. (iii) Layer parallel shear. Shear deformation also exists in the strata during limb rotation in flexural flow and flexural slip folds. Previous studies have usually applied the Riedel model to explain the fractures induced by simple shear (Riedel, 1929; Dresen, 1991; Katz et al., 2004; Misra et al., 2009). In the strata of thrust related anticlines, two sets of conjugate thrust faults are often observed, which have similar orientations as the R and P shear fractures of the Riedel model but are still interpreted as the result of layer parallel shortening (e.g., Ismat and Benford, 2007; Reif et al., 2012). Studies have also demonstrated that fractures developed during different stages of folding usually have specific orientations, positions, deformation modes, and geometrical characteristics. Because the development of fractures can be related to fold evolution, many studies have utilized fold-related fractures to analyze the variation of stress and

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strain in the folding process (e.g., Sanderson, 1982; Couzens and Dunne, 1994; Anastasio et al., 1997; Amrouch et al., 2010; Savage et al., 2010). Many studies based on fracture patterns developed in different positions in folds, such as forelimb, backlimb, hinge, and plunging crown, have deduced the overall history of fold and deformation differences between different positions (e.g., Bellahsen et al., 2006; Tavani et al., 2011). Other studies have chosen to analyze fracture data based on the dip angle of strata where the fractures are distributed, intending to interpret the fracture pattern in the strata with different deformation degrees (e.g., Engelder and Peacock, 2001).

A series of Cenozoic buckling anticlines are developed in the western Sichuan basin. These folds have similar formation mechanisms but different fold morphologies (such as gentle, open and close folds). Therefore, folded strata at different stages of folding can be observed in this region, making it a suitable place for analyzing the fracture development and rock deformation during a successive folding process. Moreover, the Sichuan basin is one of the most petroleum-rich areas in China. The dense clastic rock layers developed in the basin exhibit characteristics that are convenient for the development of fractured hydrocarbon reservoirs. Many hydrocarbon-bearing structures have been discovered in this region (Jia et al., 2006; Zhu et al., 2009). Discussion about the fracture system in the region is helpful for both understanding the development of fracture-related folds and hydrocarbon reservoir exploitation, but only few detailed studies had been carried out prior to this study.

Based on detailed field measurement and observation, the fracture patterns in the Pingluoba and adjacent anticlines in the western Sichuan basin were analyzed in this study to show the fracture development during the successive process of fold growth. Polar stereonets of fractures were generated in the field and applied to improve the efficiency and accuracy of fracture analysis. According to the comparison of fracture patterns in the folded strata at different stages of folding, the fractures developed at each stage of folding and the corresponding deformation modes of the strata were identified. The variation of fractures along with subsequent deformation and superposition of fracturing are discussed based on the statistics of fractures in the polar stereonet.

2. Fracture survey

2.1. Study area

The study area is located in the southern segment of the Longmen Mountain thrust belt in the western Sichuan basin. Four main anticlines were developed in the area, from west to east (Fig. 1): the Shuikou anticline, the Sanhechang anticline, the Pingluoba anticline, and the Qiongxi anticline. The first three folds belong to a NE–SW-striking belt. The deformation period of the belt started in the Early Cretaceous and ended in the Early Cenozoic (Jia et al., 2006; Liu, 2006; Jin et al., 2010; Deng et al., 2012). Because the Mesozoic strata are uniformly involved in the anticline, the deformation of these folds should have been initiated in the early Cenozoic. The Qiongxi anticline is located east of the NE tectonic belt and belongs to a N–S striking tectonic belt controlled by two N–S striking faults. The deformation of the Qiongxi anticline began after that of the Pingluoba anticline (Jia et al., 2007, 2009). The stress direction in this stage became an E–W compression, which can be attributed to the India–Asia collision (Dirks et al., 1994; Burchfiel et al., 1995).

The strata in the core of the Pingluoba anticline are nearly horizontal, and the strata in the southeast limb have a maximum dip of 20°. The strata in the northwest limb cannot be observed in the field because this limb is tectonically covered by the southeastern limb of the Sanhechang anticline. The southeastern limbs of the Sanhechang and Shuikou anticlines have a dip of 50–90° (Fig. 2). In the study area, the argillaceous sandstones of the Cretaceous Guankou Formation (K_2g) and the sandstones of the Cretaceous Jiaguan Formation (K_2j) are mainly exposed in the Pingluoba and Qiongxi anticlines. In the Sanhechang and Shuikou anticlines, sandy mudstone of the Jurassic Penglai Formation (J_3p), mudstone of the Jurassic Suining Formation (J_2sn), and a conglomerate of the Jurassic Shaximiao Formation (J_2s) are mainly exposed.

2.2. Field measurement

Fractures were measured at twenty-four sites covering characteristic positions, such as fold hinge, limb, and plunge (Fig. 1). At each site, continuous outcrops >10 m were measured to ensure that the observed fracture data were adequate to reflect the fracture patterns. Orientations, apertures, and surface descriptions were also recorded. In the measurement process, the location and sequence number of each measured fracture were marked on the photographs of outcrops (Fig. 3a). The Lambert application (software) on an iPad was used to record the orientation and sequence number of fractures and to generate the polar stereonet of the fractures in the field (Fig. 3b). This operation was helpful because under some conditions (such as extremely fragmented strata and outcrops facing different directions) fractures were difficult to identify. Generating the polar stereonet in the field and relating fractures in the outcrops to the poles in the stereonet made the grouping of fractures more convenient and accurate and made the field observation more targeted, thus improving the precision of the field work. The orientations for each fracture and its deformation mode were affirmed in the field based on the observation of fracture features, the direction of motion, and the abutting relationship.

The folded strata were divided into four categories based on the variation of dip angles to analyze the variation of fracture patterns, including the following: (1) nearly horizontal strata (dip angle <10°); (2) strata with a low dip angle (from 10° to 30°); (3) strata with a high dip angle (from 30° to 75°); and (4) nearly vertical strata (dip angle >75°). From the result (Fig. 2), the fracture pattern in each case has special features that might differ from other categories.

3. Fracture patterns

3.1. Fracture pattern in horizontal strata

The horizontal strata in the study area represent the initial stage of fold development. Two sets of shear fractures, forming a conjugate pair perpendicular to the bedding plane, were developed under horizontal compression (Fig. 3). The acute bisector of the conjugate fractures follows the compression direction that controls the formation of the anticline and the shortening direction of strata during folding. The conjugate shear angle is related to the angle of internal friction (Fischer and Wilkerson, 2000; Guiton et al., 2003; Ismat, 2008).

According to the field observations, these fractures have straight extending, smooth surfaces, small apertures (average aperture <0.3 mm), steps and slickenlines on the fracture surface, and no mineral fillings (Fig. 4). The movement direction indicated by the steps is perpendicular to the intersecting line of the two fractures. The steps and slickenlines show that the N–S and E–W striking fractures have sinistral and dextral displacement, respectively. Most of the fractures are stratabound, but a few are non-stratabound and cut through two or more rock layers. The fractures are uniformly distributed in the outcrops. In the polar stereonet of