Characteristics and major controlling factors of fracturing in an Archean buried-hill, Bozhong Sag, Bohai Bay Basin, China

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Abstract. Archeozoic fractured buried-hill reservoirs have been found in the Bozhong Sag, Bohai Bay Basin, but the origin, stage and distribution of fractures are still unclear. The B-block is used as an example to explore the genesis and main controlling factors on fracture formation. Core and image log data, combined with regional geology, were used to comprehensively analyze the characteristics of fractures. High-angle shear fractures and low- to moderate-angle tensile fractures were developed in the area. Fracture development was mainly controlled by lithology. The lithologies in the study area from most fracture prone to least are monzonite, granodiorite, cataclastic rock and gneiss. This study has provided a basis for the prediction of potential reservoir areas in paleo-buried hills.

Key words: Buried-hill reservoirs; Bozhong Sag; Controlling factors; Fracture; Lithology.

1. Introduction
The Bohai Bay Basin is one of the key areas for the expansion of China’s oil and gas resources. Its proven reserves within buried-hill reservoirs are relatively small, accounting for only 2.9% of total reserves [1]. However, exploration of buried hills in the Bohai Bay Basin is still in its infancy and the buried hills in this area have great potential and contain good prospects [2, 3]. In 2017, the breakthrough discovery of natural gas was made in the buried-hill reservoirs of the Bozhong Sag [4], which further confirmed the gas exploration potential of deep complex buried-hills in the sea area [5]. However, the lithology of the Archean buried hills is complex and has undergone multi-stage structural superposition reactivation, forming a type of reservoir dominated by fracture porosity. The formation mechanisms, ages and distribution of fractures are still unclear, which restricts exploration and development of these buried-hill reservoirs. Taking the B-block of the Bozhong Sag as an example, the objective of this study is to use core and image logging data, combined with regional geology to comprehensively analyze the characteristics of fractures, and explore main controlling factors.
2. Geological setting

The study area is in the B-block, southwest of the Bozhong Sag, and is surrounded by the Suizhong and Huanghekou Sags, and has excellent oil and gas resources. It is located on the near-south-north oriented tectonic ridge between the Bozhong Southwest and Main Sub-sags, and acted as an uplift tectonic among those sags (Figure 1). The main lithologies in the study area are monzonitic granites, granodiorites, cataclasite and gneiss.

![Simplified structural map of the Bozhong Sag](image)

**Figure 1.** Simplified structural map of the Bozhong Sag showing the location and structural setting of the study area. modified from [4]

3. Characteristics and major controlling factors of fracture

3.1. Fracture type

Fractures are classified differently [6, 7]. Based on drill core description and imaging log interpretations in the study area, fractures in the Archean buried-hills are relatively well developed. The section with developed fractures accounts for more than 80% of the total core thickness. Based on existing data from the research area combined with previous studies, fractures have been classified by their mechanical properties, dip and openness. Fractures in the buried-hill within the study area can be divided into tensile and shear fractures (based on mechanical properties); high-angle fracture ($\geq 60^\circ$), moderate-angle fracture ($30^\circ$-$60^\circ$) and low-angle fracture ($\leq 30^\circ$)( based on dip angle) and open or closed fractures(based on openness)(Table 1).

Shear fractures in the cores are relatively well developed, they are high- to moderate-angle fracture. This kind of fracture surface is smooth, fracture occurrence is stable, aperture is small, and can appear in groups. They are generally conjugate. Sometimes one group of conjugate shear joints is well-developed, but not the other. In the core, several groups of fractures cross-cut and restrict each other, and that the degree of filling varies. These differences occur among different stages of fracturing. Early fractures are filled with calcite and later ones are filled with clay minerals.

High-angle fractures($\geq 60^\circ$) are more abundant in well B1 and B4 than in the other two wells. Overall, moderate-angle fractures are dominant, followed by high-angle fractures, which account for more than 85% of the total number of fractures, while low angle fractures are less common.

Most of fractures in the study area are conductive (96%), while few are resistive fractures (4 %). The filling degree of fractures in each well is not high, and the proportion of open fracture is large. Closed fractures are mostly low- or moderate-angle fractures. In wells B1 and B2 high-angle fractures are all open. This may be related to the formation stages of different types of fractures and diagenetic evolution of the reservoir.
Table 1. Classification of fractures in the study area

| Classification basis | Fracture type     | Definition                                                                 | Identifying features                                                                 | Photographic examples |
|----------------------|-------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------------|----------------------|
| Mechanical properties| Tension fracture  | Produced by tensile stress. Oriented parallel to maximum and intermediate principle stresses | Occurrence is unstable, have limited extension, rough surface and open                | Sidewall core from 427m in well B2. Under fluorescent light |
| Shear fracture       | Generally generated by compressive stress. Oriented oblique to the maximum principle stress | Occurrence is stable, can be extensive, surface flat and often closed                 | Sidewall core from 4545 m in well B3. Under fluorescent light |
| Dip                  | High-angle fracture | Dip $\geq 60^\circ$                                                       | Steep dip, frequent, often through the core                                           |                      |
|                      | Moderate-angle fracture | Dip $30^\circ - 60^\circ$                                               | Moderately shallow dip, frequent, form a network                                      |                      |
|                      | Low-angle fracture | Dip $\leq 30^\circ$                                                     | Sub-horizontal to shallow dip, infrequent                                            | Core from 3878.21m in well B2 |
| Openess              | Open fracture      | Open has the ability to seep and can contribute to reservoir porosity     | Appear as dark conductive bands in the FMI image log                                 |                      |
|                      | Closed fracture    | Filled by mineralization, doesn't seep or contribute to reservoir porosity | Appear as bright resistive bands in the FMI image log                                 |                      |

Note: Mechanical properties in the table refer to [8, 9]; Dip and openness refer to [10-12]

3.2. Control factors of fracture development

Observations of fractures in core and imaging logs from the Archean buried hills show that fracture development has strong heterogeneity. Characteristics of the fracture development in different parts of the study area are various, and the development degree of vertical fractures within a well is also unlike. Studies have shown that fracture development can be related to lithology.

The lithology of the buried-hills in the study area is complex, with twenty-one types of lithology identified through observations of the cores, sidewall cores and thin section. Based on the "identification standard of thin section" and the composite classification method of "mineral composition + characteristic structure", different lithologies in the study area were classified into gneiss, and cataclastic and igneous rocks. Based on mineral composition and the content and a plagioclase ratio (the ratio of plagioclase to total feldspar), the igneous rocks were further divided into granodiorite (quartz / (feldspar+quartz) between 20% and 60%, and a plagioclase ratio < 65% and <90%), monzonitic granite (quartz / (feldspar+quartz) between 20% and 60%, and a plagioclase ratio <35% and < 65%). Based on this, the control effects of lithology on fractures were evaluated.
The fracture strike and development degree data from the same lithologies within the four studied wells (Figure 2), indicate that the monzonitic granite is prone to fracturing, and the fracture strike is consistent, mainly in the NW-SE direction. Granodiorite is also prone to fracturing, but the fracture anisotropy is relatively strong, mainly broadly E-W direction and NW-SE direction. The fracture development degree in cataclastic rocks is influenced by the late tectonic period and dominated by the NE-SW direction. Fractures in gneiss are relatively uncommon and mainly consist of E-W oriented fractures. It is suggested that the fracture development follows the sequence rule of dominant lithology (the earlier the sequence, the more likely it is to have produced fractures and have a higher degree of fracture development, while the later the sequence is, the lower the degree of fracture development), that is, monzonitic granite > granodiorite > cataclastic > gneiss.

Figure 2. Rose diagrams of fracture strike and histogram of fracture densities in different lithologies within the study area

3.3. Fracture development mode
The Archean buried-hills in the BZ19-6 structural belt of the Bohai Bay Basin have undergone multiple stages of tectonic movement that has produced a large number of fractures with an uneven distribution. Based on the data from this study a fracture development model was established for the study area (Figure 3). The lithology in the south is dominated by granodiorite with veins. The northern part is dominated by monzonitic granites and with undeveloped veins. The cataclasites are developed near fault zone, which is a tectonic fracture zone. The degree of fracture development differs from south to north. The lithology in the north is prone to fracturing, and the degree of fracture development higher than in the south. Therefore, the northern part of the study area may be more favorable for future exploration.

Figure 3. Fracture development mode of the study area
4. Conclusion
Fractures of the ancient buried hills in the study area can be divided into shear and tensile fractures according to their mechanical properties. Based on dip, the fractures can be divided into high-, moderate- and low-angle fractures, of which moderate-to high-angle fractures are dominant. 96% of all fractures.

The main controlling factor on fractures is lithology, and the development degree and stages of fracturing varies between lithologies. The dominant lithology sequence is monzonite > granodiorite > cataclasite > gneiss. The more advanced the rock is in the sequence, the more fracture prone it is and the higher the degree of fracture development. Based on this, a fracture development model was established. The northern part of the study area has good potential for fracture development and is a favorable exploration area.

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