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Architecture of buried reverse fault zone in the sedimentary basin: A case study from the Hong-Che Fault Zone of the Junggar Basin

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ABSTRACT

It is widely accepted that the faults can act as the conduits or the barrier for oil and gas migration. Years of studies suggested that the internal architecture of a fault zone is complicated and composed of distinct components with different physical features, which can highly influence the migration of oil and gas along the fault. The field observation is the most useful methods of observing the fault zone architecture, however, in the petroleum exploration, what should be concerned is the buried faults in the sedimentary basin. Meanwhile, most of the studies put more attention on the strike-slip or normal faults, but the architecture of the reverse faults attracts less attention. In order to solve these questions, the Hong-Che Fault Zone in the northwest margin of the Junggar Basin, Xinjiang Province, is chosen for an example. Combining with the seismic data, well logs and drill core data, we put forward a comprehensive method to recognize the internal architectures of buried faults. High-precision seismic data reflect that the fault zone shows up as a disturbed seismic reflection belt. Four types of well logs, which are sensitive to the fractures, and a comprehensive discriminated parameter, named fault zone index are used in identifying the fault zone architecture. Drill core provides a direct way to identify different components of the fault zone, the fault core is composed of breccia, gouge, and serpentinized or foliated fault rocks and the damage zone develops multiphase of fractures, which are usually cemented. Based on the recognition results, we found that there is an obvious positive relationship between the width of the fault zone and the displacement, and the power-law relationship also exists between the width of the fault core and damage zone. The width of the damage zone in the hanging wall is not apparently larger than that in the footwall in the reverse fault, showing different characteristics with the normal fault. This study provides a comprehensive method in identifying the architecture of buried faults in the sedimentary basin and would be helpful in evaluating the fault sealing behavior.

1. Introduction

Fault is the result of stress releasing during the tectonic movement and plays an important role in controlling the migration of crustal fluids. Years of studies have shown that faults can behave as conduits, barriers or combined conduit-barrier structures for hydrocarbon and hydrothermal fluids migration (Hooper, 1991; Cao et al., 2010; Matonti et al., 2012; Walker et al., 2013), and these effects are highly related to the internal architecture of fault zone (Chester and Logan, 1986; Brogi, 2008). The fault zone are generally composed of different components, which basically includes a fault core and damage zone, and perhaps, has a mixed zone or transition zone between the fault core and damage zone (Sibson, 1977; Chester and Logan, 1986; Caine et al., 1996; Heynekamp et al., 1999; Hesthammer et al., 2000; Faulkner et al., 2003, 2010; Kim et al., 2004; Brogi, 2008; Michie et al., 2014; Bauer et al., 2015). The composition of the fault core is diverse, including unconsolidated fault gouge, breccia, geochemically alternated rocks and so on (Sibson, 1977; Loveless et al., 2011). The damage zone usually maintains the characteristics of protolith and develops network of subsidiary structures (Chester and Logan, 1986; Antonellini and Aydin, 1994; Caine et al., 1996), and it is also an important part for fluid migration (Gibson, 1998; Faulkner et al., 2010; Sutherland et al., 2012). The development of the fault zone architecture are related to the lithology of strata and compaction of sediments and different models are proposed, such as fault model in brittle or crystalline rocks (Caine et al., 1996; Childs et al., 2009; Walker et al., 2013; Michie et al., 2014), fault model in poorly lithified rocks (Rawling et al., 2001; Rawling and Goodwin, 2003; Loveless et al., 2011) and so on.

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Different components of fault zone usually show different physical and geochemical features. Laboratory and numerical simulation demonstrated that the permeability of the damage zone, which is not filled by hydrothermal minerals, is roughly two-three orders of magnitude greater than the protolith and four to six orders of magnitude greater than the fault core in some cases (Antonellini and Aydin, 1994; Caine et al., 1996; Gibson, 1998). Developments of density of fractures in different components of the fault zone were also quite different. The fault core nearly has no fractures, but the fractures in the damage zone is highly developed and the maximum fractures density is adjacent to the fault core (Faulkner et al., 2010). In the large-scale normal fault, the damage zone of fault is usually asymmetrical and the hanging wall damage zone may be more than three times wider than the footwall damage zone (Berg and Skar, 2005; Brogi, 2008). Besides, some studies on the fault zone were conducted by using geochemical methods (Hammond and Evans, 2003; Caine and Minor, 2009; Cao et al., 2010; Molli et al., 2010) because fluid migration can change the geochemical environments and distribution of elements (Caine et al., 1996; Evans et al., 1997; Gudmundsson et al., 2001).

Overall, the architecture of a fault zone and detailed studies on the characteristics of each components highly attract the attention of researchers, and abundant of studies were carried on these aspects during the last decades (Indrevær et al., 2014). However, some questions are still unresolved. For example, most of the studies of fault zone architecture are conducted based on the filed observation (Faulkner et al., 2003; Wibberley et al., 2008; De et al., 2008; Childs et al., 2009; Faulkner et al., 2010) or numerical simulation (Aydin, 2000). Nevertheless, in the petroleum industry, people care more about how the fault zone develops and can be studied in the buried sedimentary basin, but seldom studies were carried on this topic. Besides, many studies discussed the internal architecture of strike-slip or normal faults and drawn some exciting results (Faulkner et al., 2010; Choi et al., 2016), but less attention was put to the reverse fault. Does the reverse fault similar to the normal and strike-slip fault in the characteristics of the fault zone? Therefore, in this paper, we try to put forward a way to discuss the fault zone architecture in the reverse fault of buried sedimentary basin, and the Hong-Che Fault Zone in the western margin of the Junggar Basin is chosen as an example.

The Junggar Basin is the second largest petroliferous basin in China. According to the results of third-round resource assessment, until to 2004, the total oil and gas resources reach to 106.8×10^8t, including 20.9×10^8t crude oil and 85.9×10^8t natural gas (He et al., 2004; Li, 2005). The western margin of the Junggar Basin is the most important oil and gas gathering area in this basin. Years of petroleum exploration testified that most of the oil and gas reservoirs are distributed along the faults in the plane and vertical profiles (He et al., 2004; Chen et al., 2006; Cao et al., 2010), reflecting the controlling effects of faults in the hydrocarbon accumulation. Among these faults, the Hong-Che Fault Zone is an important fault systems in the western margin of the Junggar Basin. Here, we combined with high-precise seismic, well logging and drill core data to analyze the architecture of the Hong-Che Fault Zone.

2. Geological setting

Junggar Basin is located in the junction area of Kazakhstan, Siberian and Tarim plates tectonically, and is an important tectonic unit of the famous Central Asian Orogenic Belt (CAOB) (Fig. 1a) (Sengor et al., 1993; Windley et al., 2007; Kröner et al., 2008). The western margin of the Junggar Basin is the transition region between the Zhayier- Hala'alate mountains and the basin (Fig. 1b). The mountains are mainly composed of Mesozoic and Paleozoic strata, and the basin is covered by Quaternary desert. Along the mountains, there are three large hydrocarbon-generating depressions, which are the Sikeshu, Changji and Mahu depressions (Fig. 1c). The formation and tectonic evolution of the Junggar Basin is still in debate, however, most of the studies inclined to admit that the basin was formed in the Late Carboniferous, causing by the collision and amalgamation of the CAOB (Carroll et al., 1990; Allen and Vincent, 1997; Wu et al., 2005; Chen et al., 2005). In the Mesozoic, the Junggar Basin stepped into an intracontinental depression developed stage due to the compression from the northwest and northeast (Sengör, 1990; Wu et al., 2005; Cao et al., 2010), making the formation and reactivation of the internal structure of the basin (Allen and Vincent, 1997; Wu et al., 2013; Yu et al., 2016). From the Neogene to the Quaternary, a rejuvenated foreland basin developed in the Junggar area, and this stage is affected by the collision between the India Ocean Plate and the Eurasian plate (Wu et al., 2005; Chen et al., 2005; Cao et al., 2005).

Influenced by ploycyclic tectonic movements, thousands of reverse faults were developed in this area, including the NE-trending Ke-Xia and SN-tending Hong-Che faults. Besides, three large strike-slip faults, which are the Bearlike, Tuoli and Darbut faults, were recognized in this area, and the evolution of these faults has an important impact on the evolution of the Junggar Basin (Allen et al., 1995; Allen and Vincent, 1997; Laurent et al., 2002). The strata of the Carboniferous to the Quaternary can be recognized in this area, and the total thickness of the strata is over 10 km. The stratigraphy and major lithology are summarized in Fig. 2. Besides, large amount of igneous rocks distribute in this area, including granitic intrusive rocks, tuff, ophiolite and so on (Yang et al., 2012; Gao et al., 2014).

3. Data and methods

3.1. Data source

In order to investigate the structural characteristics and architecture of the Hong-Che Fault Zone, about 19432 km^2 3D and 3000 km 2D seismic data was examined in this study. The seismic data have a vertical axis in milliseconds and have not been depth-converted. Calibration of seismic layers is based on the studies of the Xinjiang Oilfield Company. Fourteen well logging and drilling core data are also used to identify the architecture of the fault zone.

3.2. Methods in identifying the fault zone architecture of reverse faults

In the sedimentary basin, the fault zone architecture is hard to be identified because it cannot be observed directly, and the only direct proofs are the drill cores. Besides, the geophysical data also provide some information for exploring the buried area indirectly. Here we use the seismic, well logs and drilling core data to provide a comprehensive method for identifying the architecture of the fault zone.

3.2.1. Seismic interpretation

Interpretation of seismic data is an efficient way to identify fault zone in the buried strata. Generally, the faults can be recognized by the discontinuities on seismic profiles, showing as a break in a continuous reflector or a group of continuous reflectors (Grant and West, 1965; Badley, 1985; Bouvier et al., 1989; Groshong, 2006; Iacopini et al., 2016). As the description of the fault zone characteristics by Caine et al. (1996), the faults are accommodated extremely high deformation or even metamorphic. Inevitably, the seismic wave will be changed when it passes the fault zone developed area and some abnormal phenomenon should be reflected on the seismic data. The fault zone shows as two appearances in the seismic data (Fig. 3): (1) For the small scale faults, the internal architecture of the fault zone is not well developed. In this situation, faults only show the simple discontinuous of seismic reflectors (Fig. 3a). (2) For the large scale faults, the fault zone can spread over hundreds of meters (e.g. Faulkner et al., 2003), making the fault zone manifest as a belt of disturbed reflectors or strong reflectors in the seismic profiles (Fig. 3b and c).

3.2.2. Well logs identification

Well logs are another important data in the hydrocarbon