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Research paper

In-situ stress state in the Linxing region, eastern Ordos Basin, China: Implications for unconventional gas exploration and production

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ABSTRACT

The Carboniferous and Permian sedimentary rocks (mainly the Shanxi and Taiyuan formations) in the Linxing region, eastern Ordos Basin, China, host a significant volume of unconventional gas resources (coalbed methane, shale gas and tight sandstone gas). Currently, the in-situ stress state is poorly understood but knowledge of this is extremely important for a range of applications, such as gas exploration and production, fracture stimulation and wellbore stability. The maximum horizontal stress (S_{Hmax}), minimum horizontal stress (S_{hmin}) and vertical stress (S_v) magnitudes, and the S_{Hmax} orientation in the Linxing region were systematically analyzed for the first time in the present study, which can provide a reference for subsequent numerical simulation and hydraulic fracturing design. Based on borehole breakouts and drilling-induced tensile fractures interpreted from borehole imaging logs, the S_{Hmax} orientation rotates from ~NEE-SWW-trending in the southern part to ~ NWW-SEE-trending in the northern part of the Linxing region. Both conventional logs and extended leak-off tests were used for stress magnitude determination. The results revealed three types of in-situ stress fields ($S_v > S_{Hmax} > S_{hmin}$, $S_{Hmax} > S_v > S_{hmin}$ and $S_{Hmax} > S_v \approx S_{hmin}$), and a dominant strike-slip stress regime ($S_{Hmax} > S_v \geq S_{hmin}$) was found for the entire well section in the target Shanxi Formation and Taiyuan Formation in the Linxing region. In addition, differential stress increased with depth in the Linxing region, which indicates that wellbore instability might be a potentially significant problem when drilling wells that are vertical or ~ N-S-trending.

1. Introduction

In-situ stress refers to the internal stress within the Earth's crust, and is closely related to gravitational and tectonic stresses (Bell, 1996; Kang et al., 2010). Tectonic stress is relatively complicated and was greatly influenced by tectonic movements during historical geologic periods. In addition, tectonic stress is extremely irregular in spatial distribution and difficult to describe using precise analytical solutions. On the contrary, gravitational stress caused by the force of gravity on rock mass is relatively simple to determine (Kang et al., 2010; Zhao et al., 2016).

Commonly, the viability of unconventional gas production largely depends on hydraulic fractures. The ability of these fractures to transmit fluid is partially dependent on the in-situ stress conditions. Critically stressed fractures are widely regarded as being more likely to be effective fluid conduits than those that are not (Barton et al., 1995; Zoback, 2007). Furthermore, knowledge of in-situ stress states can provide a better understanding of gas exploration and development (Finkbeiner et al., 2001; Bell, 2006; Tingay et al., 2010; Li et al., 2014; Ju and Sun, 2016), wellbore stability (Zoback et al., 2003; Tingay et al., 2009), enhanced oil recovery techniques (e.g., hydraulic fracture stimulation and water flooding; Bell, 1996; Tingay et al., 2009), and reservoir management (Sibson, 1994; Binh et al., 2007; Liu et al., 2016).

In general, three types of in-situ stress regime are determined based on the relative magnitude of the maximum horizontal stress

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(S_{Hmax}), minimum horizontal stress (S_{hmin}), and vertical stress (S_v) (Anderson, 1951):

(i) normal faulting stress regime: $S_v > S_{Hmax} > S_{hmin}$;
(ii) strike-slip faulting stress regime: $S_{Hmax} > S_v > S_{hmin}$;
(iii) reverse faulting stress regime: $S_{Hmax} > S_{hmin} > S_v$.

Intraplate in-situ stress fields within the North China continental crust are regionally attributed to the stress transmission caused by plate margin collision (Li et al., 2012); whereas, at a local scale, structures can locally affect stress magnitude and orientation (Bell, 1996; Heidbach et al., 2007; Tingay et al., 2011; Brooke-Barnett et al., 2015; Williams et al., 2015). Accurate prediction of in-situ stress distributions plays an important role in estimating production potential as it can deeply affect the permeable fracture aperture and orientation. In addition, in-situ stresses can affect unconventional gas co-exploration and concurrent production in the Linxing region (Guo et al., 2012; Qin et al., 2016). Therefore, an accurate understanding of the in-situ stress state can effectively guide gas exploration and production in the Linxing region.

Our study's objective is to characterize the variations of in-situ stress magnitude and orientation within the Linxing region of the eastern Ordos Basin. Both conventional logs and extended leak-off tests have been used to investigate stress magnitude variations with depth. The in-situ stress orientation has been analyzed based on borehole breakouts and DIFs interpreted from imaging logs. More importantly, this is the first study to systematically discuss the in-situ stress state in the Linxing region, providing a reference for subsequent analysis (e.g., hydraulic fracturing design, wellbore stability, fault reactivation studies, etc.).

2. Geologic setting

The Ordos Basin, situated in the western part of the North China Craton (Zhao et al., 2005, Fig. 1), is a typical intracontinental basin with an area of more than 2.5×10^5 km^2. The Ordos Basin experienced a long and complex multicycle geological history ranging from the Middle Proterozoic to the Tertiary. During the Middle to Late Proterozoic, the earliest sediments were deposited over the basement rocks. Since the Late Carboniferous, the entire region subsided, entering a transitional period from marine to continental sedimentation. Starting from the Triassic, the basin entered into an intracontinental phase with the convergence and collision of the North and South China blocks and the collision of the Qiangtang Block with the Eurasian Plate. During the Cenozoic, tectonic forces changed from compressional to extensional stress (Darby and Ritts, 2002; Yang, 2002; He, 2003; Liu et al., 2006; Zhang et al., 2007). Present-day geomorphology indicates that the central part of the Ordos Basin is stable without many structures; whereas the margins of the basin have undergone multiple tectonic activities, resulting in structural complexity (Zhang et al., 2007; Li and Li, 2008; Ju et al., 2015, Fig. 2).

The Linxing region is an economically significant area located in the eastern Ordos Basin (Fig. 2). Paleozoic-Mesozoic layers with great depths are developed in the study area (Fig. 3). The stratigraphic strike is close to NE-SW and dips westward at 5–10°. A significant volume of unconventional gas (coalbed methane, shale gas and tight sandstone gas) has been found within this region (Guo et al., 2012). In the Linxing region, coal seams and dark mudstones in the Benxi, Taiyuan and Shanxi formations are important source rocks. The Taiyuan and Shanxi formations serve as the main unconventional gas reservoirs (Fig. 3). The Taiyuan

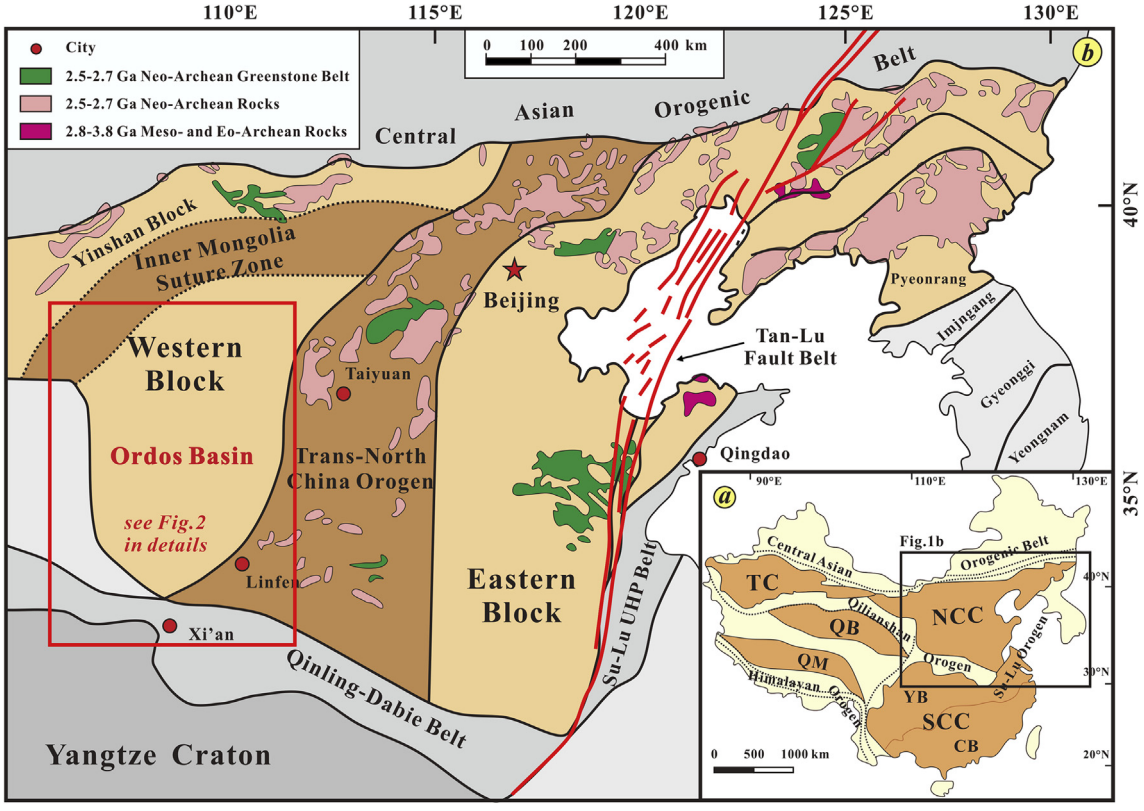

Fig. 1. Major cratonic blocks in China (a; after Santosh et al., 2012) and generalized tectonic map of the North China Craton (b; after Zhao et al., 2005). TC-Tarim Craton, NCC-North China Craton, SCC-South China Craton, QB-Qaidam Block, QM-Qiangtang Massif, YB-Yangtze Block, and CB-Cathaysia Block.