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In situ stress field in the FZ Block of Qinshui Basin,China: Implications for the permeability and coalbed methane production

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ABSTRACT

In situ stress affects reservoir permeability and stimulation, and thus coalbed methane (CBM) recovery. In this study, the in situ stress field measured from 238 CBM wells in the FZ Block of Qinshui Basin, China, was investigated. The vertical stress, horizontal maximum and minimum principal stress are 5.92–20.08 MPa, 8.03–41.75 MPa, and 5.38–21.24 MPa, respectively. The in situ stress magnitudes increase with burial depth of the coal seams. The FZ Block is dominated by reverse and strike-slip faulting stress regimes. Most of reverse fault stress regimes appear within burial depth less than 500 m, whereas normal and strike faulting stress regimes are deeper than 500 m. The relation between the coefficient of lateral stress and burial depth shows that shallow strata are characterized by horizontal stresses, whereas deep strata are generally hydrostatic pressures that approximately equal to the principal stresses. Low gas and high water production are associated with vertical hydraulic fractures, wherein the horizontal minimum principal stress is the minimum stress. High gas and low water production are associated with horizontal hydraulic fractures, wherein the vertical stress is the minimum stress. This results are attributed to the enhanced permeability of the coal seam and the communication with overlying or underlying aquifers because the minimum stress varies between vertical and horizontal minimum stress. The orientation of the horizontal maximum principal stress is ~NEE–NE and is locally distorted by faults, which can be used to optimize the drilling, completion, and stimulation of CBM wells in the study area.

1. Introduction

Studies of coal seams in America, China, Australia, and Canada have shown that the in situ stress conditions significantly affect the permeability, and gas and water production in coalbed methane (CBM) wells (Bell and Bachu, 2003; Enever et al., 1999; McKee et al., 1988; Meng et al., 2011; Xu et al., 2016; Ju et al., 2017). It has been long known that the spacing and aperture of natural and artificial fractures control the permeability of coal seams (Karacan and Okandan, 2000; Laubach et al., 1998). High stresses close fractures, resulting the decrease of coal permeability (Li et al., 2014; Meng et al., 2011). Furthermore, coal permeability depends on the in situ stress direction besides stress magnitude. The angle between the maximum principal stress and main fracture orientations also affects the permeability in coal seams, e.g., if the main fracture orientation coincides with that of the maximum principal stress and there is large difference between maximum and minimum principal stresses, then the permeability in coal seams will be high (Paul and Chatterjee, 2011).

The permeability of most coal seams in China is generally lower than 0.5 mD. Therefore, the productivity of CBM is low unless the application of hydraulic fracturing, horizontal wells, or other technologies (Lau et al., 2017; Lv et al., 2012; Su et al., 2005). The development degree and orientation of fractures strongly correlates with the in situ stress conditions. Vertical fractures develop parallel to the maximum stress direction and result in excess water production in CBM wells, whereas horizontal hydraulic fractures result in low water production (Colmenares and Zoback, 2007; Cornet and Valette, 1984). Therefore, it is significant to understand the in situ stress state due to their great effects on permeability and productivity of CBM wells.

In situ stresses depend on regional tectonics. The stresses owing to overlying strata are calculated based on burial depth and rock density, whereas stresses resulting from tectonic movements and magmatic activity vary spatially and temporally (Sandiford et al., 2004; Yang et al., 2014). Therefore, it is impossible to describe tectonic stresses using

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analytical solutions (Kang et al., 2010). The in situ stress field at any point within the strata is described by the overburden stress (σ_v) and the horizontal maximum and minimum stresses (σ_{Hmax} and σ_{hmin}). In situ stress measurements are used to investigate the present-day stress field because of its importance in tunnel design and underground engineering works, prediction of seismic activity and risk, and mining and oil and gas exploration (Bell and Bachu, 2003; Bosworth and Durocher, 2017; Jeanne et al., 2016; Meng et al., 2011; Puller et al., 2016; Rajabi et al., 2017; Yin et al., 2017; Zhao et al., 2016b; Zoback et al., 1985). Geophysical, geomechanical, and geological methods, such as hydraulic fracturing, stress relaxation, borehole breakout, acoustic emissions, and micromagnetics (Hubbert and Willis, 1957; Kang et al., 2010; Zoback et al., 2003), are used to investigate the in situ stresses (Kang et al., 2010; Ljunggren et al., 2003).

Based on the magnitudes of the principal stresses, the in situ stress field is divided into three regimes: the normal faulting stress regime ($\sigma_v > \sigma_{Hmax} > \sigma_{hmin}$), the reverse faulting stress regime ($\sigma_{Hmax} > \sigma_{hmin} > \sigma_v$), and the strike-slip faulting stress regime ($\sigma_{Hmax} > \sigma_v > \sigma_{hmin}$) (Anderson, 1951). Brown and Hoek (1978) first showed that the ratio of the average horizontal to the vertical stress depth lies within two hyperbolic curves, and it was also observed that the vertical changes of σ_{Hmax}/σ_v, $\sigma_{Hmax}/\sigma_{hmin}$, and σ_{hmin}/σ_v follow the same rule ($_v$; Jing et al., 2007; Shen et al., 2014; Zhao et al., 2016a). The in situ stress magnitudes vary regularly with burial depth. Previous studies have found that the minimum stress transformed from vertical stress in the shallow strata to horizontal minimum stress in the deep, or nearly equals to the horizontal minimum stress and the vertical stress in the deep (Flottman et al., 2013; Shen et al., 2014; Qin and Shen, 2016; Zhao et al., 2016a).

The southern Qinshui Basin has abundant coal seams and is the largest CBM development target in China. The coal seams are tight and hydraulic stimulation is required to increase the permeability of these reservoirs. The water and gas productions from CBM wells are highly variable. Additionally, lots of wells have extremely low and even none CBM production rate. Variability of the in situ stresses is deemed to be one of the most important reasons for the above questions. However, our understanding of the present-day in situ stress field and its effect on the production of CBM wells are very limited in this region. Accordingly, in this study, we evaluate the in situ stress field within the FZ CBM block, southeastern Qinshui Basin, using well logging, hydraulic stimulation, and well testing data from CBM exploration and development wells, and discuss the relation between in situ stress and permeability as well as water and gas production.

2. Geological background

The FZ CBM block is located in the southeastern Qinshui Basin, Shanxi Province, China (Fig. 1). The block is bounded by faults in the northwest and administrative boundaries in the east, south, and north. The block is a monocline that gently dips 2°–7° to NW and NNW. The Sitou normal fault is the northwestern boundary for the FZ block, trending ~ NE–ENE with a dip angle 60°–70° and a throw 60–580 m. Gas or water conductivity within this area is extremely low because of the highly cemented fault fracture zone (Zhao et al., 2016b). In the interior of the block, series of secondary high-angle normal faults are developed with S—N, NW–SE, NE–SW, and NNE–SSW trends. In addition, there are some secondary folds and small-scale reverse faults with NNE-SSW and S-N trends as well.

The coal-bearing strata in the study area are the Late Paleozoic Taiyuan and Shanxi Formations. The Taiyuan and Shanxi Formations comprise conglomerate, sandstone, siltstone, silty mudstone, mudstone, limestone, and coal seams (Fig. 1). The thick coal zones of the Taiyuan Formation were deposited in barrier bars, whereas those of the Shanxi formation formed in deltas (Shao et al., 2015). In the FZ Block, the target layer for CBM exploration and development is the No. 3 coal seam of the Shanxi Formation. The thickness of the No.3 coal seam ranges from 4.2 m to 9.7 m with an average of 6.2 m. Its burial depth varies between 239.7 m and 808.7 m with most of them shallower than 700 m. The vitrinite reflectance ($R_{o,max}$) varies between 3.32% and 4.25%, with the mean value of 3.58%. The CBM reservoir is a stable coal seam of high coal rank, high gas content, and low-pressure gradient, and low gas saturation. Gas content is 11.6–22.8 m^3/t (air-dried basis, ad) with an average value of 19.53 m^3/t. The gas is mainly methane (72.29%–99.21% with an average value of 96.43%), followed by carbon dioxide, nitrogen, and rarely heavy hydrocarbons. The Langmuir volume of the No.3 coal is 30.95–44.56 m^3/t (ad), with an average value of 38.95 m^3/t. The Langmuir pressure ranges from 1.85 MPa to 3.22 MPa with a mean value of 2.48 MPa. The well permeability is between 0.0011 mD and 0.9100 mD with an average of 0.2920 mD. The gradient of the reservoir pressure is 4.61–8.31 kPa/m with a mean value of 6.03 kPa/m. The No.3 coal seam is a typical low permeability reservoir, which restricts the development of the CBM; therefore, insights into the in situ stress in the FZ CBM block are particularly important.

3. Stress magnitude

3.1. Method

Due to the low permeability of the coal seams, hydraulic fracturing is typically adopted to stimulate the coal seams and increase the production in the FZ block of Qinshui Basin. During hydraulic fracturing, large volumes of water are pumped into the target coal seam that is isolated with inflatable packers to increase the fluid pressure until the coal seam starts to fracture (Fig. 2). The initiation of fracturing requires that the fluid pressure within the wellbore exceeds the minimum stress and tensile strength of the rock (Hillis et al., 1999). Consequently, the formation breakdown pressure can be known. After abruptly stopping the flow into the well, fracturing also stops. The pressure when fractures close is defined as the fracture closure pressure and equals to the horizontal minimum principal stress.

The horizontal maximum and minimum principal stresses are obtained from pressure–time data (Fig. 3) (Bredehoeft et al., 1976; Haimson and Fairhurst, 1969),

$$\sigma_{h\,min} = P_c \tag{1}$$

$$\sigma_{H\,max} = 3\sigma_{h\,min} - P_f + T - P_P \tag{2}$$

where σ_{hmin} is the horizontal minimum principal stress, σ_{Hmax} is the horizontal maximum principal stress, P_c the is fracture closure pressure, P_f is the formation breakdown pressure, T is the rock tensile strength, and P_p is the pore pressure of the rock.

The overburden stress (σ_v) is calculated by integrating the rock density from the surface to the target burial depth,

$$\sigma_V = \int \rho(z) g dz \approx \bar{\rho} g z \tag{3}$$

where ρ(z) is the rock density as a function of burial depth (z), g is the gravitational acceleration constant, and $\bar{\rho}$ is the average overburden density of the whole borehole based on the density logs.

3.2. Results

3.2.1. Principal stress

In this study, data were collected from the FZ CBM block of southeastern Qinshui Basin, including 238 well logging and hydraulic stimulation sites, 6 well testing sites, and 72 wells for the microseismic monitoring of hydraulic fractures.

The present-day in situ stresses were analyzed based on hydraulic fracturing data from 238 CBM wells. The results suggest that the No. 3 coal seam is mainly buried at 257.13–873.05 m, the horizontal maximum stress ranges from 8.03 MPa to 41.75 MPa with an average of 19.38 MPa (Table 1). The gradient of the horizontal maximum stress