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Research paper

Controls of hydrocarbon generation on the development of expulsion fractures in organic-rich shale: Based on the Paleogene Shahejie Formation in the Jiyang Depression, Bohai Bay Basin, East China

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ABSTRACT

The development of expulsion fractures in organic-rich shale is closely related to hydrocarbon generation and expulsion from kerogen. Organic-rich shales from the upper part of the fourth member and the lower part of the third member of the Paleogene Shahejie Formation in the Jiyang Depression, Bohai Bay Basin, East China, are used as an example. Based on thin sections, SEM and thermal simulation experiments, the characteristics of hydrocarbon generation and the conditions supporting the development of expulsion fractures were explored. The key factors influencing these fractures include the presence of kerogens, their distribution along laminae and around particle boundaries, their exposure to heat and the build-up in pressure due to confinement by low permeability. The development of excess pore fluid pressures and intrinsic low rock fracture strength are the main influencing factors. Pressurization by rapid generation of hydrocarbon provides impetus for fracture initiation and cause bitumen to migrate quickly. The shale laminae results in distinctly lower fracture strength laminae-parallel than laminae-normal and this directs the formation of new fractures in the direction of weakness. When pore fluid pressure increases, maximum and minimum principal effective stresses decrease by different proportions with a larger reduction in the maximum principal effective stress. This increases the deviatoric stress and reduces the mean stress, thus driving the rock towards failure. Moreover, the tabular shape of the kerogen aids the generation of hydrocarbon and the initiation of expulsion fractures from the tip and edge. The resulting fractures extend along the laminae when the tensile strength is lower in the vertical direction than in the horizontal direction. Particle contact boundaries are weak and allow fractures to expand around particles and to curve as the stress/strength regime changes. When pore fluid pressure fields at different fracture tips overlap, fractures will propagate and interconnect, forming a network. This paper could provide us more detailed understanding of the forming processes of expulsion fractures and better comprehension about hydrocarbon expulsion (primary migration) in source rocks.

1. Introduction

Shale oil is an important unconventional hydrocarbon resource. The successful exploitation of shale oil in the Marcellus shale in the United States (Kargbo et al., 2010) has triggered research into understanding the formation of such deposits - as the key to identifying sweet spots for their recovery. Fractures are the main

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pathways for the primary migration of hydrocarbon (Fan et al., 2010; Jin and Johnson, 2008; Katz, 2012; Katz et al., 2017; Lash and Engelder, 2005, 2009; Ozkaya, 1984). Gale et al. (2014) provides a systematic summary of the types of fractures in shale, which include fractures at a high angle to bedding, bed-parallel fractures, early compacted fractures, and fractures associated with concretions. Laminae-parallel fractures that commonly develop in organic-rich shale - identified as expulsion fractures in this article - are intrinsically related to hydrocarbon generation from kerogen and its subsequent expulsion (Ding et al., 2012, 2013; Fan et al., 2010; Lash and Engelder, 2005, 2009; Ozkaya, 1988; Rodrigues et al., 2009; Vernik, 1994). This process was observed in thermal simulation experiments (Figueroa Pilz et al., 2017; Korost et al., 2012; Panahi et al., 2013). Korost et al. (2012) discussed the reaction of matter of high organic content with a low maturation grade clayey carbonate rock sample that is heated in a nitrogen atmosphere. Alteration in pore space structures is monitored in this way, which is very helpful for the successful prediction of nontraditional reservoir zones. Panahi et al. (2013) and Figueroa Pilz et al. (2017) discussed the nucleation and growth of microcracks that were imaged at the scale of the experiment. X-ray computed tomography was performed using synchrotron beam lines, making it possible to acquire images at resolutions of a few microns with short scanning times. Al Duhailan et al. (2013, 2016), Al Duhailan and Sonnenberg (2014) studiedy the characteristics and genesis of expulsion fractures in detail. On the basis of this previous research, we use organic-rich shale from the Paleogene Shahejie Formation in the Jiyang Depression, Bohai Bay Basin, East China, as a type-example to explore the processes involved in the evolution of expulsion fractures. We conducted thermal simulation experiments and observed the characteristics of expulsion fractures by SEM. Then, the discharge rate of fluid and expansion rate of sample were calculated, and the controlling factors and formation mechanisms were analyzed. Finally, we summarized the key processes involved in the development of expulsion fractures.

2. Overview of the study area

The Jiyang Depression with abundant lacustrine shale oil resources is a potential area for shale oil, and some oil wells have begun production. The Jiyang Depression is a first-order tectonic unit of the Bohai Bay Basin, East China, which is bounded to the west by the Tan-Lu Fault, to the south by the Chengning Uplift and to the north by the Luxi Uplift. The depression has a maximum length of 240 km from east to west, a maximum width of 130 km from south to north and a total area of 26000 km^2. It is a Mesozoic-Cenozoic fault-depressed basin that developed contemporaneously with the North China Craton. The Jiyang Depression features a tectonic pattern with salients and sags. There are four negative secondary tectonic units, namely, the Dongying, Huimin, Zhanhua and Chezhen Sags. A series of positive secondary tectonic units include Gudao, Yihezhuang, Chenjiazhuang, Wudi, Binxian and Kendong-Qingtuozi Salients. The Jiyang Depression has undergone three stages of tectonic evolution: a Mesozoic fault-depression stage, a Paleogene fault-depression stage and a Neogene depression stage. More importantly for this study, several sets of deep lake, organic-rich shales accumulated duringin the Paleogene fault-depression stage. The upper part of the fourth member and the lower part of the third member of the Shahejie Formation are are thick and massive, with plenty of retarded oil (Katz et al., 2017). These are the main source rocks and major strata for shale oil exploration in East China. The organic-rich shale samples were collected from the Dongying Sag (FY 1 well, LY 1 well, NY 1 well) and the Zhanhua Sag (L69 well), as shown in Fig. 1.

3. Characteristics of expulsion fractures

Expulsion fractures are widely developed in the organic-rich shale of the upper part of the fourth member and the lower part of the third member of the Shahejie Formation in the Jiyang Depression. The fractures are closely related to kerogen genesis, and cracks develop through the middle, edge, or tip of kerogen molecules (Fig. 2a–c). Some fractures are connected with collophanite and microfossils (Dorozhkin, 2009) related to the biogenic origin (Fig. 2d–f). The crack width is from several micrometers to dozens of micrometers, and the length is from several micrometers to several centimeters. The wall of the fractures is uneven and bypasses particles, and most of the fractures are filled with bitumen (Fig. 2g–h, l, n). Fractures generated from two kerogens become closer and form a line or a rhomboic ring (Fig. 2i–j). However, fractures generated from several kerogens connect to form lines or arrange en echelon (Fig. 2k–l) and have extension or tension-shear characteristics. Most fractures extend horizontally and parallel to the direction of laminae (Fig. 2m–o), but some become curved at the end and turn towards one other (Fig. 2n). Some fractures extending horizontally are connected with each other through longitudinal fractures (Fig. 2o). If expulsion fractures develop abundantly in shale, a fracture network with a layered framework could be formed by end-to-end connections, turning connections and vertical connections (Fig. 2p).

4. Thermal simulation experiments on organic-rich shale

4.1. Samples and experimental facilities

Experimental samples were collected from the lower part of the third member of the Shahejie Formation encountered in the L69 well in the Zhanhua Sag. The lithology is grayish-brown oil shale with type I kerogen and an index of hydrocarbon generation, which belongs to high-quality source rock category with low-maturity organic matter (Table 1).

The thermal experiment was carried out by the School of Geosciences, China University of Petroleum (East China). The experimental facilities include an autoclave, a temperature control system and a pressure control system. In particular, the autoclave is made of hastelloy alloy with a maximum volume of 1000 ml, maximum tolerable temperature of 350 °C and maximum tolerable pressure of 50 MPa. The temperature control system is composed of a thermocouple, a temperature sensor and an AI-518P artificial intelligent temperature controller, which can control the heating process precisely. The pressure control system is composed of pressure sensor and GBS-STA100 gas-supercharging system.

4.2. Experimental scheme

Before the experiment, the fresh shale sample was cut perpendicular to lamina into 4 groups of regular lumpy samples; each group contained 6 experimental samples. Then, the mass and height of each sample were measured using a balance and a spiral micrometer. The thermal simulation experiment adopted the method of adding distilled water (Kobchenko et al., 2011; Lewan, 1997; Lewan and Roy, 2011), in the amount of 200 mL. In the experiment, we set four groups of different experimental temperatures and pressures. The initial temperature was 25 °C with experimental temperatures of 150 °C, 200 °C, 250 °C and 300 °C, and corresponding pressures of 15 MPa, 20 MPa, 25 MPa and 30 Mpa. These temperature and pressure conditions correspond to the formation pressure at depths of 1500 m, 2000 m, 2500 m and 3000 m underground, respectively. During the heating process,the temperature was set to increase at a constant rate and then remain