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Micro-fracture characteristics of tight sandstone reservoirs and its evaluation by capillary pressure curves: A case study of Permian sandstones in Ordos Basin, China

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A B S T R A C T

As a key factor during the development of tight sandstone reservoirs, the property of fractures and micro-fractures has a significant effect on the permeability. However, it is very hard to describe the property by conventional well logs. Using the core and microscopic thin section of a tight sandstone reservoir in the Permian of Upper Palaeozoic in Ordos Basin, we analyse the distribution of the micro-fractures in the cores and the effects of micro-fractures on porosity, permeability, pore-structure and microscopic heterogeneity. The results show that micro-fractures effectively improve the connectivity of the tight sandstone reservior, which also results in the strong reservoir micro-heterogeneity and complex pore structures. We find that relative large permeability appears in the core samples with micro-factures and the contribution curves of permeability of these samples in mercury injection test also exhibit apparent an abnormality. Based on the analysis, we proposed a method to establish a quantitative recognition criterion of micro-fractures in tight sandstone reservoirs by using a concentration function which reflects the spatial distribution of element fields to describe the contribution curve of permeability quantitatively.

1. Introduction

With the advancement of exploration techniques and petroleum engineering, tight sandstone gas has been the focus of the growth of oil and gas reserves in the world (Zou et al., 2012). Tight sandstone gas reserviors in China have great potentialities, and the proven reserves of natural gas of tight sandstone gas field is $30{,}109.2 \times 10^8$ m^3 by the end of 2010, accounting for 39.2% of the total proven reserves of natural gas (Li et al., 2013). However, these reserviors are classified as the ones with low abundance, fast production decline and high cost of economic development. According to the classification of fractures and its functions in oilfield development, the fracture system is defined as the fractures with aperture more than 50 μm. The matrix system consists of the matrix and the micro-fractures with aperture less than 50 μm. The results of the rock physical-mechanical property tests (Lorenz et al., 1991; Finkbeiner et al., 1997; Ji et al., 1998; Bai et al., 2000; Dorothea et al., 2012) show that rock experiences an extended micro-fractures developing period with the increase of confining pressure until it cracks, and the existence of these micro-fractures has a bearing on the relative large permeability zones. The micro-fractures of tight sandstone reservoirs can provide effective spaces and seepage channels, which affect the seepage system (the way of fluid flowing in rock) and enlarge gas drainage radius of producing wells (Peter and John, 1999). Evaluation and prediction of micro-fractures can help us understand the geology during the water injection development, optimization design for hydraulic fracturing and well pattern arrangement (John et al., 2002; Underwood et al., 2003; Tuckwell et al., 2003). Therefore, it is essential to understand the features and evaluate the distributions of micro-fractures for the integration study in tight sandstone reservoirs.

There are many geological analsis methods have been used for the fractures analysis of drilling outcrop, drilling core and

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microsection observation, such as fractal geometry, tracing algorithm, and Monte Carlo method (Bates et al., 1999; Dong et al., 2013), which are easy to be influenced by human factors, and the calculation efficiency mainly depends on the experience and knowledge of researchers.

At the same time, the geophysical methods for the fracture evulation mainly include imaging logs such as FMS, FMI, diplog (Barton et al., 2009; Lacazette, 2009), analysis methods based on conventional loggs such as artificial neural network, rescaled analysis and probability density function (Li et al., 2006; Hu, 2000; Sun et al., 2014), seismic fractures evluation such as VSP, coherence cube analysis, P-wave anisotropy (Yang et al., 2006; Zhang et al., 2011, 2013). These methods are very difficult for getting a high applicability and accuracy on the micro-fracture predicting due to the limitaions, such as high cost of imaging logging, poor resolution of conventional logs and seismic data (Narr and Lerche, 1984; Velde and Duboes, 1990; Narr, 1991; Maghsood et al., 2001), and mathematical model's high requirements of sample data.

The use of numerical simulation methods such as constructional curvature method (Murray, 1968), finite element modelling (Juanes et al., 2002), loading simulation and random simulation (Wu and Pollard, 1995; Wong, 2003)is also limited because of the influence of rock heterogeneity and earlier fractures (Renshaw and Pollard, 1994; Malama and Kulatilake, 1997; Turcotte et al., 2003).

It is very critical to find a method to guarantee the reliability of micro-fracture research in the micro-fracture evaluations.

As one of major tight sandstone reservoirs in China, Ordos Basin is choosen as our study area. The distribution of fractures on the developed fields in this basin have been studied thoroughly in the past few years (Shao et al., 2006; Zeng et al., 2007; Niu et al., 2014; Ren et al., 2014). However, there are very few works on the effects of the micro-fractures on the permeability of the reservoirs. The reservoir quality (mainly including permeability and porosity) (e.g.Sun and Esteban, 1994) in the Permian strata is poor due to factors such as strong diagenesis, narrow throat and fine grain size. However, we still find the relative large permeability in some cores with micro-factures as shown in Table 1. It is obvious that some micro-fractures are invisible by eyes, which can be discerned by electronic microscope. Based on this abnormal phenomenon, we do some research to find a method evaluate the pore diameter distribution by using the concentration distribution function which reflects space distribution of element fields, and then to establish criteria of micro-fractures evaluation. We use data from the 115 cores in a tight sandstone reservoir of the Permian strata in Tianhuan Depressions, Ordos Basin. The data includes the thin section analysis and the capillary pressure curves.

2. Properties of micro-fractures

2.1. Genetic classification

From thin section observations, the generation of the micro-fractures in this area mainly results from tectonic stress field during the process of diagenesis, such as tectonic lateral extrusion and the extrusion between mineral grains. In addition, some other factors also contribute to the generation of the micro-fractures, including water loss, cementation, metasomatism and recrystallization after the compaction of sedimentary which induces the rocks swell-shrink and the mineral recombine and transform. The generation and distribution of micro-fractures are controlled by sedimentary microfacies and diagenesis. The micro-fractures play an important role in connecting intergranular pores of matrix and intragranular dissolved pores of reservoirs, which make the connectivity of pores better and are helpful for the reservoir development (Nygard et al., 2004). There are mainly two types of micro-fractures including intragranular fractures and particle-edge fractures. The intragranular fractures distribute inside the mineral particles, which are the cleavage fracture of feldspar and quartz (as shown in Fig. 1A–C) and also some intergranular fractures by dissolution of authigenic cement (Fig. 1D). The fractures in the edge of the particle are usually accompanied with intragranular fractures, and they distribute along the edge of the mineral grains. The apertures are usually less than 10 μm. The micro-fractures can be divided into effective and invalid ones by the effectiveness of the seepage. The effective micro-fractures are filled by crude oil and play a primary role in the oil and gas seepage. The invalid micro-fractures are completely filled by silicon or calcite (as shown in Fig. 1E–F), which are closed under the condition of subsurface and cannot contribute to oil and gas seepage. The invalid micro-fractures can turn into effective micro-fractures during the artificial fracturing and water injection.

2.2. Porosity and permeability

It can be seen from the microscopic images that pores are mainly connected by micro-fractures in cores containing micro-fractures, while others are mainly connected by throats. The

Table 1
Core physics analysis report in Permian of Well Zh1 (portion).

Point	Depth (m)	Density (g/cm^3)	Porosity (%)	Horizontal permeability (mD)	Notes
1	4091.14–4091.19	2.73	2.14	0.041	
2	4091.43–4091.48	2.64	4.00	0.053	
3	4091.73–4091.78	2.64	3.46	0.034	
4	4092.1–4092.15	2.63	3.60	0.050	
5	4092.68–4092.73	2.67	3.76	0.645	
6	4093.26–4093.31	2.65	2.67	0.028	
7	4093.64–4093.69	2.64	3.60	0.084	
8	4094.04–4094.09	2.69	2.97	0.522	
9	4108.3–4108.35	2.66	3.20	2.658	micro-fractures
10	4108.7–4108.75	2.64	3.49	7.527	micro-fractures
11	4109.4–4109.45	2.65	3.24	0.897	
12	4113.8–4113.85	2.67	1.41	1.005	micro-fractures
13	4114.2–4114.25	2.69	1.63	0.115	
14	4114.33–4114.38	2.65	1.94	0.007	
15	4114.8–4114.85	2.68	1.33	0.006	
16	4398.5–4398.55	2.67	2.59	0.177	
17	4398.65–4398.7	2.71	1.95	0.005	
18	4398.8–4398.85	2.71	1.29	0.004	
19	4398.95–4399	2.68	1.76	0.008	