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Pore structure characterization of the Cretaceous Quantou Formation: Results from microresistivity imaging logs in the second scientific drilling borehole (SK-2 east borehole) Songliao basin, northeast China

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ABSTRACT

As the main borehole of the China Cretaceous Continental Scientific Drilling Project, the SK-2 east borehole was drilled to obtain in-situ multi-information of geophysics and investigate the paleoclimatic and environmental changes. A study based on continuous geophysical logs facilitates achievement of scientific goals, such as the establishment of the typical petrophysical properties for Songliao basin and other similar basins, analysis of sedimentary environment, resource exploration, geothermal system research, and long-term observation and fluid experiments on deep strata. Both conventional logs and microresistivity imaging logs of the Cretaceous Quantou formation have been acquired. Porosity spectra from microresistivity imaging logs are obtained by using the Archie equation. Based on analysis of porosity spectrum features, we divide the porosity spectra of K_1q in the SK-2 east borehole into twelve configurations according to the location and combination of peaks to characterize different pore structure. The porosity spectra of K_1q in the SK-2 east borehole are dominated by unimodal distribution indicating more primary porosity. Five layers dominated by unimodal distribution are considered for performing long-term observations and fluid experiments on aspects of depth, thickness or petrophysical properties. By comparing spectrum features, porosity spectrum can be used to reflect the heterogeneity and analyze the pore structure of clastic strata. Layered strata will produce complicated porosity spectra as secondary porosity will. It is better to combine porosity spectra with microresistivity image to study secondary porosity. The decline of the porosity heterogeneity in the SK-2 east borehole is demonstrated by two parameters, φ_{vk} and W from porosity spectra, which can indicate the sedimentary environment. Moreover, porosity spectra in clastic strata is favorable for determining lithology and sedimentary environment when combined with microresistivity images.

1. Introduction

The SK-2 east borehole, as the second stage of the China Cretaceous Continental Scientific Drilling Project, is located in the Songliao basin, northeastern China. The Cretaceous strata in Songliao basin is one of the most complete terrestrial sedimentary basins in the world (Wu et al., 2008a). This basin is the largest Cretaceous oil-and gas-bearing basin in the paleo-Asian continent (Huang et al., 2011) and is the exploration and development block containing the Daqing oil field. Therefore, research on the sedimentary strata plays a significant role in obtaining a complete Cretaceous terrestrial sedimentary record and achieving new breakthrough for resource exploration. Pore structure characteristics, one of the important parts of the study of sedimentary strata, are a microscopic reflection of sedimentation, diagenesis, tectonism and late fluid transformation (Lai et al., 2013). The results are favorable for determining typical petrophysical properties to provide a reference of petrophysical properties for subsequent geophysical exploration in Songliao basin and other similar basins, to analyze sedimentary environments, hydrocarbon resources and geothermal systems, and to perform long-term observations and fluid experiments on deep strata.

The size, distribution and connectivity of pores control fluid storage, flow and transport in strata (Anovitz and Cole, 2015). There are various

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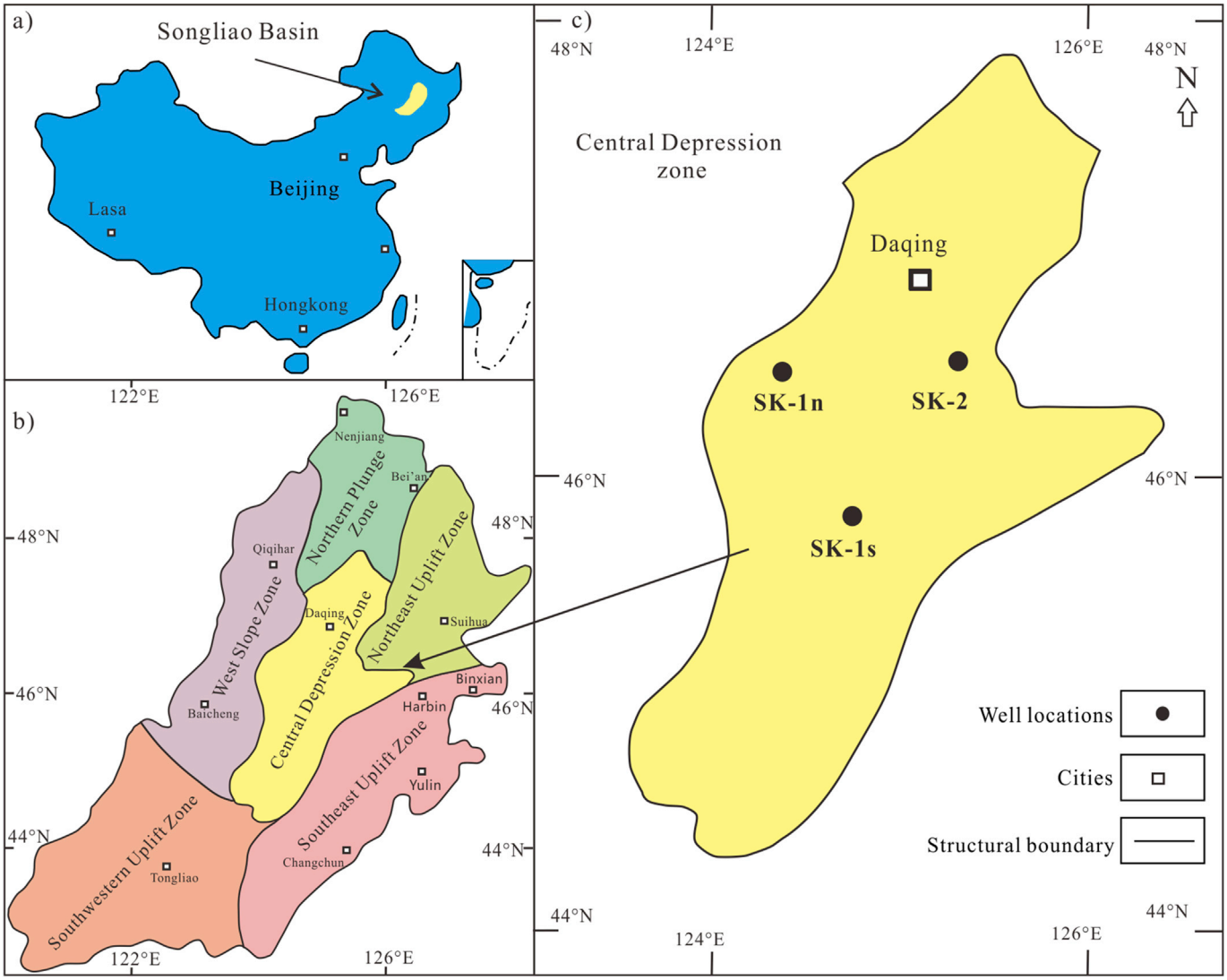

Fig. 1. Map showing the location of the SK-2 east borehole and tectonic units of Songliao basin from Huang et al. (2011) (a) Songliao basin is located in northeast China and crosses Heilongjiang, Jinlin and Liaoning provinces. (b) Distribution of six first-order tectonic units is shown, with the central depression zone encircled by other five zones. (c) The SK-1s and SK-1n boreholes from the first stage of the China Cretaceous Continental Scientific Drilling Project and have been already finished.

methods to obtain these characteristics of pores, such as core experiments or geophysical logging. Core experiments include image analysis, point count analysis, gas expansion, gas adsorption, mercury intrusion porosimetry, nuclear magnetic imaging and neutron scattering that can provide the size, geometry, connection and cementation of pore (Schmitt et al., 2013; Haines et al., 2015; Klochkov and Tagirov, 2015; McPhee et al., 2015). However, core data is not always available from wells. To replace core experiments, geophysical logging including nuclear magnetic resonance logs and imaging logs make possible the characterization of pore structure mainly from the size, distribution and development of primary and secondary porosity (Hurley et al., 1998; Cunningham et al., 2004; Ghafoori et al., 2009; Li et al., 2010; Mao et al., 2010; Xiao et al., 2016). This method not only solves the problem of missing cores but also provides the serial pore structures of strata. The porosity spectrum from microresistivity imaging logs can be used to characterize pore structure of strata such as the volume, distribution and development of porosity. Currently, porosity spectra are used mainly to investigate the development of secondary porosity and heterogeneity in carbonate formation (Newberry et al., 1996; Tyagi and Bhaduri, 2002; Meng et al., 2006; Wu et al., 2008b; Maliva et al., 2009; Zhang et al., 2011; Liu et al., 2014; Fu et al., 2016). However, the reasons why porosity spectra present various configurations are seldom discussed. In clastic strata, both the reason and the purpose are also still under investigation.

The results of formation evaluation from the SK-2 east borehole suggests that sandstones are well developed. Using geophysical logs facilitates finding the pore structure characteristics of well-developed sandstone. In this paper, we take advantage of the continuous geophysical information provided by the SK-2 east borehole to characterize pore structure by converting microresistivity imaging log section (1672 m–2512 m) into porosity spectra. Based on analyzing porosity spectrum features, we discuss the feasibility of applications to clastic strata, influential factors and the function of the porosity spectrum.

2. Geological setting

The Songliao basin is a large-scale, NNE-directed and rhombic sedimentary basin, covering approximately 260,000 km^2 (Wang et al., 2013). Generally, the Songliao basin experienced mantle upwelling, rift, postrift thermal subsidence and structural inversion tectonic stages (Feng et al., 2010). The Songliao basin is divided into six tectonic units due to tectonic evolution: central depression zone, western slope zone, northern plunge zone, northeastern uplift zone, southwestern uplift zone and southeastern uplift zone (Gao et al., 1994) (Fig. 1).

The basement of Songliao basin is composed of metamorphic rocks,