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Research paper

Paleoenvironmental conditions of organic-rich Upper Permian Dalong Formation shale in the Sichuan Basin, southwestern China

Zhifu Wei[a], Yongli Wang[a,b,**], Gen Wang[a,*], Zepeng Sun[a,c], Ting Zhang[a,c], Liang Xu[a,c], Xueyun Ma[a,c], Wei He[a,c]

[a] Key Laboratory of Petroleum Resources, Gansu Province/Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Lanzhou 730000, PR China
[b] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, PR China
[c] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Organic geochemical and trace element analysis of a suite of 33 samples collected from the Shangsi section of the Upper Permian Dalong Formation, located near Guangyuan in the northwestern Sichuan Basin, have been used to better understand the marine depositional environment of its shale lithofacies. A 15 m-thick black shale interval near the middle of the formation is enriched in total organic carbon (TOC = 1.1–14.4%, mean = 6.4%). The *n*-alkane, terpane and sterane biomarker distributions of the shale suggest that its organic matter is of predominantly marine algal origin. Pr/Ph, Pr/*n*-C_{17}, Ph/*n*-C_{18} and gammacerane/C_{30} hopane ratios demonstrate that reducing conditions prevailed during its deposition. This interpretation is supported by the redox-sensitive abundance of Mo and the trace element redox ratios Ni/Co, V/Cr, U/Th and V/(V + Ni), all of which indicate deposition in a euxinic/anoxic setting. The Mo-TOC relationship in the Dalong shales plots mid-way between those of sediments in the present-day Saanich Inlet and Cariaco Basin, suggesting a moderately restricted depocentre. However, the $\delta^{13}C_{org}$ values of these shales reveal that their organic matter is isotopically much lighter than that found in modern euxinic sediments, implying extremely anoxic bottom waters and a slow-down of oceanic circulation during the Late Permian.

1. Introduction

Shale gas is now one of the most important fossil fuel resources due to the global demand for energy (Clarkson et al., 2013). In recent years the upper Yangtze Region of southern China (Fig. 1a) has become the nation's leading area for shale gas exploration and development (Tian et al., 2013; Dai et al., 2014; Zou et al., 2015). Most of this exploration is being conducted in the southern part of the country where thick marine shales are widely distributed. Four shale-bearing stratigraphic intervals are regarded as prime targets: the Upper Sinian Doushantuo Formation; the Lower Cambrian Nuititang Formation and Qiongzhusi Formation; the Upper Ordovician Wufeng Formation and Lower Silurian Longmaxi Formation; and the Upper Permian Dalong Formation and Longtan Formation (Xia et al., 2010; Zou et al., 2010; Wang et al., 2014) (Fig. 2). Discovery of the Jiaoshiba shale gas field within the Longmaxi Formation on the southeastern margin of the Sichuan Basin (Fig. 1a) marks a significant advance and has had a guiding influence on shale gas exploration throughout China (Guo and Zhang, 2014). Previous paleoenvironmental studies focused on the Lower Cambrian and Lower Silurian black shales in the Yangtze Block, using trace element geochemical, carbon and sulfur isotope chemostratigraphic and biostratigraphic approaches (e.g., Shields and Stille, 2001; Steiner et al., 2001; Chen et al., 2003, 2009; Pan et al., 2004; Guo et al., 2007a, b; 2013; Wang et al., 2012, 2015; Dai et al., 2014; Han et al., 2015; Zhou et al., 2015; Wu et al., 2016; Li et al., 2017). Besides, the total organic carbon (TOC) content of black shale in the Dalong Formation is very high (mean 5.9%) in its trough facies where it attains thicknesses of 10–30 m and the source rocks are dominated by kerogens which mainly belong to type II_1, with a minor contribution from type II_2, resulting in high-quality hydrocarbon source rocks, which is characterized by the advantages of gas formation (Xia et al., 2010). Thus, it is necessary to rebuilt depositional environment and revaluate hydrocarbon generation potential of Dalong Formation in Sichuan Basin.

Major and trace element geochemistry has been used to elucidate the paleoenvironments of shale successions (Algeo and Maynard, 2004; Algeo and Lyons, 2006; Tribovillard et al., 2006; Calvert and Pedersen,

* Corresponding author.
** Corresponding author. Lanzhou Institute of Geology and Geophysics, CAS, 382 Donggang West Street, Chengguan District, Lanzhou, GS 730000, PR China.
E-mail addresses: wyll6800@lzb.ac.cn (Y. Wang), wanggen12@mails.ucas.ac.cn (G. Wang).

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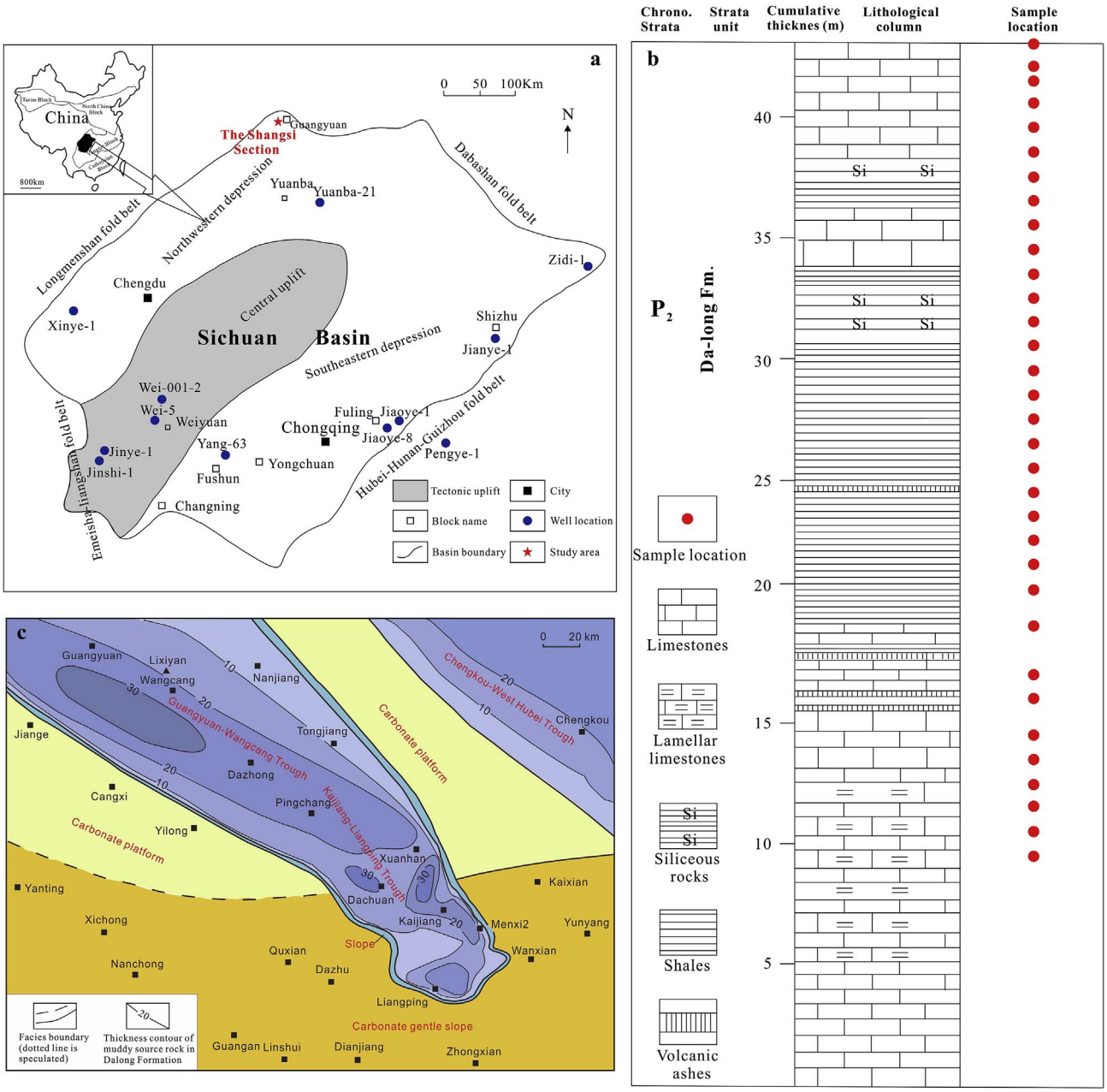

Fig. 1. Geographical map of Sichuan Basin and sampling location (a, modified after Jiang et al., 2017), Lithological column of the Da-long Formation in the Shangsi Section (b) and thickness distribution (c, modified after Xia et al., 2010) of black shales in the Late Permian Dalong Formation of the Sichuan Basin, Southwestern China.

2007). Several trace elements, including Mo, Re, U, and V, have been considered as indicators of redox conditions in paleo-depositional environments (Pratt and Davis, 1992; Crusius et al., 1996; Dean et al., 1997; Rimmer et al., 2004). Some trace element abundance ratios, such as V/(V + Ni), V/Cr, Ni/Co, U/Th (Jones and Manning, 1994; Hatch and Leventhal, 1992), have been used for restoring the redox conditions of the depositional environment. Redox-sensitive trace elements (e.g., Mo, U and V) tend to be highly enriched under reducing conditions, making elemental concentrations and ratios there of useful proxies for paleo-redox reconstruction (Tribovillard et al., 2006, 2012; Algeo and Tribovillard, 2009; Algeo and Rowe, 2012). Biogenic elements such as phosphorus and barium show significant correlation with productivity variations in different ocean basins, and thus have been used to evaluate changes in primary productivity (Dymond et al., 1992; Tribovillard et al., 2006; Calvert and Pedersen, 2007). In addition, recent studies have shown that patterns of Mo-U co-variation and Mo/TOC values can provide information concerning a wide range of paleoenvironmental parameters, including redox condition and water-mass restriction (Algeo and Lyons, 2006; Rowe et al., 2008; Algeo and Tribovillard, 2009; Tribovillard et al., 2012). Recently, substantial advances have been made in determining the depositional conditions using these redox-sensitive trace elements and carbon isotopic proxies, as well as their relationship with the total organic carbon accumulation.

In this study we present organic geochemical (TOC, $\delta^{13}C_{org}$, biomarker) and trace element data on shales from the Shangsi section of the Dalong Formation, located near Guangyuan in the northwest Sichuan Basin. These results will assist in the further evaluation of the formation's original-gas-in-place (OGIP) in this region.

2. Geological background

The Sichuan Basin is one of the most important onshore gas-producing areas in China (Fig. 1a). A summary of its regionally extensive organic-rich shale units (TOC > 2%) can be found in Dong et al. (2015).