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Research paper

Organic material accumulation of Carnian mudstones in the North Qiangtang Depression, eastern Tethys: Controlled by the paleoclimate, paleoenvironment, and provenance

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A B S T R A C T

The Late Triassic mudstones are considered to be the most significant hydrocarbon source rocks (TOC: 0.54%–3.29%) in the North Qiangtang Depression, eastern Tethys. Here, we present geochemical data from the Woruo Mountain Carnian mudstones, in order to investigate their paleoclimate, paleoenvironment, and provenance and to analyze the mechanism of organic material accumulation. The paleoclimate condition was warm and humid during the Carnian mudstones deposition, as indicated by moderate chemical index of alteration (CIA; 73–76), which may be connected with the Late Triassic Carnian stage global climate event in the Tethys. The low U/Th (0.17–0.25) and C_{org}/P_{tot} (7–33) ratio values and moderate manganese contents, reflect the oxidizing conditions during the Carnian mudstones deposition. The relatively high primary productivity in this study is supported by the relatively high P concentrations. The Al_2O_3–(CaO^* + Na_2O)–K_2O ternary plot and Th/Sc–Zr/Sc crossplot reflect that the source areas have undergone a medium chemical weathering with weak sedimentary recycling. The TiO_2–Zr, Co/Th–La/Sc, La/Th–Hf, and La/Yb–$\sum$REE bivariate diagrams indicate that the provenance of Carnian mudstones was primarily from felsic igneous rocks. The collision setting has been identified based on the multi-major elements discriminate plots in the present study. The Riwanchaka and Mayigangri masses to the southwest and south of the study area consisting mainly of Middle-Triassic granodiorite and Late-Triassic granite are likely responsible for supplying provenance to the Woruo Mountain Carnian mudstones, which have similar REE patterns. The relatively high TOC contents of Carnian mudstones are related to high paleoproductivity and fast sedimentation rates, which will lead to preservation of some organic matter even when bottom waters are completely oxidizing. The detrital input during the Carnian mudstones deposition would result in dilution of organic matter.

1. Introduction

Although much attention has been focused on the mechanisms that control organic material accumulated in sediments in previous studies, the mechanisms remain controversial due to their complex nature (Hetényi et al., 2004; Burdige, 2007; Wei et al., 2012; Pauly et al., 2013; Fu et al., 2014, 2015; Yan et al., 2015; Zeng et al., 2015). At present, three mechanisms that control organic material accumulated have been put forward, including (i) organic matter input (primary productivity); (ii) organic matter preservation (redox condition and sedimentary rate); and (iii) organic matter dilution (detrital matter input) (Tyson, 2001, 2005; Wei et al., 2012; Algeo et al., 2013; Ding et al., 2014; Fu et al., 2015; Schoepfer et al., 2015; Zeng et al., 2015). Furthermore, other factors, such as paleoclimate, provenance, and clay minerals, may also affect the accumulation of organic material (Kennedy et al., 2002; Riquier et al.,

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2006; Wei et al., 2012; Fu et al., 2015; Yan et al., 2015).

The Late Triassic Carnian climate event may be closely related to the widespread black shale events in the Triassic (Hornung and Brandner, 2005; Prochnow et al., 2006; Shi et al., 2009; Preto et al., 2010; Roghi et al., 2010). Many studies have concentrated on the black mudstones/shales not only because of their economic potential as the source rock (Zeng et al., 2013; Fu et al., 2016), but also because they record geological events (i.e. anoxic event and climate event) at critical geological intervals (Hornung and Brandner, 2005; Prochnow et al., 2006; Soua, 2014; Dal Corso et al., 2015). Late Triassic Carnian black shales and the paleoclimate have been reported in numerous areas (Hornung and Brandner, 2005; Shi et al., 2009; Roghi et al., 2010). However, a detailed study on paleoclimate during the Carnian stage in Tibet is not available in the literature at present.

In recent years, the Late Triassic organic–rich mudstones have been considered as the most significant source rocks in the North Qiangtang Depression, eastern Tethys due to their wide distributions and relatively high total organic carbon (TOC) contents (Wang et al., 2009; Zeng et al., 2013; Fu et al., 2016). The organic–rich mudstones studied here are mainly distributed in the lower part of Woruo Mountain section and their laterally extensive is ~15 km. Previous researches primarily focused on their hydrocarbon generation potential (Ding et al., 2011; Zeng et al., 2013; Chen et al., 2014). However, the factors that control the organic material accumulated have not been studied at all.

In this study, the systematic inorganic geochemistry (major and trace elements) investigations concentrating on these organic–rich mudstones are conducted. Pyrite morphology features and mineral compositions of some selected samples are also observed. The aims of this paper are to investigate the paleoclimate, provenance, paleoredox condition and paleoproductivity during the Carnian mudstones deposition, analyze which factors controlled the organic material accumulated, and establish their formation model finally. The paleoclimate features in the Carnian stage from the Woruo Mountain area will also provide an example for Carnian climate event study in Tibet, eastern Tethys.

2. Geologic setting

The Qiangtang Basin is situated at the northern Tibetan Plateau, once belonging to the eastern Tethys during the Late Triassic. Tectonically, this area is situated at the junction of the Tarim Block, Kunlun Block, Songpan–Ganzi Block, and Lhasa Block. The southern Bangong Lake–Nujiang River suture zone (BNSZ) and northern Hoh Xil–Jinsha River suture zone (HJSZ) compose the boundary of Qiangtang Basin. It can be divided into three different tectonic units from south to north, which are South Qiangtang sub-basin (depression), Central Uplift Belt, and North Qiangtang sub-basin (depression), respectively (Zhao et al., 2001; Wang et al., 2004) (Fig. 1A). It is the largest Mesozoic marine basin in the Tibetan Plateau. Much attention has been focused on the Qiangtang Basin in the past two decades is due to its great exploration potential. The formation of the Late Triassic Qiangtang Basin is connected with the subduction of the Paleotethys to the south in the Middle to Late Triassic (Kapp et al., 2003). The collision between Qiangtang Block and the Eurasian Plate in this interval led to the uplift of the Qiangtang Basin (Kapp et al., 2003). Furthermore, the presences of large–scale paleo-weathering crusts also suggest that most of Qiangtang Basin were uplifted (Wang et al., 2007).

The Woruo Mountain section lies in the south of the North Qiangtang Depression, which is dominated by Upper Triassic Tumengela Formation, Nadi Kangri Formation, Mid–Lower Jurassic Quemoco Formation (Fig. 1B). The Tumengela Formation studied here is composed of mudstone, silty mudstone, siltstone, fine sandstone, sandstone, and quartz sandstone intercalated with thin coal seams, with an average thickness of approximately 972 m (Feng et al., 2010). It was deposited in a deltaic environment according to the sedimentary structures, lithology, and fossils (Feng et al., 2010). The lower part of Tumengela Formation is mainly composed of massive mudstone/silty mudstone and is Carnian–Norian in age, as shown by the presence of typical bivalves and palynological assemblages (Fig. 2; Wang et al., 2008). Recently, three zircon grains from sample 13No.8–1 (lower part of Tumengela Formation; Fig. 2) yield the youngest $^{207}Pb/^{206}Pb$ age of 234.1 ± 2.1 Ma. This result may reflect the maximum sedimentary age of Tumengela Formation is later than 234 Ma. Therefore, the age of the Tumengela Formation should be assigned to the Carnian stage.

3. Samples and methods

The section (N: 33°44′22.4″, E: 87°44′42.5″, H: 5234 m) in the present study lies in the Woruo Mountain area, south of the North Qiangtang Depression. The organic–rich sediments in this paper were formed in a deltaic environment (Feng et al., 2010) and are marked by black and gray mudstones (Fig. 2). Fourteen black mudstones and 12 Gy mudstones were obtained from this profile. Fourteen black mudstones from W–1 to W–14 were collected with an average spacing of 0.7 m and other 12 Gy mudstones (W–15 to W–26) were obtained with an average spacing of 1.5 m. Sampling locations are given in Fig. 2.

TOC concentrations had been measured by the Leco CS–200 carbon sulfur analyzer at the Organic Geochemistry Laboratory of Exploration and Development Research Institute of PetroChina, Huabei Oilfield Branch Company. Powder samples (120 mesh) were dissolved with 15% HCl to remove the inorganic carbon (carbonate). More details about the analytical procedure are described in Yeomans and Bremner (1989).

The mineral compositions of the whole–rock were determined using the Panalytical X'Pert PRO DY2198 diffractometer equipped with Ni–filtered Cu–Ka radiation (40 kV accelerating voltage and 40 mA beam current) at the Laboratory Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China. A portion of each sample was prepared to obtain clay assemblages following the measure described by Jackson (1978). Preparation of ethylene glycol (EG) saturated, oriented, and heated clay samples are described in Hong et al. (2007). The XRD pattern was scanned from 3° to 70° with a step size of 0.02° (2θ). In addition, the humidity was controlled at 40% RH during the determinations for the XRD pattern. The XRD quantitative mineralogical analysis results of the selected samples were treated using the HighScore. More detailed processes are available in Ruan and Ward (2002).

The morphology and distribution of typical minerals in some selected samples were studied using the scanning electron microscope (SEM) of Hitachi S–3400N (20 kV and 10^{-10} A) at the Analytical Center, Chengdu Center of China Geological Survey. The analytical procedures were following the measures described by Fu et al. (2015).

All samples have been powder to 200 mesh for geochemical analysis. They were measured at the Analytical Laboratory, Beijing Research Institute of Uranium Geology, China. The Philips PW2404 X–ray fluorescence spectrometer had been applied to measure the major oxides. To determine the major oxides, samples were prepared according to Chinese National Standard GB/T14506.28–2010 National Standard of P.R. China (2011a,b). The more analytical processes were following the methods described by Ma et al. (2015) and their analysis accuracy is generally >5%. In addition, trace elements had been measured by a Finnigan MAT high–resolution inductively coupled plasma mass spectrometer (HR–ICP–MS). The