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Reprint of Very low-grade metamorphism of the upper Permian Linxi Formation from the southern Da Xing'an Mountains, NE China: Constraints from clay mineral genesis

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ABSTRACT

The metamorphic pressure–temperature conditions and the timing of metamorphism were determined for the upper Permian Linxi Formation, southern Da Xing'an Mountains, NE China, based on the genetic characteristics of clay minerals and K–Ar dating of illite from pelitic rocks. Detrital minerals are dominated by quartz and plagioclase, and clay minerals consist mainly of illite, chlorite, and mixed-layer chlorite/smectite. The XRD analytical results indicate that illite crystallinities are in the range of 0.25–0.57 (average value, 0.35), that illite polytypism is dominated by $2M_1$ and minor $2M_1 + 1M_d$ and $1M_d$ types, and the illite b dimension is in the range of 8.9982–9.0312 Å (average, 9.0174 Å). These characteristics indicate that the strata containing the illite experienced very low-grade metamorphism. The temperatures estimated by vitrinite reflectance thermometry are in the range of 202 °C–293 °C (average, 245 °C), indicating that the pelitic rocks of the upper Permian Linxi Formation experienced anchizone-grade metamorphism. The illite grains used for dating are <0.15 μm in size, which is similar to that of autogenic illite grains. The K–Ar age of the illite is 127.64 ± 2.12 Ma, which is interpreted to represent the timing of the very low-grade metamorphism.

1. Introduction

Genetic characteristics of clay minerals can provide important information for the palaeoclimate, diagenesis, and very low grade metamorphism, which have attracted much attention during the past few decades (e.g. Frey and Robinson, 1999; Wang and Yang, 2013; Wang et al., 2013; Yin et al., 2013; Zhou and Keeling, 2013). Pelitic rocks contain predominantly clay minerals. When pelitic rocks experience very low-grade metamorphism, the clay minerals are in a metastable equilibrium state, and thus do not conform to the Gibbs phase rule (Lippmann, 1981, 1982; Jiang et al., 1994, 2004; Essene and Peacor, 1995). Equilibrium mineral paragenesis does not occur during very low-grade metamorphism; rather, the factors that control mineral reactions under these conditions are temperature, reaction rate (Frey, 1987; Pollastro, 1990; Huang et al., 1993), overlying rock layer pressure, and structural stress (Frey and Robinson, 1999). Because of the absence of characteristic metamorphic minerals and characteristic paragenetic mineral associations, the study of very low-grade metamorphism using conventional equilibrium thermodynamic theory and petrographic observations is difficult. Kübler (1967a,b, 1968) has reported on illite crystallinity (KI °Δ2θ) at anchizone metamorphic intensities, thus establishing a foundation for the study of the very low-grade metamorphism of pelitic rocks. The constituents, structure, morphology, and assemblages of inorganic paragenetic minerals are the main typomorphic features useful for the study of very low-grade metamorphism and for distinguishing anchizone-intensity metamorphism (Kübler, 1968; Robinson, 1985; Frey and Robinson, 1999; Battaglia et al., 2004; Bi and Mo, 2004; Hu and Yu, 2009; Hu et al., 2010, 2011, 2012).

The maturity of organic matter in sedimentary rocks is highly sensitive to palaeogeothermal changes, and it can therefore be used to record geothermal events (Barker and Pawlewiez, 1986; Barker and Pawlewicz, 1994; Teichmuller, 1987a,b; Frings et al., 2004; Rantitsch and Russegger, 2005; Aldega et al., 2007; Rimmer et al., 2009; Noten et al., 2011). Vitrinite reflectance (Ro), which provides palaeogeothermal information, is widely used in petroleum geology, but not in regions of very low-grade regional metamorphism.

Although some researchers have considered the implications of clay mineral formation in the southern Da Xing'an Mountains (Hu and Yu, 2009; Hu et al., 2010, 2011, 2012), no comprehensive studies have been conducted on mineral constituents or the history of very low-grade metamorphism in the area. Thus, this paper focuses on the mineral constituents, genetic characteristics, and the relationship between the state of organic matter and metamorphic grade in the upper Permian pelitic rocks in the area, to reveal details of the late Permian geothermal history.

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2. Geological background and sample description

The southern Da Xing'an Mountains, NE China, also called the Great Hinggan Range or the Great Xing'an Range, is located in the eastern segment of the Central Asian Orogenic Belt and consists mainly of the Songnen block and the Xing'an block (Fig. 1A) (Sengör et al., 1993; Liu et al., 2010; Han et al., 2012). The present study area is situated between the Ondor Sum–Xar Moron and Hegenshan suture zones in the eastern segment of the Central Asian Orogenic Belt (Liu et al., 2010; Han et al., 2012). Permian strata in the study area are, from the bottom up, the Dashizhai Formation (DF), the Zhesi Formation (ZF), and the Linxi Formation (LF) (Fig. 1B). The DF is a series of shallow-marine facies eruptible intermediate-acid lavas and tuffs interbedded with some normal sedimentary clastic rocks (Shao et al., 2007). Conformably overlying the DF is the ZF which is composed of a series of clastic and carbonate rocks representing marine and marine–terrigenous facies. The ZF is mainly massive grey–green and grey-black carbonaceous siltstones, yellow-green sandstones and siltstones, grey bioclastic limestones, and siliceous sediments (EGSCIM, 1978; Shen et al., 2006; Wang et al., 2009). The LF unconformably overlies the ZF and is a series of terrestrial facies pelitic rocks (consisting of >25% muddy clay minerals) comprising pelite, silty pelite, politic siltstone, and siltstone. Some of the rocks are strongly deformed and contain a clear foliation defined by minerals with a shape-preferred orientation (EGSCIM, 1978; Huang et al., 1993; Han et al., 2012), and are thus phyllites. Previous studies suggested that the Permian strata in the area had experienced regional low-grade greenschist-facies metamorphism (Dong et al., 1986a,b; Bureau of Geology and Mineral Resources of Inner Mongolia Autonomous Region, 1991; Cheng, 1994). However, according to the results of more recent studies, the late Palaeozoic pelitic rocks in the area actually experienced very low-grade metamorphism (Hu and Yu, 2009; Hu et al., 2010, 2011, 2012). The upper Palaeozoic rocks are regionally distributed as a capping (Jiamusi–Mongolia block). According to studies of lithofacies and palaeogeography, the region during the late Carboniferous–Permian was an extensive marine sedimentary basin connected to the Palaeo-Asian Ocean in the south (Wang et al., 2008, 2009; Zhang et al., 2008). Mesozoic granites and volcanic rocks (ages, ca. 220–180 Ma) are common in the study area (Zhang et al., 2008; Wu et al., 2011).

Over 40 samples were collected from the field outcrops for the study (Fig. 1). Due to the proximity of some sample locations, we combined the samples based on stratigraphic and lithological characteristics; the final results are shown in Fig. 1 and Table 1.

3. Analytical methods

3.1. Clay mineral XRD analysis

The XRD measurements were performed using a D/max-2500 X-ray diffractometer made by Japan Rigaku Company at the Petroleum Geology Research and Central Laboratory, Research Institute of Petroleum Exploration &Development (RIPED), PetroChina. Because the diameter of the clastic minerals is usually greater than 2 μm while that of the authigenic minerals is less than 2 μm (Wang et al., 1996), we separated the clay minerals with diameter less than 2 μm for measurement to avoid the possible influence from clastic minerals. The samples were first crushed into powder (200 mesh) and then precipitated the meshed power by settling for 24 h with deionized water. According to Stokes law, the (001) oriented mount was prepared with the separated fraction. The slides were dried in air, heated, and exposed to ethylene glycol vapours.

3.1.1. Mineral content analysis

XRD analysis for mineral contents belongs to semi-quantitative analysis. In whole rock analysis, the contents of different minerals are determined by the contrast ratio of the primary peaks heights, while the

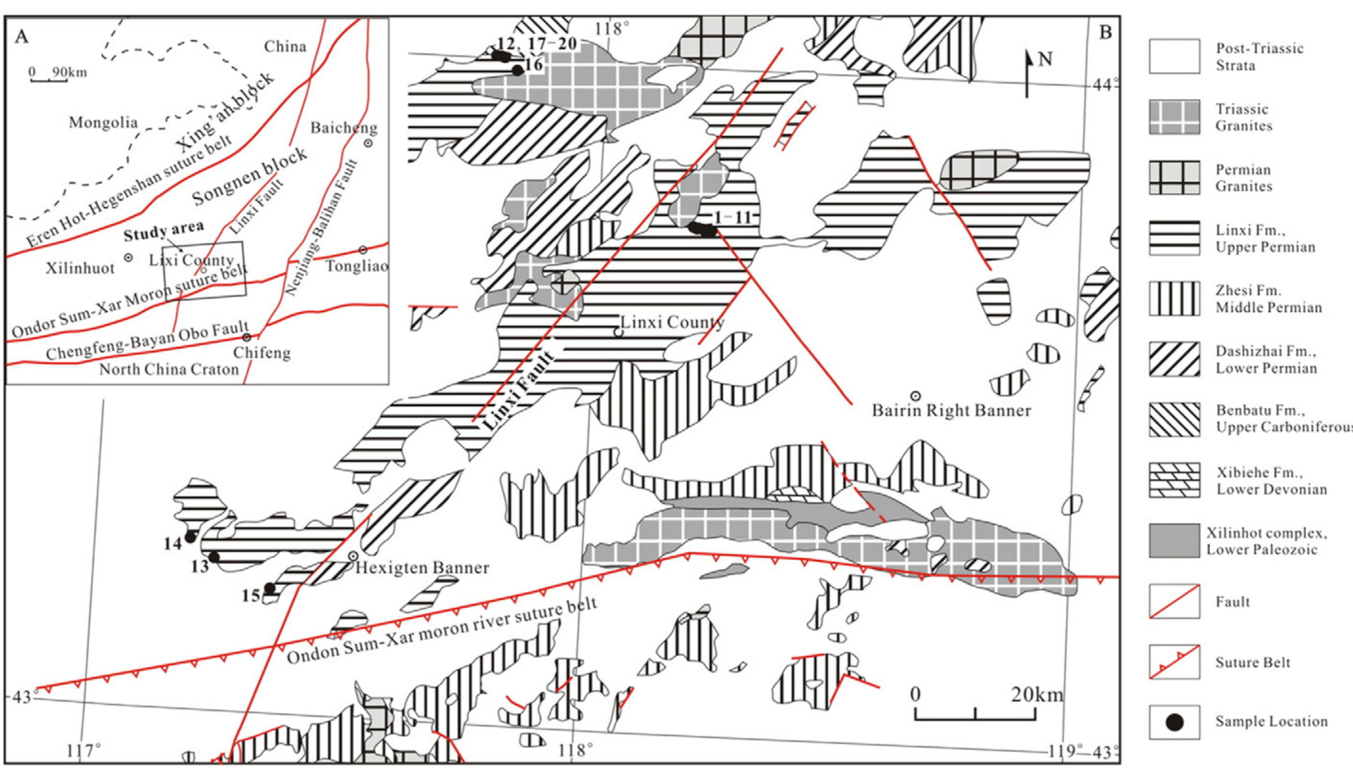

Fig. 1. Geological map of the Linxi County and Hexigten Banner areas.
Modified after Wang and Liu (1986), GMRBIN (1991), Jian et al. (2008), and Han et al. (2012).