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Pigmentation of the Early Silurian shallow marine red beds in South China as exemplified by the Rongxi Formation of Xiushan, southeastern Chongqing, central China

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Abstract

The origin and pigmentation of red beds have long been investigated, but mainly on continental settings and carbonate facies (including deep marine red beds). This paper focuses on the shallow marine clastic red beds developed in South China during the Silurian. Based on the sedimentological and geochemical analyses on red layers, green layers and laminae of the Rongxi Formation (Llandovery, Lower Silurian) of Xiushan, southeastern Chongqing, known as the 'lower red beds' (LRBs), the following observations are made: (1) the LRBs are primary red beds whereas the green layers are secondary (i.e., formed during early diagenesis); (2) the color differentiation of sediments shows little relevance to the bottom redox potential shift but has a close relationship to grain size and sediment sorting which may be caused by sea level changes and tides. The controlling factors of LRBs pigmentation are significantly different from those of deep marine red beds, and some coeval red beds in North America and Europe. It is noted that, among the shallow marine clastic red beds, the sedimentological and geochemical signatures from the laminae seem to better indicate the environmental conditions than those derived from the layers.

Keywords: Silurian; Rongxi Formation; Red beds; Granularity; Pigmentation; Xiushan, Chongqing

1. Introduction

The red beds have been under investigation for over a century, and the knowledge about such strata has been accumulated with the development of modern technologies. Early studies on red beds simply focused on the description of such rocks, and for a long time these red beds were considered as terrestrial deposits (e.g., Tomlinson, 1916; Krynine, 1950; van Houten, 1961). Since the recognition of marine red beds (Walker, 1967a, b), great and important progresses have been achieved in the study on such strata. With the development of some new analytical methods, knowledge of the origin and pigmentation of clastic marine red beds has been continuously improved. More and more attentions have been paid to those key questions on this particular topic; for example, how hematite works as the primary pigment mineral and how it originates (Robb, 1949; Krynine, 1950; Walker, 1967a, b, 1978; van Houten, 1968; Berner, 1969, 1971; Mücke, 1994); how about the amount and distribution of iron, the ratio of Fe^{2+}/Fe^{3+} in red beds and their effects (Hagemann, 1957; Pettijohn, 1957; Hunter, 1970); what the systematic classification of red beds is (Clark, 1962; Turner, 1980). Based on different sources of hematite, the red beds have been divided into at least four types (Turner, 1980): primary red beds (PRBs), the pigment of which was directly inherited from red desert or red soil; secondary red beds (SRBs), which were formed from non-red rocks; diagenetic red beds (DRBs), which are closely related to the bottom redox potential; and marine red beds (MRBs), which were deposited in pelagic marine environments.

The relationship between the Silurian red beds and their depositional environments has been systematically investigated in Western Europe and North America (e.g., Ziegler and McKerrow, 1975). The color variation from black to red in the

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Lower Silurian strata, the east Baltic Basin, was explained by the change of redox potential (Kiipli, 2004). McLaughlin et al. (2012) identified the signature of oceanic anoxic events in the Silurian of the Appalachian Basin with sedimentary and stable isotopic methods. New evidence shows that microbe activities play an important role in the colorful pink to red limestones and ironstones in the Silurian sediments from the Carnic Alps (Ferretti et al., 2012). There was ongoing debate on the origin of marine clastic red beds till the 1990s. Since the late 1990s, the deep oceanic red beds have attracted extensive attention, including the project on anoxic events and high oxic conditions in ancient marine environments (Wang et al., 1999). Comprehensive studies through various geologic disciplines on deep oceanic red beds have provided a glimpse of the paleoenvironmental, paleoceanographic, and paleoclimatic changes during the Earth history (Hu, 2002; Chen et al., 2005; Wan et al., 2005; Wang and Hu, 2005; Hu et al., 2006, 2009, 2012).

Marine red beds of various geological ages are common in China, representing different sedimentation types formed under different paleogeographic backgrounds and tectonic settings. The Silurian red beds are widely distributed in China, particularly in South China (Rong et al., 1990, 2003, 2012; Chen and Rong, 1996; Geng et al., 1999), Tarim (Zhou and Chen, 1990), the Qilian Mountains and Ningxia (Yin et al., 1958; Zhang, 1962), most of which are of shallow marine origin. In the Upper Yangtze Region of South China, two suites of shallow marine red beds developed during Llandovery, Early Silurian (Ge et al., 1977, 1979; Chen and Rong, 1996; Rong and Chen, 2003; Rong et al., 2003, 2012): one in early Telychian, known as the Lower Red Beds (LRBs) and represented by the Rongxi Formation; the other in middle to upper Telychian, known as the Upper Red Beds (URBs) represented by the Huixingshao Formation. This paper will focus on the Rongxi Formation, i.e., the LRBs and their pigmentation.

The LRBs are lithologically characterized by interbedded purple to red and yellowish green to bluish gray silty mudstones and muddy siltstones. The lower boundary of LRBs is defined by the appearance of the purple to red fine clastic beds within the Lower Silurian rocks and the upper boundary marked by the disappearance of red (or purple red) beds. Previous studies on LRBs were mainly on their stratigraphy, paleontology, and sedimentology (Mu, 1962; Ge et al., 1977, 1979; Chen and Rong, 1996; Wang, 1996; Rong et al., 2003), and LRBs were interpreted as shallow marine deposits due to shallow water ecological assemblage and exposure structures like mud cracks and ripple marks (Rong et al., 1984, 2003, 2012; Johnson et al., 1985; Rong, 1986). Rong et al. (2012) investigated the geographical distribution and dynamics of LRBs in the Upper Yangtze Region (Fig. 1), and proposed that the surrounding oldlands provided sufficient red detritus, which were transported to the sea by rivers to form the red beds. The depositional setting was believed to be a shallow marine environment with low biodiversity, low organic production, and no influence of oceanic currents. Our study will focus on the pigmentation mechanism of LRBs using petrological and geochemical methods. It is proposed that the red sequences of LRBs are primary red beds, and the green intercalations are secondary, which were formed during the early diagenesis. The LRBs pigmentation is closely related to grain size and sediment sorting.

2. Materials and methods

The study area is located in Xiushan Tujia and Miao Autonomous County, southeastern Chongqing, central China. The Silurian rocks are subdivided into six formations ascendingly: the Lungmachi, Hsiaohopo, Rongxi, Xiushan, Huixingshao, and Xiaoxi formations (Ge et al., 1977, 1979; Rong et al., 2003; Wang et al., 2011). The former five formations belong to Llandovery and are composed mainly of clastic deposits. During late Telychian, the Upper Yangtze Region was tectonically uplifted and the upper part of the Huixingshao Formation was eroded away with various degrees in different areas, forming a regional disconformity between the Huixingshao and the overlying Xiaoxi Formation which was deposited in Late Silurian (Ludlow–Pridoli) during a transgression (Wang et al., 2011). With the ending of Silurian, the entire Yangtze Region was uplifted and no deposits were accumulated till Middle Devonian (Liu et al., 1993; Wang et al., 2011).

The Rongxi section is along a country road near Rongxi town (Fig. 2), Xiushan County, and is the type section of both the Rongxi and the Huixingshao formations (NIGPAS, 1974). The outcrops of the Rongxi Formation (LRBs) are fresh and continuous owing to the road construction in 2010. The LRBs are 240 m thick at this section, composed mainly of thick red and green layers inter-bedded with red and green laminae and a large number of green nodules.

The sequences can be subdivided into two types based on color and thickness of the rocks. First, the well-laminated strata. The red and green beds are usually thicker than 50 cm in each single bed and could reach up to tens of meters (Fig. 3A). The laminae in red and green color are only 1–2 cm thick (Fig. 3B). Second, the un-stratified strata in which some isolated and coalesced green nodules often develop in red layers (Fig. 3C). The nodules range from spherical to irregular and often contain yellow-brown nucleus. The nuclei are considered to be the result of decomposing of organic matter that locally changed the microenvironment to a reducing setting (Durrance et al., 1978; Parnell and Eakin, 1989; Hofmann, 1991). Here we just focus on the pigmentation of the layered strata, and the origin of the green nodules will be investigated in a separate paper.

Based on the color variation, 44 samples were collected from the bottom to the top of LRBs (Nos: Cxr-1 to Cxr-44, hereinafter referred to as the thick layers) (Fig. 4). Besides, one 0.7 m-thick column with intercalated red and green laminae was collected, from which 60 samples were carefully stripped based on color variation (Nos: pol-1 to pol-60, hereinafter referred to as the laminae) (Figs. 3B, 4). All samples were polished and thin sectioned. The polished samples were examined using stereomicroscope and photographed. The thin sections were observed under a Zeiss XPL-50 microscope and photographed using a Canon A640 camera. One piece of each sample was ground to 200 mesh and sent to ALS minerals laboratory in Guangzhou to make geochemical analyses. Major elements were detected by XRF with relative error (RE) and relative deviation (RD) below