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Geochemistry and Re–Os geochronology of the organic-rich sedimentary rocks in the Jingtieshan Fe–Cu deposit, North Qilian Mountains, NW China

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ABSTRACT

The Jingtieshan Group in the North Qilian Mountains, NW China, is dominantly composed of banded iron formations (BIFs), copper deposits and organic-rich sedimentary rocks (ORS, carbonaceous phyllite). X-ray diffraction analysis of the ORS shows the mineral assemblage to be quartz + clay minerals. The total organic carbon contents show a range of 0.44–1.72%. Here we present the results of the geochemistry and Re–Os geochronology of the ORS from the Jingtieshan Group. The high values of Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), Plagioclase Index of Alteration (PIA), and Th/U ratio, indicate intense weathering. The Al_2O_3/TiO_2, Zr/Sc, Th/Sc, La/Th ratios, high rare earth elements abundances, light rare earth elements enrichment (normalized to chondrite), and distinctly negative Eu anomalies, suggest that the Jingtieshan Group ORS were derived mainly from felsic volcanic units. The new Re–Os isochron age of 1308 ± 100 Ma (2σ, n = 6, MSWD = 23) broadly overlap with the previous published ages determined using Sm–Nd and U–Pb isotope systems. The new age represents the depositional age of the Jingtieshan Group, as well that of BIF in the Jingtieshan area. Furthermore, the initial $^{187}Os/^{188}Os$ ratios (0.44 ± 0.07) indicate that the Os in the seawater was dominantly derived from hydrothermal fluids (~75%). The Ce anomaly (Ce/Ce* = 0.95–1.00) and V/(V + Ni) ratios (0.71–0.86), as well as the lack of enrichment in redox-sensitive trace elements such as U, V, Zn, Pb, Cu, Ni, Cr, Co and Mn, together with the presence of overlying BIF, suggest that the Jingtieshan area represents a ferruginous deep-water succession. This, and intense submarine hydrothermal activities contributed to the deposition of the Jingtieshan BIF.

1. Introduction

Atmospheric oxygen levels proceeded in two broad steps near the beginning and end of the Proterozoic eon (~2.5–0.542 Ga ago) (Bekker et al., 2004; Scott et al., 2008; Reinhard et al., 2013). However, models for the redox state of deep oceans during this interval remain controversial. Complete ocean oxidation (Holland, 1984) or sulfidic conditions in the deep ocean (Canfield, 1998; Poulton et al., 2004) have been proposed, and both models envisage the end of the deposition of banded iron formations (BIFs) at ca. 1.8 Ga. In contrast, the Mesoproterozoic Jingtieshan Group in the western segment of North Qilian Mountains contains well-preserved weakly-metamorphosed organic-rich sedimentary rocks (ORS, carbonaceous phyllite), and large BIF-type iron deposit (557 million tons) lying over the ORS. Copper mineralization (2 × 10^6 tons) was also found in the ORS, as well as in the surrounding rocks (BIF and gray-green phyllite). Hence, the study of the ORS can provide a window into the redox state in Jingtieshan area during Mesoproterozoic.

The sedimentary successions in the Jingtieshan Group, like other Proterozoic successions worldwide (e.g., Rooney et al., 2010), lack volcanic horizons that can be targeted for U–Pb or Ar–Ar geochronology and are devoid of fossils suitable for relative age dating. Previous radiometric dating of the Jingtieshan Group (Rb–Sr isochron age of phyllite, Yang et al., 1991; Pb

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model age of pyrite in BIF, Xue et al., 1997; Sm–Nd isochron age of BIF, Xia et al., 1999) has yielded a wide range of ages from ca. 1.3 Ga to ca. 0.6 Ga. More recently, we reported U–Pb age of ca. 1.3 Ga as the depositional age of the Jingtieshan Group from zircons in metasedimentary rocks and diabase (Fig. 2b) (Yang et al., 2016).

The direct dating of sedimentary rocks is generally difficult (Stille and Clauer, 1986; Kendall et al., 2009). The Rb–Sr, Sm–Nd, and K–Ar isotope systems have previously been used to date the deposition and early diagenesis of sedimentary sequences, but with only limited success (Stille and Clauer, 1986). Since the early work by Ravizza and Turekian (1989), a number of studies have utilized Re–Os geochronology to determine the time of deposition of ORS (total organic carbon (TOC) > 0.5%) (Mao et al., 2002; Kendall et al., 2004; Selby and Creaser, 2005; Yang et al., 2009; Rooney et al., 2010; Tripathy et al., 2013). The Re–Os isotopic system has a long half-life (λ ^{187}Re = 1.666×10^{-11}; Smoliar et al., 1996; Shen et al., 1998), thereby yielding precise depositional ages for ORS. Re and Os are siderophilic, chalcophilic (e.g. Shirey and Walker, 1998), organophilic, and redox-sensitive (Ravizza et al., 1991; Selby and Creaser, 2003, 2005; Selby et al., 2007). Re and Os in ORS are predominantly hydrogenous (e.g., Cohen et al., 1999; Creaser et al., 2002). The Re–Os system of ORS largely remains unaltered during hydrocarbon maturation and thermal metamorphism up to the lower greenschist facies (Creaser et al., 2002; Kendall et al., 2004, 2009). In addition, the initial ^{187}Os/^{188}Os (I_{Os}) composition determined from Re–Os isochron regressions serves as a tracer for the Os isotope composition of the Precambrian sea (Kendall et al., 2009). Furthermore, chemical and isotopic studies of ORS worldwide have provided insights into their depositional history and information on the ocean (e.g., Banerjee et al., 1986).

In this paper, we present the first geochemical and Re–Os geochronological data for ORS in the Jingtieshan area. These data allow us to constrain the sedimentary age and the formation conditions of the ORS, and contribute to further understanding of the origin of its associated BIF.

2. Geological setting

The Northern Qilian orogen in China extends NW–SE of ~1000 km, and is bounded by the Tarim Craton to the northwest, the North China Craton to the northeast, and the Central Qilian Block to the south (Fig. 1). The orogen records a protracted history of crustal evolution beginning with a Paleoproterozoic basement. The Precambrian basement, including the Paleoproterozoic Beidahe Group, the late Paleoproterozoic Zhulongguan Group, the Mesoproterozoic Jingtieshan Group, the Neoproterozoic Daliugou Group, and the Baiyanggou Group (Fig. 1) (Zhang et al., 1998, 2001; Xia et al., 1999; Mao et al., 2003), are made up of relict micro-blocks in the Northern Qilian orogen (Zuo et al., 2002). The Proterozoic basement of Northern Qilian orogen has been considered to have undergone continental rifting, initiated in the early Mesoproterozoic (e.g., Xu et al., 1996; Zhang et al., 1998), and continued until Neoproterozoic accompanied by the emplacement of bimodal volcanic rocks (Song et al., 2013).

The ~4000-m-thick Jingtieshan Group, dominated by Mesoproterozoic carbonate–clastic formations, show unconformable contact with ~1.75 Ga volcanic sequences of the Zhulongguan Group (Zhang et al., 1998; Mao et al., 2003), and is unconformably overlain by the Neoproterozoic Daliugou Group. The Jingtieshan Group can be divided into two successions. The upper successions is mainly dolomitic marble (not exposed in Jingtieshan deposit), and the lower succession which was widely distributed in the Jingtieshan deposit has been subdivided into eight units (Jt$_{1-1}$ to Jt$_{1-8}$), from bottom to top (Fig. 2a and b): (1) mottled phyllite (Jt$_{1-1}$) (415 m); (2) quartzite, locally intercalated with a sericite–quartz phyllite (Jt$_{1-2}$) (190 m); (3) siliceous phyllite plus quartzite (Jt$_{1-3}$) (120 m); (4) carbonaceous phyllite (Jt$_{1-4}$) (415 m); (5) calcareous phyllite (Jt$_{1-5}$) (200 m) (Fig. 3a); (6) gray-green phyllite (Jt$_{1-6}$) (100 m); (7) iron orebody (Jt$_{1-7}$) (150 m); and (8) black-gray phyllite (Jt$_{1-8}$) (140 m). The Jingtieshan Group has been variably affected by lower greenschist facies metamorphism (Yang et al., 1991; Mao et al., 2003, 2012). The carbonaceous phyllite (ORS) occurs within the lower part of the lower succession of the

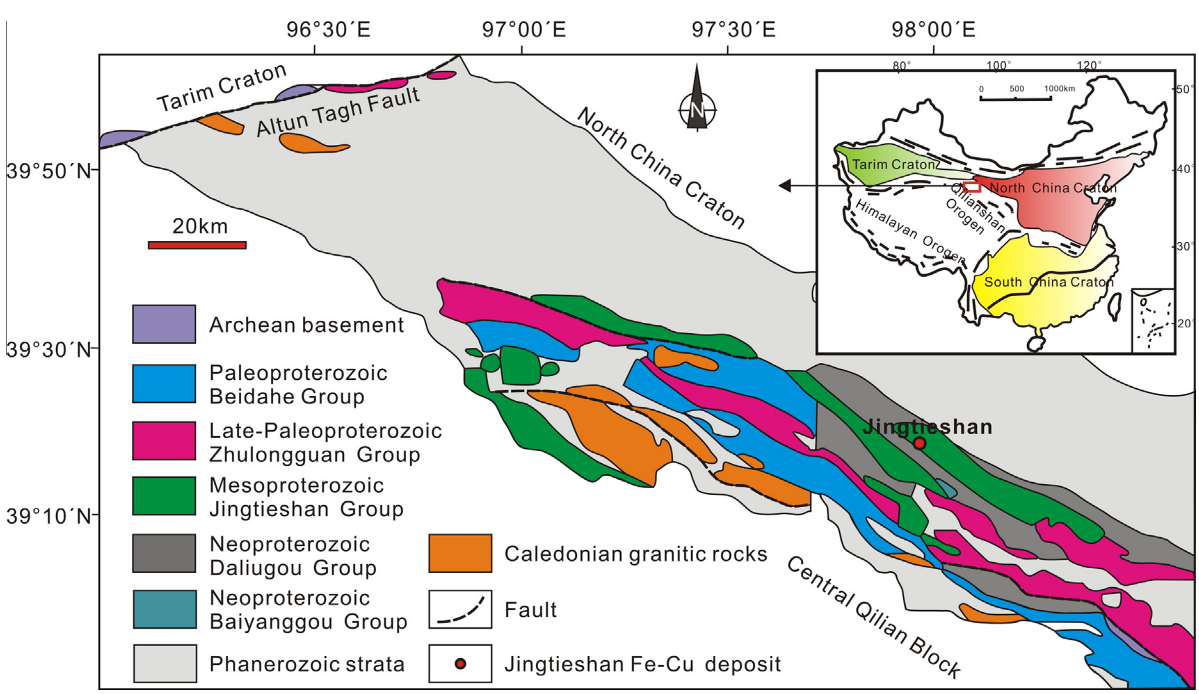

Fig. 1. Geological map of the western segment of the North Qilian area, China (modified from Mao et al., 1997).