Stratigraphic position of the Ediacaran Miaohe biota and its constraints on the age of the upper Doushantuo δ¹³C anomaly in the Yangtze Gorges area, South China

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A B S T R A C T

The siliceous shale unit that hosts the Ediacaran Miaohe biota in the Yangtze Gorges area, commonly referred to as the Miaohe Member, has an age of 551 ± 0.7 Ma. This unit is thought to be time-equivalent with the Doushantuo Member IV, which marks the top of the upper Doushantuo negative δ¹³C excursion. New bio- , sequence- and chemostratigraphic studies presented here demonstrate that the Miaohe Member is significantly younger than the Doushantuo Member IV, most likely time-equivalent with the lower Shibantan Member of the Dengying Formation. The new findings indicate that the top of the Doushantuo Formation, i.e., the top of the upper Doushantuo/Shuram δ¹³C excursion, should be much older than 551 Ma (likely ≥560 Ma). The ocean oxygenation event documented from the Doushantuo Member IV black shales should also be older than 560 Ma and predate the Miaohe biota for more than 10 Ma.

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1. Introduction

The Miaohe biota, which consists of well-preserved carbonaceous compression fossils of multicellular algae and primitive metazoans (Xiao et al., 2002), was found more than three decades ago from a siliceous shale unit (the Miaohe Member) near the Miaohe Village in the Yangtze Gorges area (Figs. 1 and 2C; Zhu and Chen, 1984; Chen and Xiao, 1991; Ding et al., 1996). The Miaohe Member has been taken as the topmost unit of the Doushantuo Formation, equivalent to the Doushantuo Member IV black shales (e.g., Lu et al., 2012, 2013; Zhu et al., 2013a,b). However, the Miaohe biota has never been found in the Doushantuo Member IV black shales besides the Miaohe section albeit enormous efforts have been done in the Yangtze Gorges area. An ash bed at the top of the Miaohe Member from the Jiujiniao section, which is on the southern side of the Yangtze River opposite to the Miaohe section, was dated as 551.1 ± 0.7 Ma (Condon et al., 2005; Zhang et al., 2005). Since the Miaohe Member was thought to be time-equivalent with the Doushantuo Member IV at the Jiulongwan section, the age of ~551 Ma has been used to mark the end of the upper Doushantuo/Shuram carbon isotope (δ¹³C) excursion (e.g., Jiang et al., 2007; Zhu et al., 2007; McFadden et al., 2008) and the time of a major ocean geochemical change (e.g., McFadden et al., 2008; Scott et al., 2008; Li et al., 2010; Kendall et al., 2015).

During the survey on the Neoproterozoic stratigraphy and paleogeography around the Huangling Anticline, we found some more localities yielding the Miaohe biota-type fossils, which enforce us to reconsider the stratigraphic position of the Miaohe biota-bearing strata. Recent chemostratigraphic study also raises questions about the correlation between the Miaohe Member and the Doushantuo Member IV. In the Jiulongwan section, the most extensively studied section for the Doushantuo Formation in the region, a prominent negative δ¹³C excursion was documented from the upper Doushantuo Member III through Member IV (e.g., Jiang et al., 2007; Zhu et al., 2013b), but in the Jiujiniao and Miaohe sections, the dolostones immediately below the Miaohe Member have positive δ¹³C values (Fig. 2; Condon et al., 2005; Zhang et al., 2005; Lu et al., 2013). In these sections, a negative δ¹³C excursion is found in much lower stratigraphic position below a thin (<5 m) black shale interval that is lithologically identical to the Doushantuo Member IV. This...
raises the possibility that the Miaobe Member is a stratigraphic unit younger than the Doushantuo Member IV, as implied by the δ^{13}C chemostratigraphy (Fig. 2). Testing this hypothesis requires an integrated stratigraphic and paleontological study from additional sections, which is currently lacking and has been limited in general by poor outcrop exposure of the Doushantuo-Dengying transition in the Yangtze Gorges area.

In this paper we present field, carbon isotope and paleontological studies across the upper Doushantuo-lower Dengying formations in a few well-exposed sections. In combination with available data and new observations, we provide a stratigraphic framework that demonstrates that the Miaobe Member is much younger than the Doushantuo Member IV and the upper Doushantuo/Shuram δ^{13}C excursion. Because the 551 ± 0.7 Ma age was obtained from the top of the Miaobe Member, the ocean oxygenation event documented from the Doushantuo Member IV must be older than ca. 551 Ma.

2. Geological background

The Ediacaran succession in the Yangtze platform of South China was thought to have deposited on a passive continental margin (Jiang et al., 2003a, 2011). The Ediacaran strata in the Yangtze Gorges area consist of the Doushantuo and Dengying formations. The Doushantuo Formation overlies the Cryogenian Nantu Formation and is subdivided into four lithostratigraphic members (Members I–IV) (Ding et al., 1996; Wang et al., 1998; Zhu et al., 2003). Member I refers to the 2–6-m-thick cap carbonate that has sedimentary structures/textures and negative carbon isotope values similar to those of the basal Ediacaran cap carbonates globally (e.g., Jiang et al., 2003b, 2006). Member II consists of alternating organic-rich black shale and thinly bedded dolostone with phosphorite-chert nodules, from which abundant acanthomorphic acritarchs have been reported (e.g., Zhou et al., 2007; McFadden et al., 2008, 2009; Liu et al., 2013). Member III is composed mainly
of thin- to thick-bedded dolostone and limestone, from which a prominent negative $\delta^{13}$C excursion has been documented and correlated with the Shuram/Wonoka $\delta^{13}$C anomaly (e.g., Jiang et al., 2007, 2011; Zhou and Xiao, 2007; Zhu et al., 2007, 2013b; McFadden et al., 2008; Sawaki et al., 2010; Lu et al., 2013; Tahata et al., 2013). Member IV refers to the 5-10 m-thick organic-rich black shales at the top of the Doushantuo Formation. Geochemical analyses from Member IV documented a prominent oxygenation event (e.g., McFadden et al., 2008; Scott et al., 2008; Kendall et al., 2015).

The overlying Dengying Formation is subdivided into three members. The Hamajing Member consists of thick-bedded to massive dolostones that seem to be in conformable contact with the underlying Doushantuo Member IV. The Shibantan Member consists of dark to black color, thinly bedded bituminous limestone, from which abundant Ediacara fossils have been recently reported (e.g., Chen et al., 2014). The upper unit of the Dengying Formation is the Baimatuo Member, which is composed mainly of thick-bedded and massive dolostones. The Dengying Formation is overlain by the Yanjahe Formation, from which a negative $\delta^{13}$C excursion (e.g., Ishikawa et al., 2008; Jiang et al., 2012) and small shelly fossils (Qian et al., 2001; Steiner et al., 2007; Guo et al., 2014) confirm its early Cambrian age.

Our study focuses mainly on the transitional interval of the Doushantuo-Dengying formations, including the upper Doushantuo Member III, Doushantuo Member IV, the Hamajing Member, and the lower part of the Shibantan Member. Because the Miaohe Member is traditionally considered as Doushantuo Member IV, it was scarcely used in the general stratigraphic subdivisions in literature. In this paper, we keep using the Miaohe Member as a stratigraphic unit for the purpose of better understanding the stratigraphic correlation, the age constraints and the popular Miaohe biota.

3. Methods

Field work has been conducted in more than 15 sections in the Yangtze Gorges area, including the sections where carbon isotope chemostratigraphy and paleontological data have been published (e.g., Jiang et al., 2007; Zhu et al., 2007, 2013b; Xiao et al., 2012; Lu et al., 2013; Liu et al., 2014). Some of the sections are partially or heavily covered; these sections are used for understanding the
overall stratigraphic pattern and sedimentary facies but no further isotope or paleontological study is conducted. Three recently exposed sections in Zhimaping, Qinglinkou and Xiangerwan are carefully checked for physical surfaces and fossil contents and sampled for carbon isotope analyses. Sections at Miaohe, Jiujiangwan and Jiuquanno are checked for physical surfaces and partially sampled to fill the gaps of existing δ13C chemostratigraphy (Fig. 2).

We define two types of physical stratigraphic surfaces: stratigraphic discontinuity and stratigraphic unconformity. Stratigraphic discontinuity refers to abrupt facies change but no obvious exposure or erosion has been observed in that particular section and its adjacent outcrops. Stratigraphic unconformity is defined when obvious exposure and/or erosional features are observed. These two types of surfaces may record lateral variations along a sequence boundary, but they could also have different meanings. Stratigraphic discontinuities could be formed by oceanographic events (e.g., the drowning unconformity; Schlager, 1999) or sudden deepening in local basins with fast subsidence controlled by syn-depositional faults. For the later case, the flooding and deepening in the basin (e.g., hanging wall of a normal fault) may correspond to shallowing and subaerial exposure/erosion in uplifted platforms (e.g., footwall of a normal fault; Howley and Jiang, 2010).

Most carbon and oxygen isotopes are analyzed at the State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences (Wuhan). About 150–400 μg sample powder was reacted with 100% phosphoric acid at 72 °C to generate CO2 that is transferred to a MAT 253 mass-spectrometer via a Finnigan GasBench II interface. A portion of the samples is analyzed at the Las Vegas Isotope Science (LVIS) Laboratory, University of Nevada Las Vegas, using a Kiel-IV–Delta-Plus system. Results are reported as per mil compared to the Vienna Pee Dee Belemnite (V-PDB) standard. Analytical precision for both δ13C and δ18O were better than 0.1‰ in both labs. New isotope results from this study and isotope data from literature are summarized in appendix table DR1.

Carbonaceous compression fossils were collected from siliceous shales in Zhimaping, Xiangerwan and Maxi sections. Samples from the Xiangerwan section did not produce identifiable fossils. For this study we focus on the taxa that are comparable with typical components of the Miaohe biota. Detailed description of fossils will be published elsewhere.

4. Data from new sections

4.1. The Zhimaping section

In the Zhimaping section (Fig. 1; 31°4′26.3″N, 110°51′55.6″E), two lithologically distinct black shale intervals are observed at the Doushantuo-Dengying transition (Fig. 3A). The lower black shale (Doushantuo Member IV) is 6.6 m thick and contains centimeter-to-decimeter-size carbonate nodules that are identical to those of the Doushantuo Member IV at the Jiujiangwan section (Fig. 2A). In spite of intensive search, no fossils have been found in this unit. The upper shale unit, which should be correlatable with the Miaohe Member at the Miaohe section, consists of 27.2-m-thick siliceous shales with thin (<5 cm) silicified dolostone interbeds. Abundant carbonaceous compression fossils have been found from the lowermost 5 m of the siliceous shale unit and from the correlative horizon at the Maxi section (Fig. 4). Some of the fossils, including Bucalphyca taeniata (Fig. 4A and B), Protoconites minor (Fig. 4C), Calyptrina striata (Fig. 4D), Sinospongia typica (Fig. 4E), Enteromorphites sianesis (Fig. 4F), Jiuguanella simplicis (Fig. 4G), Liulingitaenia allopecta (Fig. 4H), and Doushantouphyton lineare (Fig. 4I), are typical taxa of the Miaohe biota from the Miaohe section (Fig. 2C; Xiao et al., 2002). The presence of Miaohe-type fossils and their higher stratigraphic position demonstrate that the Miaohe Member is younger than the Doushantuo Member IV.

The δ13C profile from the Zhimaping section (Fig. 3A) also suggests that the Miaohe Member is younger than the upper Doushantuo negative δ13C excursion. Similar to the Jiujiangwan section (Fig. 2A), a prominent negative δ13C anomaly with low values down to −10‰ occurs in a 45-m-thick shaly dolostone and limestone interval below the Doushantuo Member IV. Carbon isotope values shift toward positive immediately after the Doushantuo Member IV and remain stable until the top of the Hamajing Member. The thin siliceous dolostone interbeds/lenses within the Miaohe Member have negative δ13C values from −4.8‰ to −18.5‰, but because of their overall low carbonate contents, these δ13C values may be of diagenetic origin. The overlying dark-black bituminous limestone of the Shibanhan Member has positive δ13C values, consistent with those of the Dengying Formation in the Yangtze Gorges area (e.g., Jiang et al., 2007; Wang et al., 2014).

Three stratigraphic discontinuities are present at the base of the Miaohe Member, the base of the Doushantuo Member IV and the middle Doushantuo Member III, respectively (Fig. 3A). Surface 1 (S-1) at the middle Doushantuo Member III is expressed as an abrupt facies change from medium-bedded cherty dolostone to thinly bedded shaly dolostone. This surface coincides with an abrupt δ13C shift from +1.3‰ to −6.9‰. Surface 2 (S-2) is displayed as an abrupt facies change from thinly bedded limestone to organic-rich black shale. Negative δ13C values initiated at surface 1 continue upward across this surface until they shift toward positive in thick-massive dolostones of the Hamajing Member. Surface 3 (S-3) at the base of the Miaohe Member is present as a sharp change from massive dolostone to siliceous shale. Minor dissolution features such as calcite-filled vugs are present in the massive dolostone but no obvious erosion is observed. These physical stratigraphic surfaces are traceable in available outcrops and their persistent lateral extension precludes substantial faulting along these surfaces.

4.2. The Qinglinkou section

Similar to the Zhimaping section, the Qinglinkou section (Fig. 1; 30°48′0.2″N, 110°55′18.5″E) has two black shale units across the Doushantuo-Dengying transition (Fig. 3B), but their thickness is much smaller. The carbonaceous shale of the Doushantuo Member IV is only 1.25 m thick and the siliceous shale of the Miaohe Member is 9.65 m thick. So far, no identifiable fossils have been found from both of these shale units.

A negative δ13C anomaly with a nadir of −3.1‰ is present in intraclastic dolopackstone-dolowackestone of the upper Doushantuo Member III (Fig. 3B). In contrast to the Zhimaping section, δ13C values shift toward near 0‰ below the stratigraphic discontinuity at the Member IV/Member III contact (S-2). In comparison with those from the Zhimaping and Jiujiangwan sections, the magnitude and temporal extension of the negative δ13C excursion is much smaller. Negative δ13C values are also found from cherty dolostones of the basal Shibanhan Member, immediately above siliceous shales of the Miaohe Member (Fig. 3B). Positive δ13C values from the middle Doushantuo Member III, the Hamajing and Shibanhan members of the Dengying Formation are comparable with those of the other sections in the Yangtze Gorges area (e.g., Jiang et al., 2007; Lu et al., 2013; Zhu et al., 2013b; Wang et al., 2014).

Stratigraphic unconformities are found in this section (Fig. 3B). Surface 1 (S-1) is expressed as an erosional unconformity with 10–30 cm local erosional relief (Fig. 5A). The intraclastic dolopackstones above S-1 consists of large (2–15 cm) elongated and angular clasts (Fig. 5B). These intraclasts are interpreted as reworked carbonate debris from an exposure surface. Similar intraclasts are also found from the correlative stratigraphic horizon in the Sixi section (Fig. 5C), 8 km south of the Qinglinkou section (see loc. in Fig. 1).
Surface 2 (S-2) is shown as an abrupt facies change from thinly bedded dolostone to organic-rich black shale. Surface 3 (S-3) at the base of the Miaohe Member records another erosional unconformity with 10–50 cm local erosional relief (Fig. 5E), which is interpreted as formed along an exposure surface at the top of the Hamajing Member.

4.3. Xiangerwan section

In the Xiangerwan section (Fig. 1; 31°13′6.2″ N, 110°57′26.8″ E), the middle Doushantuo Member III starts with light-color massive dolostone (Fig. 3C). An abrupt change from massive dolostone to a 13.4-m-thick, thinly bedded pink dolostone marks a stratigraphic discontinuity (S-1). The pink dolostone is followed by 19-m-thick, thinly bedded limestone, which is in turn overlain by a 2-m-thick, thinly bedded dolostone at the top of the Doushantuo Member III. The carbonaceous shales of the Doushantuo Member IV are thin (2 m thick) but well exposed in this section, with identical decimeter-sized carbonate concretions. Similar to the other two sections (Fig. 3A and B), the base of the Doushantuo Member IV marks a stratigraphic discontinuity (S-2) expressed by abrupt facies changes. The Hamajing Member overlying the Doushantuo Member IV is 37.6 m thick and consists of thick-bedded to massive dolostone. The Miaohe Member is almost missing in this section.
expressed only by 0.3–0.5 m thick black shales unconformably sitting on an undulated surface (S-3) at the top of the massive dolostone (Fig. 5D), from which silicification and quartz-filled vugs are locally observed. Overlying the thin black shale interval is a 3.4-m-thick, thinly bedded intraclastic dolopackstone that is commonly ascribed to the topmost Hamajing Member (Fig. 3C). The change from the dolopackstone to its overlying thinly bedded bituminous limestone of the Shibantan Member is transitional, with gradual decrease of dolostone and intraclasts.

A prominent negative δ¹³C anomaly occurs in the upper Doushantuo Member III and Member IV. In comparison with the other two sections (Fig. 3A and B), negative δ¹³C values in this section started 11 m below Surface 1 (S-1) and shift toward positive in the thin dolostone beds immediately below Surface 2 (S-2). The dolostone and limestone of the Hamajing and Shibantan members have positive δ¹³C values mostly from +1‰ to 5‰, except for a few low values (with a nadir down to −0.8‰) across Surface 3 (S-3) at the top of the Hamajing Member.

Integration of the physical stratigraphic and chemostratigraphic data from the above three well-exposed sections (Fig. 3) in the western side of the Huangling Antcline clearly demonstrates that the Miaohe Member is younger than the Doushantuo Member IV and the upper Doushantuo negative δ¹³C excursion. The Miaohe Member (siliceous shale) is not only lithologically distinguishable from the Doushantuo Member IV (organic-rich black shales), but also differs in thickness and its temporally adjacent units. Thickness variations of the Miaohe Member between Hamajing and Qinglinkou sections and disappearance of the Miaohe Member in Xiangerwan section above a stratigraphic unconformity suggest that the Miaohe Member is a highly diachronous stratigraphic unit deposited during seawater transgression. Laterally the Miaohe Member should be time-equivalent with the uppermost Hamajing Member and the lower Shibantan Member (Fig. 3).

5. Regional stratigraphic framework

With information obtained from the new sections and additional sequence-chemostratigraphic study from three typical sections at Jiulongwan, Miaohe and Jiunqiao, a regional stratigraphic framework for the upper Doushantuo and lower Dengying
Fig. 5. Field photographs showing stratigraphic discontinuities across the Doushantuo-Dengying transition in Qinglinkou and Xiangerwan sections. (A) Erosional surface between intraclastic dolostone and its underlying medium-bedded, cherty dolostone of the upper Doushantuo Member III in Qinglinkou section (S-1 in Fig. 3B). (B) Intraclastic dolopackstone interpreted as reworked carbonate debris from an exposure surface (above S-1 in Fig. 3B), Qinglingkou section. (C) Intraclastic dolopackstone from traceable horizon (S-1) in Sixi section. (D) Erosional surface at the top of the Hamajing Member in Xiangerwan section (S-3 in Fig. 3C). A thin (~0.5 m), lenticular bed of siliceous black shale and a 3.4-m-thick dolopackstone mark the transition to its overlying Shibantan Member. (E) Erosional surface at the contact between siliceous black shales of the Miaohe Member and its underlying thick-bedded dolostones of the Hamajing Member (S-3 in Fig. 3B), Qinglinkou section.

formations in the Yangtze Gorges area is provided in Fig. 6. The three physical stratigraphic surfaces at the upper Doushantuo Member III, at the base of Doushantuo Member IV, and at the top or uppermost Hamajing Member are regionally correlatable, although their expressions differ among sections.

Surface 1 (S-1) shows as an abrupt lithological change from medium-bedded dolostone to thinly bedded shaly dolostone or pink dolostone in Jiulongwan, Xiangerwan and Zhimaping sections (Fig. 6A–C). In the Miaohe section, the lithology overlying S-1 does not have shaly partings or shale beds, but the change from thick-bedded cherty dolostone to thinly bedded dolostone is still easily identifiable (Fig. 2D). In contrast, S-1 in the Qinglinkou section is expressed as an erosional unconformity (Fig. 5A) overlain by large, reworked intraclasts (Fig. 5B) possibly originated from debris of karstic breccias along an exposure surface. The occurrence of reworked karstic breccias along S-1 highlights subaerial exposure of the carbonate platform at least locally in the Yangtze Gorges area.

Surface 2 (S-2) at the base of the Doushantuo Member IV is expressed as an abrupt change from thinly bedded limestone/dolostone to organic-rich black shales (e.g., Fig. 7A and B) in all sections investigated in the Yangtze Gorges area. No obvious exposure or erosional features have been observed from any of these sections so far, although the lithology immediately below S-2 varies among sections (Fig. 6). An intriguing feature associated with S-2 is the large thickness change of the Doushantuo Member IV black shales, from ~12 m in Jiulongwan (Fig. 6A), to 6.6 m in Zhimaping (Fig. 6C), and to <2 m in other sections (Fig. 6B and D–F). While such thickness change could have been controlled by the paleo-topography of the depositional environments (e.g., Jiang et al., 2011; Zhu et al., 2013b), our observations suggest that it is likely caused, at least partially, by the sliding of the overlying massive dolostones of the Hamajing Member. In the Jiulongwan section, the base of Member IV is a sharp surface (Fig. 7A) but the contact between Member IV and its overlying Hamajing Member seems to
Fig. 6. Stratigraphic sections and δ¹³C profiles across the Doushantuo-Dengying transition in typical sections of the Yangtze Gorges area and their sequence and chemostratigraphic correlation (see Fig. 1 for loc. of sections). The Miaohe Member that has been dated at 551.7 ± 0.7 Ma is apparently younger than the Doushantuo Member II, from which most of the existing geochemical results have been obtained. See Table DR1 in the appendix for the isotope data of this study and from literature. Notice that for the Miaohe section, only data from the lowermost Shibantan Member is plotted in (D).
be transitional, with a few thin dolostone interbeds at the top of the black shales (e.g., Fig. 7C). In an adjacent section at Huajipo, 4.5 km south of the Jiulongwan section, the base of the Doushantuo Member IV is a similar sharp surface, but the top of the black shale unit does not have transitional dolostone interbeds and the thickness of the black shales is only 4.6 m thick (Fig. 7B). In addition, the base of the Hamajing Member in Huajipo section is deformed, hardened and silicified, consistent with layer-parallel sliding along a lithologically contrasting contact. In other sections with a thin Doushantuo Member IV (e.g., Fig. 6B and D–F), similar deformation and silicification of the basal Hamajing Member is present.

Surface 3 (S-3) marks a major stratigraphic unconformity at the uppermost part of the Hamajing Member (Fig. 6). In addition to the erosional features seen in Xiangerwan (Fig. 5D) and Qinglinkou (Fig. 5E) sections, exposure and erosional features are also observed in Jiulongwan and Miaoho sections. In the Jiulongwan section, the upper part of the Hamajing Member is brecciated and contains well-preserved tepee structures (10–50 cm wide and 5–20 cm high). Above this interval, sandstone lenses up to 1.2 m thick locally fill depressions along the surface (Fig. 7D). In the adjacent section at Huajipo, an undulated surface with up to 1.5 m local erosional relief is observed. In the Miaoho section (Fig. 6D), the topmost 2 m of the Hamajing Member is brecciated, with downward-penetrating dykes filled with siltstone, clay and pedogenic carbonate cements. All these features indicate subaerial exposure and erosion/truncation after deposition of the uppermost Hamajing Member. The overlying siliceous shales of the Miaoho Member and bituminous limestones (with minor dolostone) of the lower Shibanman Member record time-equivalent strata deposited during transgressions (Fig. 6).

The upper Doushantuo δ13C excursion apparently predates the Miaoho Member and shows significant local variations. The temporal extension and magnitude of the δ13C excursion seem to be lithologically dependent. The most negative and temporally extensive δ13C values occur in thinly bedded dolostones and limestones with shaly partings or very thin (commonly < 5 cm) shale interbeds in Jiulongwan, Xiangerwan, and Zhimaping sections (Fig. 6A–C). When these particular lithologies disappear in Miaoho, Juquiao and Qinglinkou sections, the magnitude and temporal extension of the δ13C excursion are much smaller (Fig. 6D–F). In Jiulongwan, Xiangerwan and Miaoho sections (Fig. 6A, B and D), negative δ13C values start before S-1 and shift toward positive after the Member IV black shales. In contrast, in Zhimaping and Qinglinkou sections, the negative δ13C shift coincides or slightly postdates S-1. Such regional δ13C heterogeneity raises uncertainties on which δ13C values should be representative of the Ediacaran seawater isotope signature.

Negative δ13C values are also found across S-3 in the lower Dengying Formation, particularly in sections where siliceous shales of the Miaoho Member are present (Fig. 6C–F). In these sections, the magnitude of the δ13C “anomaly” is comparable to that of the upper Doushantuo δ13C excursion, although we suspect that negative δ13C values at this interval are most likely of diagenetic origin because (1) in sections where the siliceous shales are absent (Fig. 6A and B), δ13C values only show a minor shift down to ≥ −1‰; (2) the most negative δ13C values (≤ −5‰) are only found in dolostones immediately below and/or above the siliceous shales (Fig. 6D and E) or in thin, silicified dolostone interbeds within the Miaoho Member (e.g., Fig. 6C); and (3) the most negative δ13C values occur below a major stratigraphic unconformity (Fig. 6D and E) and are not
regionally persistent. Nonetheless, the shape of the negative δ¹³C shift, particularly those from the Miaoho, Jiuquqiao and Qingleinkou sections (Fig. 6D–F), is identical to that of the upper Doushantu δ¹³C excursion reported from Baiguoyuan (Zhu et al., 2013b), Chenjiayuanzi (Liu et al., 2014), and Tianjiayuanzi (Li et al., 2012) sections. In those sections, negative δ¹³C values start in carbonates below the Doushantu Member IV black shales and shift toward positive a few meters above the black shales. In all those sections, the thickness of their reported Doushantu Member IV is >20 m. The litho- and chemostratigraphic correlation between these sections (Baiguoyuan, Chenjiayuanzi, and Tianjiayuanzi sections) and those in Fig. 6 requires further investigation.

6. The age of the upper Doushantu/Shuram δ¹³C excursion

The stratigraphic framework outlined in Fig. 6 demonstrates that the Miaoho biota and the Miaoho Member are younger than the Doushantu Member IV. The age of 551.1 ± 0.7 Ma was obtained from the top of the Miaoho Member in the Jiujingqiao section (Fig. 5E; Condon et al., 2005). Considering the higher stratigraphic position of the Miaoho Member (and the Miaoho biota) and a major stratigraphic unconformity at the uppermost Haoming Member, the Doushantu Member IV should be much older than ca. 551 Ma. No other precise age constrains are available for the upper Doushantu δ¹³C excursion. A Re–Os age of 595 ± 22 Ma from the base of the Doushantu Member IV in the Jiuqianlong section (Fig. 6A; Zhu et al., 2013a) only roughly constrain the upper Doushantu Formation within a range of 617–573 Ma.

The upper Doushantu δ¹³C excursion has been generally correlated with the Shuram/Wonoka δ¹³C excursion (e.g., Jiang et al., 2007; Zhuo and Xiao, 2007; McFadden et al., 2008; Li et al., 2013; Zhu et al., 2013b; Zhang et al., 2015), but the duration of the Shuram δ¹³C excursion was estimated as from >5 Ma (Bowring et al., 2007; Minguez et al., 2015) up to 50 Ma (e.g., Le Guerroué et al., 2006). On the basis of increasing Sr isotopes, Cui et al. (2015) estimated that the upper Doushantu δ¹³C excursion may have had a minimum duration of 15 Ma. If we take this estimation and assume that the initiation of the upper Doushantu/Shuram δ¹³C excursion coincided with the Gaskiers glaciation at ca. 580 Ma (e.g., Fike et al., 2005), the top of the δ¹³C excursion may be at ca. 565 Ma. In this case, the ocean oxygenation event documented from the Doushantu Member IV black shales (e.g., McFadden et al., 2008; Scott et al., 2008; Kendall et al., 2015) may be also older than ca. 565 Ma. Such estimations, however, bear too many uncertainties and can only be used as a rough reference. What is certain is that the Miaoho biota, previously assumed as coincident with the oxygenation event, should be much younger than the ocean geochemical change recorded in the Doushantu Member IV black shales.

7. Conclusions

Sequence and δ¹³C chemostratigraphic study of the upper Doushantu and lower Denying formations, in combination with new paleontological findings, demonstrates that the Miaoho Member is time-equivalent with the lower Shibanbian Member of the Denying Formation. The 551.1 ± 0.7 Ma age from the top of the Miaoho Member in the Jiuqianqiao section should be much younger than Doushantu Member IV and the upper Doushantu/Shuram negative δ¹³C excursion. If the initiation of the upper Doushantu/Shuram negative δ¹³C excursion coincided with the Gaskiers glaciation at ca. 580 Ma, the ocean oxygenation event documented from the Doushantu Member IV black shales may be older than 560 Ma. The data also reveal significant regional δ¹³C heterogeneity across the Doushantu-Denying transition, part of which must have been resulted from diagenetic alteration across stratigraphic unconformities. The magnitude and temporal extension of the upper Doushantu δ¹³C excursion are lithologically dependent, raising uncertainties on the representative seawater isotope signature.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jprecamres.2015.10.007.

References


