The stratigraphic complexity of the middle Ediacaran carbon isotopic record in the Yangtze Gorges area, South China, and its implications for the age and chemostratigraphic significance of the Shuram excursion

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Abstract: The middle Ediacaran Shuram excursion represents the most pronounced negative carbon isotopic shift in Earth history, and has been considered as evidence for a profound disturbance to the global carbon cycle and proposed as a key chemostratigraphic marker for Ediacaran stratigraphic subdivision and global correlation. Previous study has revealed a pronounced negative $\delta^{13}\text{C}$ shift (EN3) in the upper Doushantuo Formation of South China, which has been interpreted as an equivalent of the Shuram excursion. Detailed $\delta^{13}\text{C}$ investigation of multiple sections of the Ediacaran Doushantuo Formation around the Huangling Anticline, western Hubei Province, South China, indicates that the $\delta^{13}\text{C}$ variations in the upper

Doushantuo Formation is more complex than previously reported. In the western region of the Huangling anticline, a moderately positive $\delta^{13}\text{C}$ excursion (here termed the Diaoyapo positive excursion) bisects two strongly negative $\delta^{13}\text{C}$ excursions (here termed the Jiuqunao negative excursion and the younger Miaohe negative excursion), with a ~551 Ma ash bed capping the Miaohe negative excursion. In the central region, there is only one negative $\delta^{13}\text{C}$ excursion, whereas in the eastern region, the negative $\delta^{13}\text{C}$ excursion is absent. The variable stratigraphic expression of these $\delta^{13}\text{C}$ excursions is most parsimoniously interpreted as reflecting local facies variation, diagenesis, and/or a cryptic unconformity. The more complete but more complex $\delta^{13}\text{C}$ chemostratigraphic record in the western region of Huangling Anticline implies that, depending on how this record is correlated with the Shuram excursion, the latter may be significantly older than 551 Ma if it does represent a global chemostratigraphic marker.

Key words: Shuram $\delta^{13}\text{C}$ anomaly, chemostratigraphy, Ediacaran Period, Doushantuo Formation, South China

1. Introduction

As the most pronounced negative carbon isotopic shift in Earth history (Grotzinger et al., 2011) and a potential chemostratigraphic tool for Ediacaran subdivision and global correlation (Xiao et al., 2016), the middle Ediacaran Shuram excursion and its possible equivalents have been reported in many places around the world, including the eponymous Shuram Formation in Oman (Burns and Matter, 1993;

Fike et al., 2006; Le Guerroué et al., 2006a; Osburn et al., 2015), the upper Doushantuo Formation in South China (EN3, Jiang et al., 2007; Lu et al., 2013; McFadden et al., 2008; Wang et al., 2012; Zhou and Xiao, 2007), the Wonoka Formation in Adelaide Rift Complex of South Australia (Calver, 2000; Husson et al., 2015), the Johnnie Formation in western United States (Bergmann et al., 2011; Kaufman et al., 2007; Verdel et al., 2011), the Zhuya Formation in the Patom Complex of central Siberia (Pokrovskii et al., 2006), the Girssta Limestone in Shetland, Scotland (Prave et al., 2009), the Leivset marble of the Scandinavian Caledonides (Melezhik et al., 2008), the Marra Member of the Dabis Formation in southern Namibia (Wood et al., 2015), and the Gametrail Formation in the Wernecke Mountains of northwestern Canada (Macdonald et al., 2013). While some researchers argue that the Shuram excursion may have been caused by meteoric or hydrothermal diagenesis of the carbonate sediments (Derry, 2010; Knauth and Kennedy, 2009; Loyd et al., 2015) or by carbonate authigenesis (Schrage et al., 2013), others support a primary origin (e.g., Osburn et al., 2015). The age and duration of the Shuram excursion is uncertain, although it is often stated that the Shuram excursion terminated at ~551 Ma (e.g., Lu et al., 2013).

To date, most examples of $\delta^{13}\text{C}$ excursions correlative to the Shuram excursion show a simple stratigraphic pattern with a sharp shift to negative $\delta^{13}\text{C}$ values followed by slow recovery to positive values (Grotzinger et al., 2011). The upper Doushantuo Formation around the Huangling Anticline, western Hubei Province, South China, however, gives a more complex picture. Whereas the Shuram excursion is expressed

67 in the upper Doushantuo Formation as a single negative excursion at some sections
68 (for example, EN3 at the Jiulongwan section, McFadden et al. 2008), other sections
69 contain two negative excursions bisected by a moderately positive excursion (An et al.,
70 2015; Condon et al., 2005; Lu et al., 2013). This complexity raises important questions
71 about the chemostratigraphic correlation of the upper Doushantuo Formation around
72 the Huangling Anticline, and leads to debates on the chemostratigraphic correlation
73 between $\delta^{13}\text{C}$ excursions in the upper Doushantuo Formation and the Shuram
74 excursion elsewhere. For example, Lu et al. (2013) and Zhu et al. (2013b) argue that
75 the carbonate unit recording the in-between positive excursion is a large block of
76 olistostrome; hence, only two negative excursions represent true chemostratigraphic
77 signals preserved in situ, and together they are correlated with EN3 and with the
78 Shuram excursion. An et al. (2015) question the olistostrome interpretation on the
79 basis of regional consistency of the in-between positive excursion. They instead
80 propose that the lower negative excursion alone is equivalent to EN3 and to the
81 Shuram excursion, and that the in-between positive excursion and upper negative
82 excursion are considered as correlatives of the Hamajing and Shibantan members,
83 respectively, of the Dengying Formation that overlies the Doushantuo Formation. This
84 reinterpretation, if correct, would have major impacts on regional stratigraphic
85 correlation, and would entail a reevaluation of evolutionary and environmental
86 significance of the rich paleontological and geochemical data from the Miaohe and
87 Shibantan members (Chen et al., 2014; Kendall et al., 2015; Li et al., 2015; Och et al.,
88 2016; Xiao et al., 2002). Furthermore, how to correlate two negative excursions in the

upper Doushantuo Formation with the Shuram excursion would determine the relevance of the 551.09 ± 1.02 Ma date, which comes from an ash bed atop of the upper negative excursion, to the age of the Shuram excursion.

To further understand the $\delta^{13}\text{C}$ chemostratigraphic complexity of the upper Doushantuo Formation, we investigate a number of Ediacaran sections around the Huangling Anticline. Our data support previous observation that there are two negative excursions separated by an in-between positive excursion in the western region, one negative excursion (EN3) in the central region, and no negative excursion in the eastern region of the Huangling Anticline. This spatial pattern is inconsistent with the olistostrome interpretation, and an integration of biostratigraphic and chemostratigraphic data also questions An et al.'s (2015) correlation of the Miaohé and Shibantan members. Instead, the variable stratigraphic expression of the negative $\delta^{13}\text{C}$ excursions in the upper Doushantuo Formation may be related to local facies variation, diagenesis, and/or cryptic unconformities. However, our data do not directly address and leave the open question whether the lower or upper negative excursion, or both together is equivalent to the Shuram excursion. Thus, if the lower negative excursion alone is equivalent to the Shuram excursion, as An et al. (2015) suggested, then the Shuram excursion might be significantly older than 551 Ma.

2. Methods

We measured more than 20 Ediacaran sections around the Huangling Anticline in western Hubei Province in the past two decades. Some paleontological and

chemostratigraphic data have been published previously (McFadden et al., 2008; McFadden et al., 2009; Xiao, 2004; Xiao et al., 2012; Xiao et al., 2002; Zhou et al., 2012; Zhou and Xiao, 2007; Zhou et al., 2007; Zhou et al., 2005; Zhou et al., 2004). Together with data published by others (e.g., (An et al., 2015; Jiang et al., 2007; Liu et al., 2014b; Liu et al., 2013; Lu et al., 2013; Zhu et al., 2013b; Zhu et al., 2007), these measured sections provide a more complete view of the regional variation of lithostratigraphic and chemostratigraphic variations. Among these sections, we choose the Qinglinkou, Miaohe, Liaojiagou, Zhimaping, and Gaolan sections in the western region, the Jiulongwan, Zhengjiatang, Tianjiayuanzi, and Baiguoyuan sections in the central, and Niuping sections in the eastern region of the Huangling Anticline area as representative sections (Fig. 1) to establish a regional litho- and chemostratigraphic framework.

Carbonate samples were collected in 0.2–1.0 m stratigraphic intervals for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses at the State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. An aliquot of 80 to 100 μg of each powder sample drilled on polished slabs was reacted with orthophosphoric acid for 150–200 s at 72 °C in a Kiel IV carbonate device connected to a MAT 253. The analytical precision was better than $\pm 0.05\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ values. Results are reported as per mil deviation from the Vienna Pee Dee Belemnite (VPDB) standard (Table 1).

3. Lithostratigraphic variations of the upper Doushantuo Formation around the

Huangling Anticline

Overlying terminal Cryogenian diamictite of the Nantuo Formation and underlying terminal Ediacaran dolostone of the Hamajing Member of the Dengying Formation, the Doushantuo Formation as a whole can be easily correlated around the Huangling Anticline. The Doushantuo Formation generally consists of four members, they are cap dolostone unit (Member I) at the base, followed upsection by interbedded dolostone and black shale (Member II), carbonate (Member III), and black shale (Member IV) at the top (e.g., Zhou and Xiao, 2007). Our recent field investigations indicate that the cap dolostone of Member I and interbedded dolostone and black shale of Member II can be easily traced and mappable around the Huangling Anticline, whereas the lithostratigraphy of the upper Doushantuo Formation shows greater variations among sections from the eastern, central, and western regions of the Huangling Anticline area (Figs. 1–4).

3.1. Eastern region

In the eastern region of the Huangling Anticline area, the upper Doushantuo Formation is characterized mainly by dolostones, the top black shale unit is thin, for example, less than 1 m thick at Jiangjiapo section, or even absent in some places, including the Niuping section (Fig.3)(Liu et al., 2013).

3.2. Central region

In the central region of the Huangling Anticline area, the upper Doushantuo

Formation generally consists of a carbonate unit (Member III) succeeded by a black shale unit (Member IV), with some lithostratigraphic variations in Member III as shown in Fig. 3. In the east-central region, for example at the Tianjiayuanzi section (Lu et al., 2012; Zhou et al., 2012), Member III (~50 m thick) consists mainly of medium to thick-bedded dolostone with chert nodules/bands yielding abundant acanthomorphic acritarchs (Liu et al., 2014b; McFadden et al., 2009; Zhou et al., 2007), and thin-bedded dolostone at the top. The overlying Member IV is composed of ~20 m of black shales which is overlain by the Hamajing Member dolostone (~20 m thick) and the Shibantan Member bituminous limestone of the Dengying Formation. Similarly, at the Baiguoyuan section, Member III is about 30 m thick and consists of dolostone with chert nodules in the lower part. Member IV is also characterized by ~20 m of black shales which are overlain by the Dengying Formation dolostone (Zhu et al., 2013b).

In the west-central region, stratigraphic successions are similar to those in east-central region, but there is a limestone unit in Member III. At the Jiulongwan section (McFadden et al., 2008; Zhou et al., 2012; Zhu et al., 2013), for example, Member III is composed of a lower dolostone unit (~30 m thick; medium-bedded dolostone with chert nodules/bands, followed by thin-bedded dolostone), an upper limestone unit (~25 m thick; ribbon rocks, or thin-bedded limestones intercalated with silty dolostone layers), and ~0.3 m of dolostone at the top. Member IV is ~10 m of black shales with large carbonate concretions, which is overlain by the Hamajing Member dolostone (~20 m thick) and the Shibantan Member limestone of the

Dengying Formation. Similarly, at the Zhengjiatang section (Fig. 1; 31°13.898'N, 110°58.220'E), Member III begins with ~30 m of thick-bedded grey dolostones with chert bands, followed upsection by ~17.5 m of medium- to thin-bedded grey dolostone, ~13.5 m of thin-bedded light purple dolostone, ~13 m of ribbon limestone, and ~4 m of thin-bedded dolostone at the top. Member IV is about 3 m thick, and consists of black shale, which is overlain by dolostone of the Hamajing Member of the Dengying Formation. The Zhengjiatang section is close to the Xiangerwan section described in An et al. (2015), and both have similar stratigraphic sequence for the upper Doushantuo Formation.

3.3. Western region

In the western region of the Huangling Anticline area, five sections including the Qinglinkou, Miaohe, Liaojiagou, Zhimaping, and Gaolan were studied. There, the upper Doushantuo Formation has a more complex stratigraphic succession than in the eastern and central regions (Fig. 3). It consists of four units—in ascending order, a lower carbonate unit, a lower black shale unit, an upper dolostone unit, and upper black shale unit (i.e., the Miaohe Member in An et al., 2015). This stratigraphic succession is very consistent in the western region, although there are some variations in lower carbonate unit (traditionally regarded as Member III), which consists of a lower dolostone and an upper limestone in the northwestern region (e.g., the Gaolan, Zhimaping, and Liaojiagou sections) but of only dolostone in the southwestern region (e.g., the Qinglinkou and Miaohe sections).

At Qinglinkou, the lower carbonate unit consists mainly of ~50 m of dolostone, with chert nodules/bands in the lower part and intraclasts in the upper part. The lower black shale unit is ~1 m thick, which is followed by 10 m of dolostone of the upper dolostone unit, and ~7 m of silicified black shales of the upper black shale unit at the top of the Doushantuo Formation. The upper black shale unit is overlain by the Hamajing Member dolostone (~5 m thick) and the Shibantan Member limestone of the Dengying Formation.

At Miaohu (Fig. 2B, D), the lower carbonate is composed of dolostone with chert nodules and bands. The lower black shale unit is ~2.5 m thick, followed by ~6.5 m dolostone of the upper dolostone unit. The upper black shale unit is ~23 m thick, and consists of black shales, thin-bedded chert, and silicified black shales in the lower, middle, and upper parts, respectively. Abundant and morphologically diversified macroscopic algae fossils preserved as carbonaceous compressions were found in the lower part of the black shales (Xiao et al., 2002). The upper black shale unit is overlain by the Hamajing Member dolostone (~5 m thick) and the Shibantan Member limestone of the Dengying Formation.

At Liaojiagou (31°00.263'N, 110°52.067'E), the lower carbonate unit consists of ~10 m of medium-bedded dolostone with chert bands in the lower part, and ~12 m of limestone (ribbon rocks). The lower black shale unit is ~2 m thick, followed by ~7.5 m of thick-bedded dolostone, and ~10 m of silicified black shales, which is overlain by the Hamajing Member dolostone (~5 m thick) and the Shibantan Member limestone of the Dengying Formation.

At Zhimaping, the lower part of Member III is not exposed, and the exposed section of the lower carbonate unit consists of ~3 m of medium-bedded dolostone, ~18 m of thin-bedded dolostone, and >26 m of thin-bedded limestone. The lower black shale unit and its contact with the underlying limestone and the overlying dolostone are not exposed along the road section at Zhimaping. The exposed upper dolostone unit is ~12 m thick, and its contact with the upper black shale unit is also covered. The upper black shale unit is ~20 m thick and silicified, with macroscopic algae fossils occurring in the lower part (An et al., 2015). It is overlain by the Hamajing Member dolostone (~2.8 m thick) and the Shibantan Member limestone of the Dengying Formation. The Zhimaping section in the present study is lithostratigraphically similar to that reported by An et al. (2015), except the upper dolostone unit is much thicker and the Hamajing Member dolostone is not shown in their stratigraphic column.

At Gaolan, the lower part of the Member III of the Doushantuo Formation is covered by road construction. The exposed section of the lower carbonate unit consists of ~6 m of light purple thin-bedded dolostone and ~12 m of limestone (ribbon rocks)(Fig. 2C). The lower black shale unit is ~3 m thick, and contains large carbonate concretions. The upper dolostone unit is composed of ~15 m of dolostone, and at the top of the Doushantuo Formation is a ~10-m-thick unit of black shale, which is overlain by the Dengying Formation dolostones (Fig. 2A).

Lu et al. (2013) and Zhu et al. (2013) reported the upper dolostone unit with positive $\delta^{13}\text{C}$ values at the Jijiawan (Jiuqunao) and Miaohe sections, and interpreted

this dolostone unit as an allochthonous olistostrome due to slumping or faulting. However, its widespread and consistent occurrences in the western region of the Huangling Anticline area and clearly conformable stratigraphic contacts with both overlying and underlying strata indicate the upper dolostone unit is autochthonous, although it is possible that this unit may be locally distorted by faults (e.g., at Jiuqunao) as it is sandwiched within two weak units of black shales. Thus, the lithostratigraphic variations of the upper Doushantuo Formation around the Huangling Anticline area may reflect facies changes (Fig. 4) and/or cryptic disconformities (e.g., around the Doushantuo/Dengying boundary at Niuping section), rather than olistostromes, and the stratigraphic sequence of the upper Doushantuo Formation is more complete in the western than in eastern region of the Huangling Anticline area.

4. Stratigraphic variations of $\delta^{13}\text{C}$ in the upper Doushantuo Formation

$\delta^{13}\text{C}$ profiles of the Ediacaran successions in the Yangtze Gorges area (southern part of the Huangling Anticline, Fig. 1) have been reported by many researchers (Jiang et al., 2007; Lambert et al., 1987; Sawaki et al., 2010; Yang et al., 1999; Zhu et al., 2013b; Zhu et al., 2007). Generally the $\delta^{13}\text{C}$ curves show, in chronostratigraphic order, 1) negative $\delta^{13}\text{C}$ values (EN1) in the cap dolostone; 2) a pronounced positive $\delta^{13}\text{C}$ excursion (EP1) in the lower Doushantuo Formation; 3) a negative $\delta^{13}\text{C}$ excursion (EN2) in the middle Doushantuo Formation; 4) a positive $\delta^{13}\text{C}$ excursion (EP2) in the upper Doushantuo Formation; 5) a pronounced negative $\delta^{13}\text{C}$ excursion (EN3) in the upper Doushantuo Formation; 6) a positive $\delta^{13}\text{C}$ excursion (EP3) in the

lower Dengying Formation; followed by 7) a stable $\delta^{13}\text{C}$ plateau (EI) in the middle and upper Dengying Formation, and 8) a pronounced negative $\delta^{13}\text{C}$ excursion (EN4) immediately below the Ediacaran–Cambrian boundary (Zhou and Xiao, 2007). This carbon isotopic curve is generally consistent in South China Block (Jiang et al., 2007; Jiang et al., 2011; Zhu et al., 2013b; Zhu et al., 2007), and it generally agrees with the composite carbon isotope curve compiled by Halverson et al. (2005) and could be used to subdivide and correlate the Ediacaran System (Narbonne et al., 2012; Xiao et al., 2016).

However, deviations from the general description of Zhou and Xiao (2007) have been noted in various $\delta^{13}\text{C}$ profiles of the upper Doushantuo Formation at different sections in the Yangtze Gorges area and other regions in South China. In particular, additional $\delta^{13}\text{C}$ excursions and variations in the magnitude and stratigraphic expression of these excursions have been noted in the literature (Zhu et al., 2007, 2013; Zhou et al., 2012; Liu et al., 2013, 2014; An et al., 2015), suggesting that the $\delta^{13}\text{C}$ chemostratigraphic patterns of the upper Doushantuo Formation may be more complex than previously appreciated. This complexity is confirmed in the present study.

One of the most significant developments in the past few years is the recognition of two negative $\delta^{13}\text{C}$ excursions in the western region of the Huangling Anticline, in strata that are traditionally correlated with the upper Doushantuo Formation corresponding to EN3 at the Jiulongwan section (Zhou and Xiao, 2007; McFadden et al., 2008). This was first noted in the Jijiawan (Jiuqunao) section, where a negative

$\delta^{13}\text{C}$ excursion down to $\sim -7\text{‰}$ is present in the upper Doushantuo Formation, but this negative excursion is succeeded by positive values in the dolostones (= upper dolostone unit in this paper) below the Miaohé shale (Condon et al., 2005). Similar $\delta^{13}\text{C}$ patterns were confirmed at several other sections in the western region of the Huangling Anticline (Lu et al., 2013; An et al., 2015; this study). This new development leads to a controversy about the correlation of the upper Doushantuo Formation between the western and central regions of the Huangling Anticline. Lu et al. (2013) argue that the positive excursion is recorded in an olistostrome and thus represents a chemostratigraphic artifact. Contrary to the traditional correlation, An et al. (2015) contend that only the negative $\delta^{13}\text{C}$ excursion in lower carbonate unit is equivalent to EN3, and the upper dolostone and upper black shale that record the succeeding positive and negative $\delta^{13}\text{C}$ excursion are equivalent to the Hamajing and Shibantan members of the Dengying Formation (Fig. 5). To avoid confusion resulting from different correlation models, we propose a different set of terms to describe the $\delta^{13}\text{C}$ excursions in the western region of the Huangling Anticline: the negative $\delta^{13}\text{C}$ excursion in the upper part of the lower carbonate unit is here named the Jiuqunao negative excursion, the succeeding positive excursion in the upper dolostone unit is named the Diaoyapo positive excursion, and the negative excursion at the top of the upper dolostone unit is named the Miaohé negative excursion. These names are derived from geographic localities in the Jiuqunao-Miaohé area in the southwestern region of the Huangling Anticline.

New $\delta^{13}\text{C}$ data generated in this study confirm that this more nuanced

chemostratigraphic pattern, like the lithostratigraphic succession described above, is very consistent in the western region of the Huangling Anticline, thus disfavoring the olistostrome interpretation. For example, at the Liaojiagou, Zhimaping, and Gaolan sections, the Jiuqunao negative $\delta^{13}\text{C}$ excursion is very well developed, spanning >20 m of limestone as opposed to ~20 m of dolostone at the Qinglinkou and Miaohe sections. In all these sections, $\delta^{13}\text{C}$ returns to positive values (Diaoyapo positive $\delta^{13}\text{C}$ excursion) in the upper dolostone unit, but plunges to negative values again (Miaohe negative $\delta^{13}\text{C}$ excursion) in the uppermost meters of the upper dolostone unit, with the most negative $\delta^{13}\text{C}$ value around -10‰ (VPDB) at the Gaolan section (Fig. 3).

In contrast, there is only one pronounced negative $\delta^{13}\text{C}$ excursion (EN3) in the upper Doushantuo Formation in the central region of the Huangling Anticline area (Fig. 3). At the Jiulongwan and Zhengjiatang sections, this negative excursion begins and reaches a nadir of -10‰ in the dolostone of Member III, continues into overlying limestone of Member III at -10‰ , but shows sign of recovering just below Member IV. At the Baiguoyuan and Tianjiayuanzi sections, as well as the Chenjiayuanzi section that is just a few hundred meters from the Tianjiayuanzi section (Liu et al., 2014a), there is no limestone in Member III and $\delta^{13}\text{C}$ values continue to decrease sharply toward the top of Member III, appearing to be top-truncated relative to those at Jiulongwan and Zhengjiatang (Fig. 3). The stratigraphic expanse of EN3 is thus dependent on the thickness of the limestone unit in Member III.

In sharp contrast to the central and western regions, EN3 is completely absent in the eastern region of the Huangling Anticline area. For example, $\delta^{13}\text{C}$ values of the

upper Doushantuo Formation at the Niuping section are entirely in the positive territory (Liu et al., 2013). This is also seen at the Jiangjiapo section (Pengju Liu, personal communication). Indeed, even the lower Doushantuo Formation, save for the cap carbonate, is characterized by positive $\delta^{13}\text{C}$ values without any trace of EN2, making it difficult to correlate with the Jiulongwan section using $\delta^{13}\text{C}$ chemostratigraphic data (Xiao et al., 2012).

5. Discussion

5.1. Litho- and chemostratigraphic correlations

The variations in lithostratigraphy and thickness of the upper Doushantuo Formation, even within a few tens of kilometers of the Huangling Anticline, make stratigraphic correlation difficult. However, the strata above and below the upper Doushantuo Formation, i.e., Member II black shales and Hamajing Member, respectively, are very consistent around the Huangling Anticline, allowing us to bracket the upper Doushantuo Formation. Thus, traditionally, upper Doushantuo Formation bracketed between Member II black shale and Hamajing dolostone is correlated around the Huangling Anticline despite its lithostratigraphic variations (Fig. 4).

Recently, in a radical deviation from the traditional model, An et al. (2015) correlate the lower black shale unit, upper dolostone unit, and Miaohe shale unit in the western region of the Huangling Anticline area, respectively with the black shale of Member IV, dolostone of the Hamajing Member, and limestone of the Shibantan

Member in the central region of the Huangling Anticline (e.g., the Jiulongwan and Tianjiayuanzi sections) (Fig. 5). This correlation contradicts the traditionally accepted stratigraphic framework, which uses black shales in the uppermost Doushantuo Formation as a lithostratigraphic marker (Ding et al., 1996; Liu, 1991). This revised correlation also introduces black shale to the Shibantan Member, which is previously considered to consist of bituminous limestone with no trace of black shale.

As supporting evidence, An et al. (2015) point to the lack of macroalgal fossils in Member IV at the Jiulongwan section. In the western Huangling Anticline, abundant macroalgal fossils occur in the upper black shale unit or the Miaohu Member at the Miaohu, Zhimaping, and Maxi sections (Xiao et al., 2002; An et al., 2015), whereas no fossils have been discovered from the lower black shale unit. Thus, An et al. (2015) favors a correlation of Member IV in the central region with the non-fossiliferous lower black shale rather than the fossiliferous Miaohu Member in the western region. However, stratigraphic correlation based on the absence of macroalgal fossils (negative evidence) can be problematic, given the taphonomic vagaries of these soft-bodied fossils. Indeed, the upper black shale unit can be non-fossiliferous at many sections in the western region (e.g., Qinglinkou and Jiuqunao sections).

On the contrary, the presence of fossils (positive evidence) can provide a biostratigraphic test of An et al.'s (2015) correlation model, which predicts that the Miaohu Member in the western region and the Shibantan Member in the central region would be biostratigraphically correlated and contain similar fossils. Although both members are fossiliferous (Chen et al., 2013; Chen et al., 2014; Ding et al., 1996;

Meyer et al., 2014; Xiao et al., 2002), the fossils assemblages in the Miaohé and Shibantan members seem to be distinct. The Miaohé Member contains more than two dozens of macroalgal species, none of which have been reported from the Shibantan Member, save for the possible presence of *Vendotaenia*-like and *Enteromorphites*-like fossils in both formations (Xiao et al., 2002; Yin and Gao, 1995; Xiao et al., unpublished). In contrast, the Shibantan Member contains abundant Ediacara-type fossils, tubular fossils, and trace fossils characteristic of the Nama assemblage (Chen et al., 2013, 2014). None of these fossils have been found in the Miaohé Member. Instead, the Ediacara-type fossils reported from the Miaohé Member, including *Eoandromeda* and *Beltanelliformis*, are both characteristic of the older White Sea assemblage (Xiao et al., 2002; Zhu et al., 2008). Thus, from a biostratigraphic point of view, the Miaohé Member seems to be older than, not coeval with, the Shibantan Member.

The overlying Dengying Formation consists of the Hamajing Member dolostone, Shibantan Member bituminous limestone, and Baimatuo Member dolostone. This classical lithostratigraphic sequence can be seen in the central and western region of the Huangling Anticline area, suggesting a consistent stratigraphic sequence of the Dengying Formation. If the Dengying Formation is coeval in the central and western regions, the An et al.'s (2015) correlation of Member IV in the central region with the lower black shale unit in the western region requires a significant sedimentary break between Member IV and the overlying Dengying dolostone in the central region. However, sedimentary evidence for this predicted break has not been found in the

field. Additionally, An et al.'s (2015) correlation of the upper dolostone unit in the western region with the Hamajing Member dolostone of the Dengying Formation in the central region implies that the Miaohé, Hamajing, and Shibantan members in the western region be equivalent to the Shibantan Member in the central region. This predicted correlation, however, does not live with the lithostratigraphic and biostratigraphic consistency of the Shibantan Member in both the central and western regions.

In light of these difficulties in reconciling An et al.'s (2015) correlation and the biostratigraphic and lithostratigraphic data, we favor the traditional correlation that Member IV in the central region is correlated with the sum of the lower black shale unit, the upper dolostone unit, and the Miaohé Member black shales in the western region (Fig. 4). This correlation implies facies change from west to east, with the upper dolostone unit in the western region wedging and eventually disappearing toward the central region, resulting in the merging of the lower and upper black shale units to form Member IV. Further to the east in the eastern region, all three units wedge out to a cryptic unconformity (Fig. 4). This correlation suggests that the lithostratigraphic sequence of the upper Doushantuo Formation is more complete in the western and central regions than in eastern region of the Huangling Anticline area.

The traditional correlation would also imply that the upper Doushantuo Formation yields more complete carbon isotope profiles in the western region than in the central and eastern regions of the Huangling Anticline. This expectation is met by the observation that two negative $\delta^{13}\text{C}$ excursions (Jiuqunao and Miaohé negative

excursions) occurs in the western region, only one in the central region—i.e., EN3 (McFadden et al, 2008; Zhou and Xiao, 2007) or DOUNCE (Lu et al., 2013; Zhu et al., 2013), and none in the eastern region. This correlation indicates that EN3 in the central region is correlated with the Jiuqunao negative $\delta^{13}\text{C}$ excursion in the western region, whereas the Diaoyapo positive and Miaohé negative $\delta^{13}\text{C}$ excursions were not preserved in the central region due to the facies disappearance of the upper dolostone unit, and all three excursions are missing in the eastern region due to a cryptic unconformity.

Alternatively, the lower black shale unit in the western region can be correlated with Member IV in the central region as in An et al.'s (2015) model, but the upper dolostone unit, Miaohé Member shale, and the ~5 m Hamajing Member in the western region may be equivalent to the Hamajing Member in the central region (Fig. 6). The latter part of this correlation is different from An et al.'s (2015) model. An appealing aspect of this alternative model is that the Miaohé Member in the western region may wedge into an erosional surface within the Hamajing Member in the central region (S3 in fig. 6, An et al., 2015). Although this alternative correlation is consistent with available biostratigraphic data, it predicts a complex subsidence history in the Huangling Anticline area: the central region was deeper than the western region before the mid-Hamajing erosional surface developed, but shallower after (Fig. 6). More field investigation is needed to further test this alternative correlation. In the present study, we prefer the traditional correlation framework (Fig. 4).

5.2. Implications to the Shuram excursion

The Shuram excursion in Oman (Burns and Matter, 1993; Fike et al., 2006; Le Guerroué et al., 2006a; Osburn et al., 2015), and its possible equivalents in the Wonoka Formation of South Australia (Calver, 2000) and Johnnie Formation of southeast California (Verdel et al., 2011), are characterized by a rapid drop in $\delta^{13}\text{C}$ values to the most negative values of ca. -12‰ , followed by a slow recovery to $\delta^{13}\text{C}$ values of 0‰ in the lower Buah Formation (Fike et al., 2006), in the upper Jonnie Formation (Verdel et al., 2011), and in the upper Wonoka Formation (Calver, 2000), respectively. The carbon isotope curves from these areas closely match with each other, suggesting that this may be a global event in the middle Ediacaran Period (Verdel et al., 2011).

However, emerging chemostratigraphic data suggest that an additional negative $\delta^{13}\text{C}$ excursion may immediately follow the Shuram excursion. For example, the composite $\delta^{13}\text{C}$ curve for the Johnnie Formation, compiled from several sections (Kaufman et al., 2007; Bergmann et al., 2011; Verdel et al., 2011), shows two negative excursions separated by positive $\delta^{13}\text{C}$ values (Verdel et al., 2011), similar to the Jiuqunao-Diaoyapo-Miaohe excursions in the upper Doushantuo Formation in the western region of the Huangling Anticline (Fig. 3). Verdel et al. (2011) suggested that the lower negative excursion in the Johnnie Formation is equivalent to the Shuram excursion in Oman and the upper negative excursion in the Johnnie Formation represents an additional event. If correct, then it is likely that EN3 and Jiuqunao excursions are equivalent to the Shuram excursion, and this correlation is supported

by the similar stratigraphic expression of these excursions, all with a rapid declining arm and a slow recovery arm despite the difference in their absolute stratigraphic expanses. The Miaohé negative excursion, on the other hand, could represent a $\delta^{13}\text{C}$ anomaly not recorded in Oman and South Australia. In Oman, the Shuram Formation is mainly composed of shales and siltstones (Le Guerroué et al., 2006a), and the rare occurrences of carbonate beds suitable for carbon isotope analysis together with a sequence boundary at the contact between the Buah Formation and Ara Group (Bowring et al., 2007) means that the preserved $\delta^{13}\text{C}$ record could be incomplete. In South Australia, the $\delta^{13}\text{C}$ profile of the Wonoka Formation only shows the recovery part from the most negative values, and the declining arm of the Shuram excursion is not preserved (Calver, 2000; Husson et al., 2015). Furthermore, the Wonoka excursion is top-truncated by an incision valley, representing a missing record of unknown duration (Calver, 2000; Husson et al., 2015). Thus, it is possible that the Miaohé negative $\delta^{13}\text{C}$ excursion is not preserved in Oman and South Australia.

This correlation raises an important question about the geological age and duration of the Shuram excursion. It has often been stated that the Shuram excursion ended at ~551 Ma (Le Guerroué et al., 2006b; Lu et al., 2013), based on the assumption that the Miaohé excursion is equivalent to the Shuram excursion and a zircon U-Pb age of 551.09 ± 1.02 Ma from an ash bed just above the Miaohé Member at the Jijiawan or Jiuqunao section (Condon et al., 2005). The present study, however, indicates that the Miaohé excursion may post-date the Shuram, and the 551 Ma only provides a minimum age of the Shuram excursion (Fig. 3). Accepting the Re-Os age

of 591.1 ± 5.3 Ma as the depositional age of the lower Member IV (Zhu et al., 2013a), EN3 and hence its likely equivalent—the Shuram excursion—could be tens of millions of years older than 551 Ma. This further implies that the duration of the Shuram excursion could be much less than previously thought by some geologists (Le Guerroué et al., 2006b), and a short duration can be used to evaluate the different hypotheses about the origin of this excursion (Bjerrum and Canfield, 2011; Derry, 2010; Grotzinger et al., 2011; Knauth and Kennedy, 2009; Schrag et al., 2013).

The stratigraphic expression of EN3 in different sections in the Huangling Anticline area indicates that the shape of $\delta^{13}\text{C}$ curve is dependent on the occurrence of thin-bedded limestone. At Qinglinkou and Miaohe, where limestone is absent in the upper Doushantuo Formation, the $\delta^{13}\text{C}$ curve consists of a decreasing and an increasing parts, while at Liaojiagou, Zhimaping, and Zhengjiatang, there is a sustained interval of extremely negative $\delta^{13}\text{C}$ values between the lower decreasing and upper increasing arms, though this interval shows a slightly increasing trend upsection, as seen at the Gaolan section (Fig. 3). The presence and absence of thin-bedded limestone (ribbon rock) in different sections around the Huangling Anticline area may indicate a much complicated local subsidence (depositional water depth) that results in quick lateral facies change and/or unrecognizable sedimentary break.

6. Conclusions

Regional lithostratigraphic and $\delta^{13}\text{C}$ chemostratigraphic investigations of the

upper Doushantuo Formation in the Huangling Anticline area, western Hubei Province, South China indicate that more complete lithostratigraphic sequence and $\delta^{13}\text{C}$ variations occur in sections of the western region. Regional lithostratigraphic correlations suggest that two black shale intervals and an intervening dolostone unit in the upper Doushantuo Formation of the western region is approximately equivalent to the Member IV black shale at the top of the Doushantuo Formation in the central region(e.g., the Jiulongwan section).

The more complete sections of the upper Doushantuo Formation in the western region record two negative $\delta^{13}\text{C}$ excursions (Jiuqunao and Miaohe negative excursions) separated by a positive excursion (Diaoyapo positive excursion), rather than a simple negative excursion (EN3) as recorded in the central region. Circumstantial evidence suggests that the Jiuqunao negative excursion is equivalent to EN3, Shuram, and Wonoka excursions. If true, then the Shuram excursion may be significantly older than 551 Ma.

The stratigraphic complexity of $\delta^{13}\text{C}$ negative excursion in the upper Doushantuo Formation also implies that caution must be exercised when using $\delta^{13}\text{C}$ profile as a tool for stratigraphic correlation. All carbon isotope excursions may not occur at all sections, especially when the sections are dominated by siliciclastic rocks or compromised by sedimentary breaks. $\delta^{13}\text{C}$ chemostratigraphy is most useful in the subdivision and correlation of Ediacaran successions when integrated regional facies analysis and biostratigraphy.

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712 Figure captions

713 Fig. 1. Simplified geological map of the Huangling Anticline area, showing location
 714 of sections. 1, Qinglinkou; 2, Miaohe; 3, Liaojiagou; 4, Zhimaping; 5, Gaolan; 6,
 715 Jiulongwan; 7, Zhengjiatang; 8, Tianjiayuanzi; 9, Baiguoyuan; 10, Niuping; 11,
 716 Jiangjiapo. Dashed lines mark the western, central, and eastern regions of the
 717 Huangling Anticline area.

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719 Fig.2. Field photographs showing outcrops of the upper Doushantuo Formation in the
 720 western region of the Huangling Anticline. A, Gaolan section; B, Miaohe section; C,
 721 thin-bedded limestones (ribbon rocks) at the Gaolan section; D, upper dolostone unit
 722 and the overlying Miaohe Member at the Miaohe section.

723

Fig. 3. Lithostratigraphy and $\delta^{13}\text{C}$ profiles of the upper Doushantuo Formation in the Huangling Anticline area. Dashed lines showing proposed lithostratigraphic correlations, bars in different grey colors show $\delta^{13}\text{C}$ excursions and their correlations among sections, which are numbered as in Figure 1. DY, Dengying Formation; HMJ, Hamajing Member; MM, Miaohé Member; UD, upper dolostone unit; LBS, lower black shale unit; LC, lower carbonate unit; MNE, Miaohé negative $\delta^{13}\text{C}$ excursion; DPE, Diaoyapo positive $\delta^{13}\text{C}$ excursion; JNE, Jiuqunao negative $\delta^{13}\text{C}$ excursion, EN3, Ediacaran negative $\delta^{13}\text{C}$ excursion 3; EP2, Ediacaran positive $\delta^{13}\text{C}$ excursion 2. $\delta^{13}\text{C}$ data sources: Jiulongwan and Tianjiayuanzi sections (Zhou et al., 2012), Baiguoyuan section (Zhu et al., 2007), Niuping section (Liu et al., 2013).

Fig. 4. Favored lithostratigraphic correlation of the upper Doushantuo Formation in the Huangling Anticline area. HMJ, Hamajing member; SBT, Shibantan member. See Figure 1 for section locations and Figure 3 for legends.

Fig. 5. An et al.'s (2015) lithostratigraphic correlation of the upper Doushantuo and lower Dengying formations in the Huangling Anticline area. DY, Dengying Formation; HMJ, Hamajing Member; SBT, Shibantan Member; MM, Miaohé Member; UD, upper dolostone unit; LBS, lower black shale unit; LC, lower carbonate unit. See Figure 1 for section locations and Figure 3 for legends.

Fig. 6. An alternative lithostratigraphic correlation of the upper Doushantuo Formation

746 in the Huangling Anticline area. HMJ, Hamajing Member; SBT, Shibantan Member.

747 See Figure 1 for section locations and Figure 3 for legends.

748

749 Table 1. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data for the upper Doushantuo Formation carbonates in the
750 studied sections.

751

Sample	Depth(m)	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)
Qinglinkou section			
13ZC-28	68.3	-2.1	-2.3
13ZC-29	68.7	-1.9	-2.7
13ZC-31	71	0.6	-1.8
13ZC-32	72.3	2.2	-2.2
13ZC-33	73.7	0.9	-4.7
13ZC-34	74.7	2.1	-1.7
13ZC-35	76.7	3.3	-2.1
13ZC-36	77.7	2.8	-2.0
13ZC-37	78.8	2.8	-1.2
13ZC-38	80.4	-0.5	-1.4
13ZC-38-1	81.2	0.7	-2.2
13ZC-39	83.2	-2.9	-1.5
13ZC-40	84.5	-2.6	-1.6
13ZC-41	85.5	-2.2	-2.6
13ZC-42	85.8	-2.4	-1.8
13ZC-43	86.3	0.9	-2.5
13ZC-45	86.8	1.7	-2.9
13ZC-46	87.8	2.5	-3.9
13ZC-48	88.7	4.5	-3.8
13ZC-49	90.6	3.5	-2.4
13ZC-50	96.4	4.3	-3.3
13ZC-51	97.4	2.8	-3.3
13ZC-52	98.6	3.7	-2.7
13ZC-54	99.4	3.6	-1.6
13ZC-55	100.4	2.3	-1.7
13ZC-56	102.1	3.1	-6.1
13ZC-57	103.1	4.0	-2.6
13ZC-58	104.2	3.8	-4.6
13ZC-59	105.2	3.3	-7.5
13ZC-60	106.2	4.1	-1.6
13ZC-61	107.2	3.4	-7.5
13ZC-63	108.15	3.6	-3.6
13ZC-64	108.95	3.5	-2.4
13ZC-65	109.15	3.8	-3.3
13ZC-66	110.15	3.2	-2.5
13ZC-67	111.15	2.2	-3.5
13ZC-68	112.15	2.4	-4.4

13ZC-69	113.15	2.0	-3.9
13ZC-70	113.4	1.9	-4.1
13ZC-71	114.4	1.8	-5.5
13ZC-72	114.6	-0.3	-5.3
13ZC-73	115.5	-0.2	-4.7
13ZC-75	116.7	0.2	-4.9
13ZC-76	117.7	0.4	-4.9
13ZC-78	118.7	0.3	-5.1
13ZC-80	119.7	-0.5	-5.1
13ZC-81	120.4	-0.4	-2.0
13ZC-82	121.6	-1.0	-3.3
13ZC-83	122.6	-2.2	-2.6
13ZC-84	124.6	-2.3	-1.3
13ZC-85	125.6	-2.9	-1.9
13ZC-86	126.7	-2.9	-1.7
13ZC-87	127.7	-3.0	-2.2
13ZC-88	128.7	-2.9	-1.0
13ZC-89	129.7	-2.2	-1.9
13ZC-90	130.7	-1.5	-2.2
13ZC-91	131.7	-1.6	-3.4
13ZC-92	132.7	-1.2	-3.5
13ZC-93	133.7	-1.1	-2.5
13ZC-94	134.7	-1.1	-1.3
13ZC-95	135.7	-0.7	-1.6
13ZC-96	136.2	-0.5	-3.1
13ZC-97	136.7	-0.5	-2.7
13ZC-98	137.9	0.6	-0.8
13ZC-99	138.7	0.5	-4.2
13ZC-100	140.5	2.8	-4.1
13ZC-101	141	1.8	-0.4
13ZC-102	141.8	4.5	-4.0
13ZC-103	143.1	4.1	-0.7
13ZC-104	143.8	1.9	-0.1
13ZC-105	144.5	1.9	-1.6
13ZC-106	145	1.7	-0.4
13ZC-112	145.5	1.9	-0.1
13ZC-107	146	1.3	-0.4
13ZC-111	146.75	1.0	-1.8
13ZC-108	147	0.7	-2.9
13ZC-110	147.25	0.6	-2.2
13ZC-109	147.5	-0.4	-1.9
13ZC-113	154	-3.0	-4.2
13ZC-114	154.5	-2.8	-5.2

13ZC-115	155	-2.4	-5.2
13ZC-116	155.5	-2.1	-5.0
13ZC-117	156.5	-1.6	-5.3
Miaohe section			
ZC11-85	0	2.3	-4.2
ZC11-86	0.3	2.4	-4.3
ZC11-87	0.7	2.1	-4.3
ZC11-88	1	1.9	-4.2
ZC11-89	1.35	1.7	-4.5
ZC11-90	1.95	2.1	-3.8
ZC11-91	2.25	2.1	-4.8
ZC11-92	2.65	2.9	-4.1
ZC11-93	2.95	2.3	-4.3
ZC11-94	3.25	1.9	-4.5
ZC11-95	3.55	0.6	-2.6
ZC11-96	3.85	0.3	-3.0
ZC11-97	4.15	0.8	-3.6
ZC11-98	4.5	0.6	-5.0
ZC11-99	4.8	0.4	-3.8
ZC11-100	5.2	0.8	-3.4
ZC11-101	5.5	0.8	-3.7
ZC11-102	5.8	0.3	-4.0
ZC11-103	6	0.4	-3.6
ZC11-104	10.5	-0.6	-5.0
ZC11-105	10.8	-0.5	-3.8
ZC11-106	11.2	-1.1	-5.2
ZC11-107	11.5	-0.4	-4.5
ZC11-108	11.8	-1.4	-5.3
ZC11-109	12.15	-1.2	-5.2
ZC11-110	12.45	-1.3	-5.5
ZC11-111	13.05	-3.7	-3.9
ZC11-112	15.55	-6.8	-2.0
ZC11-113	15.85	-6.9	-1.9
ZC11-114	16.15	-6.9	-1.6
ZC11-115	16.45	-6.5	-2.0
ZC11-116	16.75	-6.5	-2.4
ZC11-117	17.05	-6.4	-2.4
ZC11-118	19.05	-5.2	-1.0
ZC11-119	19.35	-5.1	-1.9
ZC11-120	19.65	-4.9	-0.9
ZC11-121	19.95	-4.9	-1.5
ZC11-122	20.25	-4.7	-1.7
ZC11-123	20.55	-4.6	-1.1

ZC11-124	20.85	-4.5	-1.1
ZC11-125	21.25	-3.7	-1.5
ZC11-126	21.55	-3.7	-1.7
ZC11-127	21.75	-3.9	-1.0
ZC11-128	24.25	-1.8	0.3
ZC11-129	24.65	0.8	-3.4
ZC11-130	24.95	1.1	-1.8
ZC11-131	25.35	1.4	-3.0
ZC11-132	25.65	3.2	-1.8
ZC11-133	25.95	2.4	-1.1
ZC11-134	26.25	2.2	-0.6
ZC11-135	26.65	2.8	-0.8
ZC11-136	26.95	1.5	-1.0
ZC11-137	27.35	2.0	-0.8
ZC11-138	27.65	2.2	-3.4
ZC11-139	27.95	2.6	-2.2
ZC11-140	28.25	2.5	-4.5
ZC11-141	28.85	0.8	-3.0
ZC11-142	29.1	1.1	-1.0
ZC11-143	29.4	0.9	-2.3
ZC11-144	29.7	-2.4	-2.9
ZC11-145	30	-2.1	-5.4
ZC11-147	30.6	-5.1	-0.7
ZC11-148	30.95	-7.1	-4.3
ZC11-149	48.45	-3.0	-4.1
ZC11-150	48.6	-2.5	-3.7
ZC11-151	48.7	-2.1	-3.6
ZC11-152	48.9	-2.0	-4.6
ZC11-153	49.1	-1.8	-4.5
ZC11-154	49.2	-1.6	-4.7
ZC11-155	49.4	-1.4	-5.0
ZC11-156	49.65	-1.0	-5.0
ZC11-157	50.05	-1.1	-5.4
ZC11-158	50.25	-1.4	-5.3
ZC11-159	50.75	-1.5	-5.9
ZC11-160	51.35	-0.7	-5.5
ZC11-161	52.35	0.2	-6.4
ZC11-162	53.05	0.4	-6.0
ZC11-163	53.55	3.1	-5.6
ZC11-164	54.15	3.6	-5.0
ZC11-165	54.75	4.1	-5.6
ZC11-166	55.35	3.7	-6.1
ZC11-167	56.35	3.3	-6.3

ZC11-168	56.95	3.9	-5.9
Liaojiagou section			
15LJG-1	32.9	-8.3	-2.9
15LJG-2	32.6	-3.0	-3.8
15LJG-3	32.3	-1.5	0.6
15LJG-4	31.9	0.3	-1.6
15LJG-5	31.4	1.8	-5.4
15LJG-6	30.9	0.0	-6.6
15LJG-7	29.7	2.0	-4.2
15LJG-8	28.7	0.9	-0.8
15LJG-9	28.2	0.7	-4.1
15LJG-10	27.6	0.1	-4.6
15LJG-11	26.6	0.0	-6.3
15LJG-12	26.1	0.6	-5.3
15LJG-13	25.7	0.3	-3.6
15LJG-14	25.4	-2.2	-5.1
15LJG-15	23.4	-7.6	-9.2
15LJG-16	22.8	-7.7	-9.2
15LJG-17	22.3	-5.3	-10.1
15LJG-18	21.8	-8.0	-9.0
15LJG-19	16.8	-8.4	-9.4
15LJG-20	13.6	-8.7	-9.5
15LJG-21	11.6	-8.6	-9.5
15LJG-22	10.6	-7.1	-6.3
15LJG-23	9.8	-8.9	-4.8
15LJG-24	8.8	-8.5	-5.2
15LJG-25	7.8	-8.4	-4.6
15LJG-26	6.8	-7.5	-3.5
15LJG-27	5.8	-5.1	-4.8
15LJG-28	4.3	-0.1	-5.3
15LJG-29	3.3	0.8	-5.3
15LJG-30	1.8	2.3	-7.7
15LJG-31	1	2.3	-2.8
15LJG-32	0	2.0	-2.8
Zhimaping section			
15ZMP-1	0	-0.2	-4.6
15ZMP-2	1	1.2	-4.8
15ZMP-3	2	0.8	-5.0
15ZMP-4	3.5	-7.7	-5.0
15ZMP-5	4.7	-7.9	-5.3
15ZMP-6	6	-9.2	-4.2
15ZMP-7	8	-10.4	-10.7
15ZMP-8	10	-6.9	-5.1

15ZMP-9	12	-7.9	-5.3
15ZMP-10	14.2	-7.5	-5.8
15ZMP-11	16.2	-7.8	-5.1
15ZMP-12	18.6	-7.9	-5.3
15ZMP-13	20.1	-9.5	-3.9
15ZMP-14	22.6	-9.4	-9.8
15ZMP-15	24.2	-9.2	-8.3
15ZMP-16	26.2	-9.2	-9.4
15ZMP-17	27.7	-8.4	-8.6
15ZMP-18	29.7	-9.8	-10.2
15ZMP-19	31.7	-9.3	-10.0
15ZMP-20	33.7	-7.8	-5.5
15ZMP-21	35.2	-8.4	-9.0
15ZMP-22	36.7	-8.8	-9.6
15ZMP-23	38.2	-8.7	-9.5
15ZMP-24	40.2	-8.1	-9.7
15ZMP-25	42.2	-8.1	-9.5
15ZMP-26	44.2	-7.5	-10.0
15ZMP-27	47.2	-7.3	-9.7
15ZMP-28	60	0.2	-5.0
15ZMP-29	61	0.7	-5.9
15ZMP-30	62	0.3	-6.3
15ZMP-31	63	0.1	-6.9
15ZMP-32	64.5	1.1	-3.0
15ZMP-33	65.5	0.6	-6.5
15ZMP-34	66.5	1.5	-2.9
15ZMP-35	67.5	1.0	-4.3
15ZMP-36	68.5	1.4	-2.6
15ZMP-37	69.5	1.9	-1.6
15ZMP-38	70.5	1.9	-4.0
15ZMP-39	71.3	1.3	-2.8
Gaolan section			
13ZC-124	0	-10.4	-8.0
13ZC-125	0.6	-10.4	-8.4
13ZC-126	1	-11.3	-10.8
13ZC-127	1.4	-11.2	-10.8
13ZC-128	1.9	-10.9	-10.0
13ZC-129	2.4	-10.8	-9.9
13ZC-130	2.9	-10.3	-9.8
13ZC-131	3.4	-10.1	-9.6
13ZC-132	3.9	-10.3	-9.7
13ZC-133	4.4	-9.9	-9.4
13ZC-134	4.9	-10.0	-9.7

13ZC-135	5.4	-9.2	-9.1
13ZC-136	5.9	-9.3	-9.4
13ZC-137	6.2	-9.1	-9.0
13ZC-138	6.5	-9.3	-8.9
13ZC-139	6.8	-9.2	-8.7
13ZC-140	7.8	-8.9	-9.1
13ZC-141	8.8	-8.5	-9.4
14ZC-001	9.3	-8.4	-9.2
14ZC-002	9.9	-8.2	-10.2
14ZC-003	10.4	-8.3	-9.3
14ZC-004	10.9	-8.3	-9.1
14ZC-005	11.9	-8.5	-8.2
14ZC-006	12.6	-8.4	-8.5
14ZC-007	13.1	-8.1	-8.5
14ZC-008	13.6	-8.1	-8.3
14ZC-013	14.1	-8.0	-9.9
14ZC-014	14.6	-8.0	-9.9
14ZC-015	15.1	-7.6	-9.2
14ZC-016	15.6	-7.8	-9.4
14ZC-017	16.1	-7.4	-9.9
14ZC-018	16.4	-2.9	-10.2
14ZC-019	17.2	-7.6	-9.9
14ZC-020	17.7	-6.7	-9.0
14ZC-021	20.9	-1.8	-2.8
14ZC-022	21.5	-1.2	-4.2
14ZC-023	22	0.3	-1.1
14ZC-024	22.5	0.2	-1.6
14ZC-025	23	0.1	-3.3
14ZC-026	23.5	0.5	-2.5
14ZC-027	24.5	0.3	-3.6
14ZC-028	25.7	0.5	-2.7
14ZC-029	26.2	1.8	-1.9
14ZC-030	26.7	1.9	-1.7
14ZC-031	27.2	1.3	-1.3
14ZC-032	27.7	1.8	-1.2
14ZC-033	28.2	1.4	-2.9
14ZC-034	28.7	1.4	-3.3
14ZC-035	29	1.2	-3.1
14ZC-036	30	2.2	-3.2
14ZC-037	30.5	2.2	-3.2
14ZC-038	31.3	1.6	-3.4
14ZC-039	31.8	1.6	-5.1
14ZC-040	32.8	-2.0	-3.5

14ZC-041	33.6	-10.7	-4.2
14ZC-042	34.1	-6.3	-1.8
Zhengjiatang section			
14ZC-043	0	4.3	-3.6
14ZC-044	0.3	3.3	-4.3
14ZC-045	0.6	3.0	-3.4
14ZC-046	0.9	3.5	-3.2
14ZC-047	1.2	3.2	-2.6
14ZC-048	1.5	1.5	-3.1
14ZC-049	1.9	1.3	-3.5
14ZC-050	2.2	-2.0	-4.8
14ZC-051	2.5	-1.9	-4.3
14ZC-052	2.8	1.8	-4.0
14ZC-053a	3.1	-0.1	-3.4
14ZC-054	3.2	2.4	-3.9
14ZC-055	3.4	-0.9	-5.2
14ZC-056	3.8	2.8	-2.1
14ZC-057	4.1	3.3	-2.0
14ZC-058	4.45	2.6	-4.1
14ZC-059	4.85	2.2	-4.0
14ZC-060	5.15	1.9	-2.8
14ZC-061	5.45	1.1	-3.4
14ZC-062	5.95	0.5	-3.9
14ZC-063	6.45	-0.3	-2.2
14ZC-064	6.95	0.2	-2.7
14ZC-065	7.45	-1.3	-3.8
14ZC-066	9.45	-0.4	0.5
14ZC-067	10.65	-1.6	-1.0
14ZC-068	13.15	-3.3	-1.3
14ZC-149	50	4.3	-2.2
14ZC-148	50.6	4.6	-1.8
14ZC-146	52.6	5.8	-8.9
14ZC-144	53.6	5.4	-6.6
14ZC-143	54.6	5.4	-2.5
14ZC-142	55.6	5.1	-2.4
14ZC-141	56.6	6.6	-8.8
14ZC-140	57.6	6.5	-7.4
14ZC-139	58.6	6.0	-5.8
14ZC-138	59.6	5.1	-3.0
14ZC-137	62.8	5.0	-3.9
14ZC-135	64	3.8	-4.3
14ZC-134	65	2.8	-4.2
14ZC-133	65.5	3.5	-2.4

14ZC-132	66.5	2.9	-3.8
14ZC-131	67.5	2.9	-1.9
14ZC-130	67.6	0.6	-8.6
14ZC-129	68.6	1.8	-4.4
14ZC-128	69.6	1.7	-3.2
14ZC-127	70.6	1.7	-3.0
14ZC-126	71.6	1.0	-3.2
14ZC-125	72.6	0.8	-3.0
14ZC-069	77.6	1.6	-3.2
14ZC-070	78.6	1.0	-2.7
14ZC-071	79.6	0.3	-3.7
14ZC-072	80.6	-1.8	-2.9
14ZC-073	81.6	-0.8	-2.3
14ZC-074	82.6	0.1	-1.2
14ZC-075	83.6	-0.2	-2.3
14ZC-076	84.6	-1.5	-3.5
14ZC-077	85.1	-1.1	-4.3
14ZC-078	86.1	-6.6	-4.7
14ZC-079	87.1	-4.5	-2.0
14ZC-080	88.1	-4.9	-2.6
14ZC-081	89.1	-5.5	-4.8
14ZC-082	90.1	-4.9	-3.5
14ZC-083	91.1	-7.1	-5.1
14ZC-084	92.1	-6.9	-4.4
14ZC-085	93.1	-7.0	-4.2
14ZC-086	97.1	-9.0	-10.5
14ZC-087	98.1	-9.0	-9.6
14ZC-088	99.1	-9.0	-9.3
14ZC-089	100.1	-8.9	-8.6
14ZC-090	101.1	-8.9	-8.6
14ZC-091	102.1	-8.8	-8.4
14ZC-092	103.1	-8.8	-8.3
14ZC-093	104.1	-8.7	-8.3
14ZC-094	105.1	-8.7	-8.3
14ZC-095	106.1	-8.6	-8.3
14ZC-096	106.6	-8.6	-8.4
14ZC-097	107.6	-8.5	-8.3
14ZC-098	108.6	-8.5	-8.3
14ZC-099	109.6	-8.5	-8.3
14ZC-100	110.2	-8.5	-8.1
14ZC-101	111.2	-8.4	-8.2
14ZC-102	112.2	-8.4	-8.2
14ZC-103	113.2	-8.2	-7.9

14ZC-104	114.7	-6.9	-3.3
14ZC-105	115.7	-8.2	-8.0
14ZC-106	116.7	-8.1	-7.9
14ZC-107	117.7	-8.1	-7.9
14ZC-108	118.7	-7.9	-8.6
14ZC-109	119.7	-7.9	-8.5
14ZC-110	120.7	-7.6	-9.9
14ZC-111	121.4	-7.4	-9.1
14ZC-112	121.8	-6.8	-5.2
14ZC-113	122.4	-6.6	-5.4
14ZC-114	123	-5.2	-6.6
14ZC-115	123.6	-5.7	-4.8
14ZC-116	124.2	-4.4	-3.7
14ZC-117	124.8	-3.3	-1.2
14ZC-118	125.2	-1.0	-1.0
14ZC-119	128.2	0.3	-0.1
14ZC-120	128.4	0.2	-0.1
14ZC-121	128.6	1.0	2.4
14ZC-122	128.8	3.0	-0.9
14ZC-123	129	3.2	2.7
14ZC-124	129.2	3.4	-2.3

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Western Region Central Region Eastern Region

6. Jiulongwan 8. Tianjiayuanzi

Western Region Central Region Eastern Region

2. Miaohe

3. Liaojiagou

6. Jiulongwan 8. Tianjiayuanzi

10. Niuping