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Cyclic cold climate during the Nantuo Glaciation: Evidence from the Cryogenian Nantuo Formation in the Yangtze Block, South China

Xianguo Lang, Jitao Chen, Huan Cui, Ling Man, Kang-Jun Huang, Yong Fu, Chuanming Zhou, Bing Shen

Abstract

Geological and paleomagnetic data indicate that the ice sheets might have extended to low-latitude regions in the Cryogenian (720–635 Ma). The ‘snowball Earth’ hypothesis proposed that the Earth was completely ice-covered during global glaciation. However, the glacial sedimentary record seems to contradict with the snowball Earth hypothesis. Detailed sedimentological investigations of the glacial deposits would provide the first-order constraint on the nature of global glaciation. The Nantuo Formation (~654–635 Ma) in the Yangtze Block of South China has been correlated with the Marinoan snowball Earth. In this study, we conducted systematic sedimentological analyses of six sections/cores of the Nantuo Formation. Three facies associations were recognized: the proximal glaciomarine, distal glaciomarine, and non-glacial marine facies associations. The vertical stacking pattern of facies associations can be correlated among the five slope and basin sections, while their correlation with the shelf section remains obscure. Our data indicate two episodes of glaciation that are separated by an interglacial interval during the Nantuo Glaciation. The first glacial episode is recorded by successions of coarse-grained facies (e.g., massive diamictite) in the lower part of the Nantuo Formation. The reappearance of massive diamictite in the middle to upper part of the Nantuo Formation indicates onset of the second glacial episode. These two glacial episodes were separated by a siltstone/shale sequence of several 100s m thick, suggesting an interglacial period with limited influence from glaciation. The top of Nantuo Formation consists of alternative distal-glaciomarine and non-glacial marine facies associations, representing the deglaciation sequence of the Nantuo Glaciation. The sedimentary facies analysis indicates that the cold climate during the Nantuo Glaciation may be cyclic. Finally, our sedimentary analysis confirms a lag between the deglaciation and precipitation of cap carbonate.

1. Introduction

Geological and paleomagnetic evidence indicates that ice sheets might have extended to the low latitude sea level during the Sturtian (ca. 717–660 Ma) and Marinoan glaciations (ca. 650–635 Ma) (Hoffman et al., 1998; Hoffman and Li, 2009; Hoffman and Schrag, 2002; Kirschvink, 1992; Macdonald et al., 2010). The snowball Earth hypothesis proposed that the Earth’s surface was completely frozen during these two global glaciations (Hoffman et al., 1998; Hoffman and Schrag, 2002). Global freezing resulted in the stagnation in hydrological cycle, leading to a weak continental weathering and negligible marine primary productivity. As a result, atmospheric pCO2 level could continuously rise due to volcanic degassing during the global glaciation (Hoffman and Schrag, 2002). The Earth remained completely frozen for tens of million years until atmospheric pCO2 level reached a threshold that caused a catastrophic meltdown of the global glaciation (Bao et al.,...
activities (Jiang et al., 2011; Jiang et al., 2003; Wang and Li, 2003). This stage is represented by the Liantuo/Chengjiang Formation in northwest and the Banxi/Xiajiang/Danzhou Group in southeast (Jiang et al., 2011) (Table 1). The Liantuo/Chengjiang Formation is composed of sandstones of < 300 m thick, whereas the sandstone-siltstone successions of the Banxi/Xiajiang/Danzhou Group have a thickness of several kilometers (Huang et al., 2014; Wang and Li, 2003; Zhang et al., 2011), suggesting the rift basin dipping toward southeast, i.e. deepening toward southeast. The overlying Cryogenian (720-635 Ma) strata thickens from < 100 m in northwest to several kilometers in southeast (Jiang et al., 2011; Wang and Li, 2003). Significant reduction of volcanic and magmatic activities in Cryogenian suggests the late rifting stage of the Yangtze Block (Table 1) (Wang and Li, 2003) (Fig. 1B).

The overlying Ediacaran succession, consisting of, in ascending order, the Doushantu and Dengying/Liuchapo/Laobao formations, attenuates from northwest (< 1000 m) to southeast (< 250 m) (Jiang et al., 2011). It was proposed that the Ediacaran succession represents the thermal subsidence stage of the Yangtze Block (Jiang et al., 2011, 2003; Wang and Li, 2003). Alternatively, recent studies indicate widespread hydrothermal activities occurred in the Liuchapo Formation along the platform margin of the Yangtze Block, indicating an intensified tectonism rather than a passive continental margin in late Ediacaran (Wang et al., 2012). This scenario is also supported by multiple hydrothermal dolomitization in the Dengying Formation in the Upper Yangtze Block area (Jiang et al., 2016). Therefore, the late Ediacaran successions may represent a gentle extensional to a thermosubsidence stage of the Yangtze Block (Zhao et al., 2017).

2.2. The Cryogenian stratigraphy in the Yangtze Block

The Cryogenian deposits in the Yangtze Block can be divided into three units: in chronological order, the Jiangkou/Chang’an glacial deposits, the Datangpo/Fulu interglacial deposits, and the Nantuo glacial deposits (Zhang et al., 2011). The Jiangkou/Chang’an glacial deposits are represented by the Gucheng/Tiesiao/Dongshanfeng (GTD) formations in the slope and the Chang’an and Fulu (only the lower portion) formations in the basin environments (Table 1) (Zhang et al., 2011). The GTD formations unconformably overlie the Banxi Group, and are mainly composed of massive diamictite with thickness varying between ~2 m and several tens of meters. In the basin environment, the Chang’an Formation is defined by a thick sequence of massive diamictite intercalated with sandstone/siltstone, and conformably overlies the Tonian Gongdong Formation (Lan et al., 2014). The overlying Fulu...
Formation can be divided into five lithological members (Member I–V), and consists of, in stratigraphic order, banded iron formation (BIF) or ironstones (Member I), pebbly sandstone (Member II), stratified sandstone (Member III), massive diamictite (Member IV), and siltstone and mudstone (Member V). It is proposed that the member IV of the Fulu Formation can be correlated with the GTD formations in the slope environment, and represents the second episode of the Sturtian glaciation (Lan et al., 2015). Three U–Pb zircon ages of 725 ± 10 Ma, 715.9 ± 2.8 and 714 ± 5.2 Ma from tuff beds in the top of the Tonian Banxi/Danzhou Group (Lan et al., 2014; Song et al., 2017; Zhang et al., 2008a), suggest the lower glacial interval in the Yangtze Block can be correlated with the Sturtian glaciation, which is dated at 713.7 ± 0.5 Ma from Oman and 715.9 ± 2.8 Ma from Canada (Bowring et al., 2007; Macdonald et al., 2010; Rooney et al., 2015).

The interglacial deposits are represented by the Datangpo Formation (663–654 Ma) in the slope and the Member V of the Fulu Formation in the basin environments (Zhang et al., 2008b; Zhou et al., 2004). The Datangpo Formation (~10–500 m thick) is dominated by shale/mudstone or siltstone (Li et al., 2012), and conformably overlies the GTD formations. Manganese carbonate at the base of the Datangpo Formation has been interpreted as the cap carbonate of the Sturtian glaciation (Yu et al., 2017). The Member V (~30–80 m thick) of the Fulu Formation is mainly composed of siltstone with occurrences of several carbonate layers in some sections.

The upper glacial interval is called the Nantuo Formation. The Nantuo Formation was radiometrically dated between ~654 and 635 Ma (Condon et al., 2005; Zhang et al., 2011, 2008b), and thus can be correlated with the Marinoan global glaciation (Zhang et al., 2011). The thickness of the Nantuo Formation ranges from several meters to several tens of meters in the terrestrial and inner shelf settings to > 2000 m in the basinal settings (Jiang et al., 2011; Zhang et al., 2011). The Nantuo Formation unconformably overlies the Chengjiang/Liantuo formations in terrestrial and inner shelf environments (Figs. 1B and 3A, Tables 1 and 2) (Zhang et al., 2011), and has a conformable contact with the underlying Datangpo and Fulu formations in the slope and basinal environments (Fig. 3C and D) (Zhang et al., 2008b). The Nantuo Formation underlies a 3–6 m thick dolostone in the base of Doushantuo Formation (Fig. 3B and E), which represents the cap carbonate of the Marinoan glaciation (Jiang et al., 2006; Lang et al., 2016). In this study, 4 outcrop sections and 2 drill cores of the Nantuo Formation were investigated. Basic information of the studied sections is presented in Table 2.

3. Lithofacies

Ten lithofacies were identified from the Nantuo Formation. The descriptions and interpretations are summarized in Table 3 and discussed below.

3.1. Massive diamictite (Dmm)

3.1.1. Description

This lithofacies (grayish-green or less commonly purple-red in color) accounts for 30–50% of the Nantuo Formation in stratigraphic successions (a few meter to > 50 m thick) (Fig. 2). The diamictite comprises dominantly of silty and clayey matrix and < 30% (mostly < 5%) of polymictic gravels that are dominated by granite, sandstone and mafic igneous rocks, with rare occurrences of carbonate and mudstone (Fig. 4A). Gravels are angular to rounded in outline, and poorly sorted (~0.2–10 cm in size) occasionally with giant boulders up to 1 m in size (Fig. 4B). Glacial striations are commonly observed on pebbles (Fig. 4C). Diamictite is commonly massive but sometimes normal-graded, showing a fining upward in gravel size (Fig. 2). Intercalated siltstone layers are rarely observed in massive diamictite. Liquefied fine-sand veins are sporadically present in diamictite of the Daotuo drill core (Fig. 4D and E). The bounding surfaces of massive diamictites are commonly planar, displaying a steady distribution in transverse.

3.1.2. Interpretation

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transported downslope through a canyon or submarine channel and deposited as massive diamictite in distal glacimarine environment. Normal-graded diamictite and intercalated siltstone layers are likely deposited from turbidity currents that are generated during retreating and advancing of ice sheets. When the glacial efflux charge is low, subglacial or basal streams that previously acted on seabed would be detached from sediment surface and form a turbulent jet due to water buoyancy (Boulton, 1990; Boulton and Deynoux, 1981). Outilsized gravels floated in the massive diamictite are supported by cohesive strength of clayey matrix and transported in debris flows. Purple-red color of massive diamictics likely resulted from the enrichment of iron oxides that were either transported into the ocean by glaciers or

Table 2
Locations and descriptions of 6 logged sections/cores.

<table>
<thead>
<tr>
<th>Section name</th>
<th>GPS Location</th>
<th>Depositional environment</th>
<th>Main lithologies</th>
<th>The bottom boundary of the Nantuo Formation</th>
<th>The top boundary of the Nantuo Formation</th>
<th>Thickness of the Nantuo Formation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jiulongwan</td>
<td>N30°48′14.49″</td>
<td>Glacial littoral</td>
<td>Massive diamictite, crudely stratified diamictite, pebbly sandstone, shale</td>
<td>Unconformable contact</td>
<td>Conformable contact</td>
<td>83</td>
</tr>
<tr>
<td>Wuluo</td>
<td>N28°04′14.30″</td>
<td>Slope</td>
<td>Massive diamictite, pebbly sandstone, massive sandstone, siltstone/shale</td>
<td>Conformable contact</td>
<td>Conformable contact</td>
<td>172</td>
</tr>
<tr>
<td>Daotuo</td>
<td>N28°07′11.83″</td>
<td>Slope</td>
<td>Massive diamictite, massive sandstone, siltstone/shale</td>
<td>Conformable contact</td>
<td>Conformable contact</td>
<td>220</td>
</tr>
<tr>
<td>Nangao</td>
<td>N26°24′11.59″</td>
<td>Slope</td>
<td>Massive diamictite, crudely stratified diamictite, shale</td>
<td>Conformable contact</td>
<td>Covered</td>
<td>ca.210</td>
</tr>
<tr>
<td>Shennongjia</td>
<td>N31°27′19.37″</td>
<td>Slope</td>
<td>Massive diamictite, pebbly sandstone, massive sandstone</td>
<td>Erosive contact</td>
<td>Covered</td>
<td>ca.260</td>
</tr>
<tr>
<td>Yazhai</td>
<td>N25°50′46.50″</td>
<td>Basin</td>
<td>Massive diamictite, massive sandstone, pebbly sandstone</td>
<td>Conformable contact</td>
<td>Conformable contact</td>
<td>350</td>
</tr>
</tbody>
</table>

Fig. 2. Six Stratigraphic logs of the Nantuo Formation from the Yangtze Block. The Nantuo Formation can be divided into four parts according to the stacking pattern of facies association. Lithofacies codes are corresponding to those in Table 3. LT: Liantuo Formation; DTP: Datangpo Formation; DST: Doushantuo Formation. Grain sizes from left to right: Cl = clay, S = silt, F = fine sand, M = medium sand, C = coarse sand, G = gravels.
originated from oxidation of ferrous iron minerals in subaerial conditions. Liquefied sand veins are caused by dewatering of rapid deposition of the massive diamictite.

3.2. Crudely stratified diamictite (Dms)

3.2.1. Description

Crudely stratified diamictite is widespread in the Nantuo Formation, but its abundance is subordinate to massive diamictite (Figs. 2 and 4F). The total thickness of this lithofacies is commonly less than several meters, except in the Jiulongwan and Nangao sections where it is > 10 m thick. This lithofacies is clay/mud matrix supported and contains 1–5% of polymictic, sub-rounded to rounded gravels (0.2–10 cm in size). This lithofacies is weakly stratified and commonly overlies massive diamictite. Irregular stratifications are reflected mainly by the variation in clasts content and can only be traced in a limited distance laterally.

3.2.2. Interpretation

This lithofacies is commonly deposited in the ice margin or the ice grounding line areas where hydrodynamic energy is high (Eyles et al., 1985). In the ice grounding line areas, massive sediments loaded in glaciers would be quickly dumped into sea water and deposited as massive diamictite (Allen et al., 2004; Eyles et al., 1985). These poorly sorted, massive diamictites would be slightly reworked by tidal currents or waves, generating crude stratification. Irregular stratifications in this lithofacies indicate a temporal reworking of previous sediments. Changes in the velocity of subglacial streams can also produce a weakly stratified diamictite. Near ice margins, subglacial streams often generate an underflow at the tunnel jet when massive sediments are loaded (Eyles et al., 1985). At a constant velocity, the underflow would remain in contact with sediments along a runout distance after dumping into the ocean. Once the velocity of the underflow increases, massive sediments would be modified, producing weak stratifications.
3.3. Dropstone-bearing laminated siltstone (Fdl)

3.3.1. Description

Laminated siltstone contains rounded, heterolithic, and poor-sorted pebbles that range from 1 to 10 cm in size. This lithofacies makes up a relatively small proportion of the Nantuo Formation (Fig. 2). The continuity of laminations is commonly interrupted by pebbles, showing a typical ‘drop-stone’ structure (Fig. 5A). These siltstones are commonly wavy laminated (Fig. 5B).

3.3.2. Interpretation

Dropstone-bearing laminated siltstones are commonly deposited with transient fall-out of heterolithic clasts from icebergs (Allen et al., 2004; Condon et al., 2002). Ice-rafted deposition may take place in either proximal or distal glaciomarine environments during ice sheet melting. In proximal glaciomarine environments, dropstone-bearing laminated siltstones are often intercalated with coarse-grained lithofacies, whereas distal glaciomarine settings are dominated by fine-grained lithofacies, such as laminated siltstone/mudstone. Presence of thin layers of siltstone suggests this lithofacies was likely deposited from a series of dilute turbidity currents in distal glaciomarine environments.

3.4. Stratified to massive pebbly sandstone (Sp)

3.4.1. Description

This lithofacies consists of fine to medium sandy matrix with dispersed, poorly sorted, sub-angular to sub-rounded pebbles (< 5%) (Fig. 5C and D). These pebbly sandstones are mostly massive and less commonly stratified. The sandstone beds show various thickness ranging from several centimeters to several meters (Fig. 2). Thin beds of stratified pebbly sandstone are locally intercalated with thin-layer siltstone, whereas thick pebbly sandstone beds are normally massive and are commonly interbedded with conglomerate or massive fine sandstone (Fig. 2). Stratified to massive pebbly sandstone beds commonly have planar bounding surfaces.

3.4.2. Interpretation

Stratified to massive pebbly sandstones are transitional deposits between conglomerate and sandstone, representing deposits of debris flows (Allen et al., 2004; Eyles et al., 1985). Over-steepening of ice grounding line fans could produce debris flow currents, depositing massive or graded pebbly sandstone. Overturn of icebergs in the open ocean is another mechanism for pebbly sandstone deposition. Notably, stratified to massive pebbly sandstone formed in the distal glaciomarine environments is commonly thin bedded. Such a thin-bed pebbly sandstone is associated with dropstone-bearing laminated siltstone.

3.5. Normal-graded conglomerate (Gg)

3.5.1. Description

This lithofacies only appears in the Daotuo drill core (Fig. 6A), and the conglomerate bed is only ∼10 cm in thickness. The conglomerate is clasts-supported and normal graded and contains > 50% of heterolithic, poorly sorted, but well-rounded pebbles.

3.5.2. Interpretation

The graded clasts-supported conglomerate represents the deposits of high density turbidity currents (i.e., the basal units of the Bouma sequence) (Allen et al., 2004; Le Heron et al., 2014). Rounded pebbles indicate that the gravels are transported over a long distance before deposition, or are sourced from pre-existing sediments.

3.6. Massive/normal-graded sandstone (Sm)

3.6.1. Description

This lithofacies occupies a significant fraction (~10–40%) of the Nantuo Formation and can be observed in all deep water sections (Figs. 2 and 6B). The sandstone is mostly massive and sometimes normal-graded. The massive sandstone bed is >1 m thick and can be laterally traced for long distances. This lithofacies can upward change to thin-bedded siltstone locally.

3.6.2. Interpretation

Massive/normal-graded sandstones can be deposited by relatively low-density turbidity currents, as the basal unit (i.e., Tn) of the Bouma sequence (Sumner et al., 2009; Talling et al., 2012a,b). The overlying siltstone represents the tail deposits of the turbidity currents (Talling et al., 2012b).
3.7. Parallel-laminated sandstone (Sh)

3.7.1. Description
This lithofacies is characterized by the parallel lamination, and consists of fine sands (Fig. 6C). The sandstone beds range from \( \sim 1\) m to several meters in thickness and can be laterally traced for > 10 m. The parallel-laminated sandstone beds commonly overlie massive or normal-graded sandstone conformably.

3.7.2. Interpretation
Parallel lamination is usually formed by currents under the upper flow regime (Southern et al., 2017). Association with massive or normal-graded sandstone in the Nantuo Formation indicates that this lithofacies is deposited under turbidity current (Talling et al., 2012b).

3.8. Ripple cross-laminated siltstone (Fr)

3.8.1. Description
This lithofacies is often underlain by massive sandstone or intercalated with laminated siltstone/mudstone (Fig. 6D). The siltstone beds are usually < 10 cm in thickness. Ripples are asymmetric with a wavelength of centimeter scale. Soft-sediment deformation structures are commonly observed (Fig. 6E and F).

3.8.2. Interpretation
Ripple cross-laminated siltstone represents the \( T_c \) deposits of dilute turbidity currents (Stow and Piper, 1984; Talling et al., 2012b). Soft-sediment deformation structures are formed by earthquakes or sediment over-steepening triggered liquefaction and fluidization. Water-escaping structures suggest this lithofacies may have a relatively high sedimentary rate.
3.9. Laminated dolostone (Pl)

3.9.1. Description
Laminated dolostone can be observed in all logged deep-water sections. This lithofacies is usually intercalated with siltstone or mudstone. The dolostone beds can be traced laterally at outcrop scale and varies between 10 cm and 3 m in thickness (Fig. 6G).

3.9.2. Interpretation
This lithofacies is deposited in relatively low-energy, clean seawater conditions when siliciclastic input was shut down (Labaj and Pratt, 2016), representing deposits in non-glacial condition.

3.10. Laminated siltstone/mudstone (Fl)

3.10.1. Description
Laminated siltstone/mudstone can be observed in all logged sections/cores and constitute a significant fraction (5–40%) of the Nantuo Formation. This lithofacies comprises rhythmic lamination of siltstone and mudstone (Fig. 6H). The siltstone/mudstone beds vary in thickness between several centimeters and several tens of meters (Fig. 2). Locally, this lithofacies may contain pyrite laminations (e.g. in the Wuluo drill core; Fig. 6I).

3.10.2. Interpretation
Laminated mudstones represent suspension fall out of fine-grained terrestrial materials from water column (Sumner et al., 2009), whereas laminated siltstones may represent the T1 deposits from a dilute turbidity current (Talling et al., 2012b). This lithofacies was commonly deposited in the slope environments.

4. Facies associations

4.1. Proximal glaciomarine facies association
In all logged section/cores, proximal glaciomarine facies association constitutes a significant fraction (10–90%) of the Nantuo Formation. Massive diamictite (Dmm) is the dominant lithofacies in this facies association (Allen et al., 2004; Eyles et al., 1985). The coarse-grained sediments are deposited from a series of subglacial debris flows with transient rainout of ice rafts by gravity. If hydrodynamic condition was high, massive diamictite would be modified, generating a weakly or crudely stratified diamictite (Dms). Other than diamictite, fine-grained facies could also be deposited in the ice grounding line areas, such as
pebbly sandstone (Sp), massive sandstone (Sm) or even laminated siltstone (Fl). Sandstones deposited in this environment are commonly enriched in sedimentary structures, such as soft-deformation and water-escaping structures. These structures were caused by rapid sedimentation or ice-sheet push. It is notable that these sandstones usually have a limited thickness and are always associated with coarse-grained facies.

4.2. Distal glaciomarine facies association

Distal glaciomarine facies association is commonly dominated by fine-grained facies, such as laminated siltstone/mudstone (Fl), and drop-stone bearing siltstone (Fdl). Sometimes coarse-grained facies, including massive diamictite (Dmm) or pebbly sandstone (Sp), may also present. In contrary to proximal glaciomarine facies association, massive diamictite (Dmm) and pebbly sandstone (Sp) in this facies association are thinner, normally < 1 m thick. As far away from the ice calving line or ice grounding line zone, sediments in distal glaciomarine environments were mainly deposited from low-density gravity flows (Allen et al., 2004). Transient hyper-concentrated debris flows could be generated by overturn of icebergs, leading to the deposition of thin-bed pebbly sandstone or conglomerate. A specific feature of the facies association in distal glaciomarine environments is frequent variation in lithofacies, which may attribute to pulsed transformations between debris flows and dilute turbidity currents.

4.3. Non-glacial marine facies association

Non-glacial marine facies association represents deposits formed in normal marine environments without the influence of glaciation. In such environments, the most common facies is laminated siltstone/mudstone (Fl) and ripple cross laminated siltstone (Fr). Additionally, massive sandstone (Sm), laminated carbonate (Pl) and parallel
laminated sandstone (Sh) can also deposit in non-glacial marine environments. Some stratified fine-grained lithofacies might be the reworked deposits from massive diamictite (Dmm) by subaqueous debris flow or liquefied/turbidity current along the submarine canyon. However, this scenario only seems to explain vertical lithofacies variation within a short distance (kilometer-scale). Well-correlated fine-grained/stratified lithofacies across the whole Yangtze Block (hundreds of kilometer-scale) cannot be simply interpreted as deposits after Dmm modification. Instead, these fine-grained lithofacies may reflect the non-glacial or interglacial intervals intercalated within glaciations. Laminated carbonate (Pl) is most likely precipitated in a high sea-level condition. This facies association is present in all logged successions with a thickness ranging from several to several tens of meters. High sea-level conditions may result from substantial melting of ice sheets, indicating an interglacial or deglacial period of the Nantuo Glaciation.

5. Lateral and vertical distributions of facies associations

In the shallow water environments (inner shelf), the Nantuo Formation is mainly composed of coarse-grained glacial deposits. At the Jiulongwan section (inner shelf), a thick sequence of massive diamictite and pebbly sandstone (~15 m) that represents the proximal glaciomarine deposit unconformably overlies the sandstones of the Tonian Liantuo Formation. These proximal glaciomarine deposits are directly succeeded by a 2-m thick shale layer in the lower part of the Nantuo Formation, indicating a possible non-glacial deposition. The middle part of the Nantuo Formation is dominated by proximal glaciomarine facies association that consists of massive diamictite and crudely stratified diamictite, although there is a 3-m thick pebbly sandstone layer indicating the possible distal glacial marine deposition (Fig. 2). The upper part of the Nantuo Formation is mainly composed of crudely stratified diamictite lithofacies, representing proximal-glaciomarine deposition. The top of the Nantuo Formation at the Jiulongwan section is represented by a massive diamictite unit of >20 m thick, and this diamictite unit is separated from the basal Doushantuo cap dolostone by a 0.5-m thick gravelly siltstone layer (Fig. 2).

In the slope and basin environments, the five investigated Nantuo sections have similar vertical stacking patterns of facies associations. In these sections, the Nantuo Formation conformably overlies the interglacial deposits of the Datangpo and Fulu formations, as indicated by a gradual transition from laminated siltstones of the upper Datangpo/Fulu Formation to massive diamictites (Fig. 2). These observations indicate that the lower Nantuo Formation may represent a glacial deposit with ice sheets probably extended to the deep-water environment of the Yangtze Block.

The lower Nantuo Formation is succeeded by a sequence of fine-grained deposits dominated by fine sandstone, siltstone or shale, representing the non-glacial marine facies association (Fig. 2). This non-glacial succession has been found throughout the Yangtze Block, but shows significant variations in thickness. This non-glacial interval is represented by a ~30 m and ~60 m thick laminated siltstone/mudstone layer in the Daotuo and Wuluo drill cores, whereas this non-glacial layer is ~20 m and ~10 m thick in the Nangao and Shennongjia section, respectively (Fig. 2). At the Yazhai section from the basin environment, this non-glacial deposit is dominated by laminated siltstone of ~15 m thick (Fig. 2).

The non-glacial deposit is directly overlain by glaciomarine deposits, suggesting the renewal of glaciation. At the Wuluo drill core, a 3-m thick massive diamictite layer underlies a thick sequence of pebbly sandstone and massive sandstone, representing a dominant distal glaciomarine deposition, whereas at the nearby Daotuo drill core, after a 35-m thick alternating deposition of massive diamictite and massive sandstone, a 40-m thick sequence of massive diamictite deposition represents the proximal glaciomarine deposition (Fig. 2). In the following 15 m interval, reoccurrence of pebbly sandstone-sandstone alternations may indicate a transition from proximal to distal glaciomarine deposition (Fig. 2). At the Nangao section, the middle part of the Nantuo Formation is dominated by massive diamictite of 50 m in thickness, representing an overwhelming proximal glaciomarine deposition. Upward, massive diamictite gradually grades into crudely stratified diamictite and thin-bed diamictite with total thickness of ~60 m (Fig. 2), indicating a transition from proximal to distal glaciomarine deposition. At the Shennongjia and Yazhai sections, massive diamictite and massive sandstone facies directly overlie the non-glacial deposit. Both sections show frequent changes in lithology, representing the oscillation between the proximal and the distal glaciomarine environments (Fig. 2).

Deposition of thin laminated siltstone above the glaciomarine deposits in the upper part of the Nantuo Formation may indicate a glacial to non-glacial transition. At the Daotuo and Wuluo drill cores, a sandstone-siltstone succession that ranges from 5 to >20 m thick represents the deposition in non-glacial conditions (Fig. 2). This succession can be correlated with ~20 m thick laminated siltstone succession at the Yazhai section. This suggests the ice sheet might have been melted in the open ocean. The top of the Nantuo Formation in the slope environment is characterized by the alternating deposition of massive sandstone-stratified sandstone-laminated siltstone (e.g., from the Daotuo and Wuluo drill cores). The local occurrences of thin-layered diamictite may indicate the distal glaciomarine deposition near the end of the Nantuo Glaciation, although a debris flow deposition by reworking of glaciogenic diamictite cannot be ruled out either. At the Yazhai section, the top of the Nantuo Formation is dominated by crudely stratified diamictites that are intercalated with thin-layer siltstone, representing distal glaciomarine deposits.

In summary, the Nantuo Formation displays pronounced variations in facies association both laterally and vertically. However, the stratigraphic correlation between the shallow water (i.e., inner shelf) and deep water (i.e., slope and basin) sections are not straightforward, probably due to incomplete record of the glacial deposits in the shallow water sections. In addition, faults occurred in the lower part of the Nantuo Formation in the Jiulongwan section may also obscure its correlation with other sections.

6. Discussion

6.1. Dynamic evolution of the Nantuo Glaciation

It is proposed that excessive topography relief would result in complex facies associations during the Neoproterozoic global glaciation (Hoffman et al., 2017b). Particularly, deposition of diamictite during ice sheet melting might create topographic variations even within short distance. Oversteepening of diamictite could generate reworked sediments, such as crudely stratified diamictite, pebbly sandstone and stratified sandstone (Hoffman et al., 2017b). This scenario seems to be a good explanation for variable thickness and vertical facies change of glacial deposits within a short distance. However, well-correlated laminated siltstone/mudstones and carbonate beds in the middle of the Nantuo Formation cannot be simply interpreted as deposits during ice sheet melting. Rather, these fine-grained facies may reflect the non-glacial or interglacial interval intercalated within glaciations, suggesting multiple ice-sheet advancing-retreating cycles during the Nantuo Glaciation (Fig. 7).

Accordingly, four depositional stages of the Nantuo Formation are reconstructed in this study and are summarized below:

6.1.1. Stage I

In the earliest stage of Nantuo Glaciation, ice sheets have experienced an entire advancing-retreating cycle (Fig. 7A). Deposition of glaciomarine facies association at the base of the Nantuo Formation suggests that ice sheets might have extended to the open ocean of the Yangtze Block. Ice-sheet advance could have led to a significant sea-level fall, resulting in a coarsening-upward sequence (Fig. 2). Local
massive diamictites at the Jiulongwan and Shennongjia sections and the Wuluo and Daotuo drill cores may indicate the ice grounding line may have maintained a balance between advancing and retreating during this period. At the Nangao and Yanzhai sections, the absence of massive diamictite at the top of this interval may be attributed to relatively far distance away from the ice margin area.

6.1.2. Stage II

This stage represents an interglacial period during the Nantuo Glaciation (Fig. 7B), as evidenced by a package of fine-grained facies pervasively occurred in the middle part of the Nantuo Formation. Notable thickness variations in the interglacial deposits may be attributed to different accommodation space between the shallow and deep water environments. Deposition of laminated carbonate implies a relatively low terrestrial input and warm climate (Tucker et al., 1990). Therefore, these fine-grained siliciclastic lithofacies and laminated carbonates (dolostones) were most likely deposited in a high sea-level condition, with no influence of ice sheet. Since the Yangtze Block was located at ∼30° N in latitude in late Neoproterozoic (Li et al., 2013), ice sheets during the Stage II may have retreated to mid to high latitude regions.

6.1.3. Stage III

This stage was the second glacial episode of the Nantuo Glaciation (Fig. 7C). In the upper part of the Nantuo Formation, reappearance of massive diamictite represents re-advance of ice sheets after the interglacial period. Above these massive diamictites, oscillations between distal and proximal glaciomarine facies associations, such as in the interval between 105 m and 120 m at the Daotuo drill core, may indicate a dynamic ice grounding line during this stage. Although massive sandstone or siltstone commonly intercalate with massive diamictite, facies analysis suggests that all sediments were deposited in glaciomarine environments. Stacked glacial-related facies assemblages strongly demonstrate an overall tendency of ice sheet advancing. The thicker interval of coarse-grained glacial deposits compared to the lower interval (Stage I) suggests the second glacial episode may have been more severe than the first episode of the Nantuo Glaciation.

6.1.4. Stage IV

During this period, ice sheets were gradually retreating and the Nantuo Glaciation was finally terminated (Fig. 7D). This stage was recorded in the top of the Nantuo Formation. Packages of non-glacial and distal glaciomarine facies associations can be correlated throughout the Yangtze Block (Fig. 2), suggesting the ice sheet retreat may have occurred at least regionally. In addition, occurrence of fine-grained lithofacies, such as ripple-mark siltstone, laminated siltstone or carbonate, suggest some part of the oceans may have remained ice free before ultimate meltdown of the Marinoan glaciation.

Taken together, the four depositional stages (I–IV) of the Nantuo Formation suggest two cycles of ice sheet advance and retreat before the deposition of the Marinoan cap carbonates at 635 Ma.

6.2. Was the Nantuo Glaciation a snowball Earth event?

Multiple cycles of ice sheet advance and retreat as well as non-glacial deposits in the middle of the Nantuo Formation may suggest that the Nantuo Glaciation as a whole cannot be a hard snowball Earth. However, existing geochemical evidence strongly suggests the presence of snowball Earth interval (Bao et al., 2008; Huang et al., 2016), though its duration is poorly constrained. Then, how can the snowball Earth hypothesis reconcile the sedimentology evidence?

One possible solution that can explain such discrepancy is that, the onset of the Marinoan glaciation was a diachronous process in a global scale. Although the Snowball Earth hypothesis asserts that its onset was synchronous (Hoffman et al., 2017a), regional glaciations might have occurred before the Marinoan snowball Earth. This argument is consistent with radiometric ages, although diachronous ages could also be
attributed to low stratigraphic resolution of glacial deposits (Hoffman et al., 2017a). Therefore, the Stage I may represent a regional glaciation before the onset of Marinoan snowball Earth. If the Marinoan snowball Earth indeed existed, we suggest that the snowball Earth might be represented by the Stage III deposition of the Nantuo Glaciation, recording a more severe glaciation than the earlier regional glaciation (Stage I). It should be noted that the sedimentological analyses alone cannot differentiate a regional glaciation from a snowball Earth glaciation. The assignment of the Stage III as the Marinoan snowball Earth deposit is mainly based on the assumption of the presence of a snowball Earth interval during the Marinoan glaciation. The stage IV deposition that consists of a mixture of distal glaciomarine and non-glacial deposits indicates the melting stage of possible snowball Earth glaciation (Huang et al., 2016).

6.3. A Lag between deglaciation and cap carbonate precipitation

Cap carbonate is commonly interpreted to be precipitated immediately after termination of the glaciation or concurrent with deglaciation (Hoffman et al., 2007; Shields, 2005; Zhou et al., 2010). However, facies analysis demonstrates that the upper part of the Nantuo Formation is dominated by distal glaciomarine facies association and locally intercalated with non-glacial facies association (Fig. 2), suggesting that deglaciation was initiated during the stage IV of the Nantuo Glaciation. In addition, a thin siltstone or gravelly siltstone bed commonly underlies the Doushantuo cap carbonate in the Yangtze Block (Fig. 2) (Zhang et al., 2008b). These observations are consistent with recent Mg isotopes study shows that an extreme chemical weathering event may have occurred in the upper part of the Nantuo Formation (Huang et al., 2016), considerably predating precipitation of the Doushantuo cap carbonate. The moderate facies transitions from the Nantuo Formation to the Doushantuo Formation indicate that a lag may have existed between the onset of deglaciation and the Doushantuo cap carbonate precipitation.

7. Conclusions

Detailed facies analysis of six successions of the Nantuo Formation in the Yangtze Block was conducted in this study. The main conclusions are listed as below:

(1) The Nantuo Formation includes ten lithofacies and three facies associations. These facies and facies associations display pronounced lateral and vertical changes among different sections. The change of well-correlated facies associations may suggest dynamic ice sheets in certain period of the Nantuo Glaciation.

(2) Four depositional stages of the Nantuo Glaciation are recognized: Stage I includes an entire cycle of ice sheet advance-retreat, representing the first episode of the Nantuo Glaciation. Stage II represents ice sheets retreat to high latitude regions, implying an interglacial period during the Nantuo Glaciation. Re-advance of ice sheets in the second episode of Nantuo Glaciation (Stage III) is succeeded by the deglacial interval of Stage IV.

(3) Sedimentary facies analysis of the Nantuo Formation indicates that the Nantuo Glaciation includes at least two major episodes of glaciation that were separated by an interglacial interval. The discovery of non-glacial facies association in the top of the Nantuo Formation suggests that the melting of the Nantuo Glaciation was earlier than the deposition of the Doushantuo cap carbonate.

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