Thematic set: Paleoceanography and paleoclimate

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

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**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 re-appearance 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 10s 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 association, representing the deglacial 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.

**Key words：**Ice sheets; Glacial cycle; Snowball Earth; Neoproterozoic

**1. Introduction (一级标题，左对齐，1.5倍行距，Times New Roman小四，加粗)**

正文部分（两端对齐，首行缩进2字符，1.5倍行距，Times New Roman小四）

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 the weak continental weathering and negligible primary productivity in the ocean. 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 10s of million years until atmospheric pCO2 level reached a threshold that caused a catastrophic melting of the global glaciation (Bao et al., 2008; Fabre and Berger, 2012; Higgins and Schrag, 2003; Hoffman et al., 1998; Hoffman and Schrag, 2002; Le Hir et al., 2007; Lewis et al., 2007).

The snowball Earth hypothesis provided a reasonable interpretation for the global precipitation of 12C-enriched cap carbonate immediately above glacial deposits (Hoffman et al., 1998). However, this scenario cannot be completely supported by the glacial sedimentary record. Some sedimentary structures observed in glacial marine deposits, such as thin-bedded mudstone intercalated with diamictite (Allen and Etienne, 2008; Allen et al., 2004; Busfield and Le Heron, 2014; Hu et al., 2011), wave ripples, and hummocky cross stratification (Busfield and Le Heron, 2016; Le Heron, 2015; Le Heron et al., 2016), indicate the presence of water current and sediment transportation during the global glaciation. Although wave-induced current would have become negligible when the ocean was completely covered by ice (Allen and Etienne, 2008; Allen et al., 2004), recent study proposed that water motion could be induced by tidal force and hydrothermal activities, and thus may still exist even in the ice-covered ocean (Hoffman et al., 2017a). Therefore, the presence of certain sedimentary structure alone hardly supports the presence of an open ocean (i.e. not covered by ice) during the global glaciation. Instead, analysis of multiple glaciomarine depositional sequences in a basin¬-to-platform transect might provide more valuable information about the nature of global glaciations (Hoffman et al., 2017a).

In this study, we conducted systematic sedimentary analyses of 6 sections of the Nantuo Formation (654–635Ma) in the Yangtze Block of South China. Our study demonstrates that the Nantuo Formation may deposit under a cyclic cold-warm climatic fluctuations rather than a long-lasting global glaciation with the Earth’s surface being entirely frozen.



Fig.1 (A) Paleogeographic map of the Nantuo Formation in the Yangtze Block (Modified after Zhang et al. (2011)). Red dots showing the localities of investigated sections in this study; (B) Depositional model of the Tonian and Cryogenian successions in the Yangtze Block.

**2. Geological setting**

The South China Block consists of the Yangtze Block to the northwest (present orientation) and the Cathaysia Block to the southeast (Fig. 1A) (Wang and Li, 2003; Zhao and Cawood, 2012; Zheng et al., 2013). The Yangtze and Cathaysia blocks were considered as having been amalgamated along the Jiangnan Orogenic Belt during the assembly of the supercontinent Rodinia at 830 Ma, followed by a rifting and thermal-subsidence cycle in late Neoproterozoic (Wang and Li, 2003).

The early rifting stage that was initiated at ca. 820 Ma was dominated by siliciclastic deposition along with widespread magmatic 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 less than 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 Doushantuo 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; Jiang et al., 2003; Wang and Li, 2003). But recent studies indicate widespread hydrothermal activities occurred in the Liuchapo Formation along the shelf margin, suggesting intensified tectonism rather than a thermal subsidence margin in the late Ediacaran (Wang et al., 2012). This intensified tectonism 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 stage of the Yangtze Block (Zhao et al., 2017).

**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) (二级标题，左对齐，1.5倍行距，Times New Roman小四，加粗)

### 3.1.1. Description (三级标题，左对齐，1.5倍行距，Times New Roman小四)

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 (Figs. 4A). Gravels are angular to rounded, and poorly sorted (~0.2¬–10 cm in size) occasionally with large boulders up to 1 m in size (Fig. 4B). Glacial striations are commonly observed on pebble surfaces (Fig. 4C). Diamictite is commonly massive but sometimes normal-graded, showing a fining upward trend 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 (Figs. 4D and 4E). The bounding surfaces of massive diamictites are commonly planar, displaying a steady distribution in transverse.

3.1.2. Interpretation

This lithofacies is deposited from a series of glaciogenic subaqueous debris flows (Allen et al., 2004; Boulton and Deynoux, 1981). In the ice-grounding line zone, debris flows generated during ice sheet melting would result in a rapid deposition of massive diamictite, forming ice margin fans and/or ice-grounding line fans (Boulton, 1990; Boulton and Deynoux, 1981). Massive sediments loaded in the debris flows can be transported downslope through a canyon or submarine channel and deposited as massive diamictite in distal glaciomarine 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). Outsized gravels floated in the massive diamictite are supported by cohesive strength of clayey matrix and transported in debris flows. Purple-red color of massive diamictites likely resulted from the enrichment of iron oxides that were either transported into the ocean by glaciers or originated from oxidation of ferrous ion minerals in subaerial conditions. Liquefied sand veins are caused by dewatering of rapid deposition of the massive diamictite.

**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 seawater hydrodynamics was high, massive sediments would be modified immediately, 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.

**5. Discussion**

## 5.1. 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 the 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).

**6. Conclusions**

Detailed facies analysis of six successions of the Nantuo Formation in the Yangtze Block was conducted in this study. The Nantuo Formation includes ten lithofacies and three facies associations. These facies and facies associations display pronounced lateral and vertical changes among different successions. The change of well-correlated facies associations may suggest dynamic ice sheets in certain period of the Nantuo Glaciation. Four depositional stages of the Nantuo Formation 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 area, 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. 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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