Front. Earth Sci. 2012, 6(1): 101–108
DOI 10.1007/s11707-011-0179-9

RESEARCH ARTICLE

Multiple cycles of glacier advance and retreat during the Nantuo (Marinoan) glacial termination in the Three Gorges area

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Abstract The Snowball Earth hypothesis suggests that the sea water had totally been kept frozen for millions of years in Neoproterozoic glaciation, followed by a rapid and catastrophic deglaciation resulting from the elevated concentration of atmospheric CO_2. However, the sedimentary records are not consistent with the Snowball Earth hypothesis. The Nantuo Formation in Three Gorges area is composed of diamictites, sandstones and siltstones. The geochronology and the unconformity with underlying Liantuo Formation indicate that the Nantuo Formation in Three Gorges area may be the partial record (i.e., the final stage) of the Nantuo glaciation. Our studies on sedimentary successions of the Nantuo Formation convince the stepwise transition from the Cryogenia icehouse to the Ediacaran greenhouse, in which multiple glacier advance-retreat cycles rather than a catastrophic termination could be identified.

Keywords multiple glacier advance-retreat cycles, Neoproterozoic, Three Gorges area, glaciomarine environment, Snowball Earth hypothesis

1 Introduction

Extensive Neoproterozoic glacial deposits, especially those at low latitudes, have been interpreted as evidences for the presence of the Snowball Earth (Hoffman et al., 1998; Hoffman and Schrag, 2002). This hypothesis suggests that ice-albedo feedback causes a rapid expansion of sea ice, resulting in a globally frozen Earth and the shutting down of hydrologic cycle over a very long period of time, followed by a rapid deglaciation when atmospheric CO_2 level accumulated sufficiently to trigger glacial melting. Since the Snowball Earth hypothesis was proposed, considerable debates have been raised. Paleontological and molecular lipid evidences suggested that eukaryotes and photosynthetic bacteria survived during the low-latitude Neoproterozoic glaciation, which indicates an open continental shelve or equatorial ocean may have existed without ice (Olcott et al., 2005; Corsetti et al., 2006). Condon et al. (2002) examined six separate Neoproterozoic glaciomarine successions in Oman and found interbedded glacial-rainout intervals with background sedimentation in the absence of glacial rainout, which indicates a dynamic and open sea sedimentary environment. Leather et al. (2002) presented new sedimentological and stratigraphic data in the Fiq Member of Oman and reached the same conclusion. Besides, Allen and Etienne (2008) found some rippled sandstone beds and transgressive-regressive cycles in the Fiq Member of Oman, indicating an active hydrological cycle in this period. Le Heron et al. (2011) presented an abundant hummocky cross-stratification in the Sturtian deposits, demonstrating a significant ice melting and the presence of open water within the Sturtian glacial interval. Besides, the chemical index of alteration (CIA) in Neoproterozoic glacial deposits record a fluctuant glaciation (Rieu et al., 2007; Passchier and Erukanure, 2010). While the paleontological and sedimentological records in many sites of the world argue against a rapid deglaciation, the detailed sedimentological and stratigraphic investigations on the glacial sequences in the Three Gorges area of South China are relatively rare. The earlier studies and discussions of this glacial stratigraphic interval in South China have mainly focused on the intrinsic character of the diamictite, with few dealing with the Snowball Earth theory (Liu, 1991; Zhang, 1995; Jiang et al., 1996; Tong et al., 2002).

Indications of repeated glacier advance and retreat in Neoproterozoic sequences have been argued against the

Received June 22, 2011; accepted August 22, 2011

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global frozen condition (Condon et al., 2002; Leather et al., 2002; Allen and Etienne, 2008). However, Hoffman and Schrag (2002) argued that it is difficult to identify the glacial deposits of a specific glacial cycle. Hoffman (2011) further explained that most preserved glacial deposits record the retreat of an ice sheet from its last maximum limit, when vigorous and open water did indeed exist. Previous studies and discussions of the glacial stratigraphic intervals mainly focused on whether a complete shutdown of the hydrological cycle had appeared during the Neoproterozoic global glaciation (e.g. Condon et al., 2002; Leather et al., 2002; Passchier and Erukanure, 2010). In this paper, we focus on the transition interval from the Cryogenia icehouse to the Ediacaran greenhouse rather than the whole glaciation. We aim to characterize the termination processes of the Nantuo (Marinoan) glaciation.

2 Stratigraphy and geochronology

The Nantuo Formation is distributed widespread in South China, and its correlation with the Marinoan glaciation is widely recognized (Zhang et al., 2008; Zhang et al., 2009). Its thickness increases from north shelf to south basin (Liu, 1991). Jiulongwan, the study area of this paper, is located in the Three Gorges area at Yichang (Fig. 1(a)). The Neoproterozoic section consists of the Liantuo, Nantuo, Doushantuo, and Dengying Formations in ascending order. The unconformable contact between Nantuo Fm. and Liantuo Fm. is widely regarded as a sedimentary hiatus in Yangtze Gorges, correlated with the records of Gucheng/ Jiangkou Fm. and Datangpo Fm. in South China (Liu, 1991; Dobrzinski and Bahlburg, 2007). Doushantuo Dolomite Member overlies the Nantuo Fm. and is equivalent to the Marinoan cap carbonates in the world because of its distinctive carbonate facies and associated negative δ^{13}C values (Jiang et al., 2003; Condon et al., 2005; Wang et al., 2008). Geochronology is vital to evaluate such a global glaciation correlation. Condon et al. (2005) reported a remarkable U-Pb age of 635.2±10 Ma within the cap dolostone in this area, constraining the age of glacial termination (Fig. 1(b)). A U-Pb age of 654.5±3.8 Ma near the top of Datangpo Fm. from Maopingdong section is interpreted as a maximum

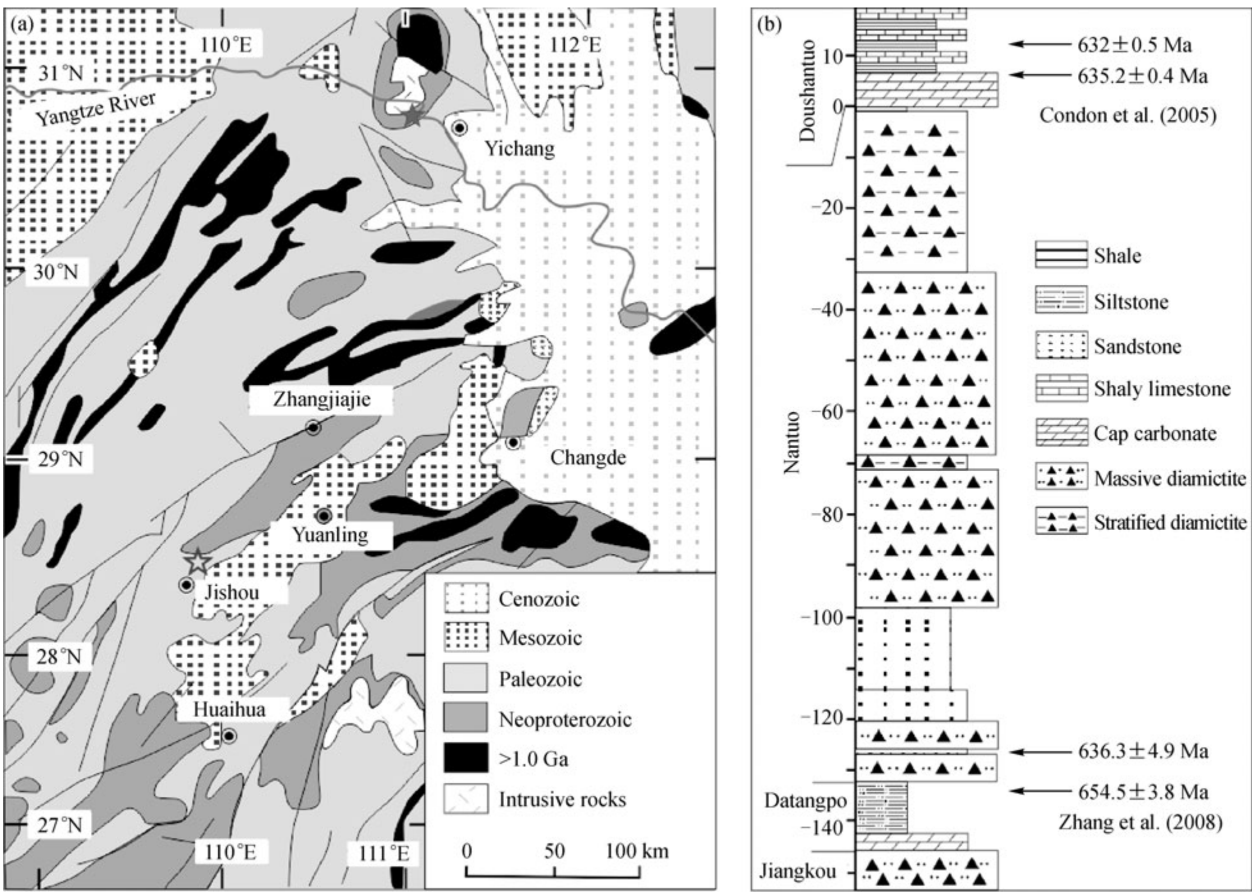

Fig. 1 (a) Simplified geological map showing locality of the studied section (Jiulongwan section denoted as the solid star) and dated section (Maopingdong section denoted as the hollow star) (modified from Zhang et al. (2008)); (b) simplified geochronology column of Nanhua strata in South China from the section denoted as the hollow star (modified from Zhang et al. (2008)), with the ages reported by Condon et al. (2005) and Zhang et al. (2008)

bound to the glacial onset (Figs. 1(a), (b)). However, the age of 636±4.9 Ma from the basal Nantuo Fm. suggests that the typical Nantuo Fm. in the continental shelf of the Yangtze platform may have been deposited within only a few million years at the end of the Marinoan glaciation (Zhang et al., 2008).

3 Sedimentary sequences

The Nantuo Fm. in the Three Gorges area can be divided into three facies: massive and crudely stratified diamictite, massive and laminated sandstone, and massive siltstone. Massive and laminated sand-siltstones are interbeded with the diamictite facies (Fig. 2).

3.1 Diamictite facies

Diamictites comprise a large portion of the Nantuo Fm. outcropped in Jiulongwan section. They are featured by thick beds (> 5 m) in greenish black (Fig. 3(a)), and appear to be massive or weakly stratiformed (Fig. 3(b)). The diamictites are of matrix-supported textures. The matrix is composed of mud and sand grains with varied clast content, and the number of clast changes vertically between clast-poor and clast-rich gradually. The lithology of clasts is of large variety, containing igneous, metamorphic and sedimentary rocks with angular to subrounded sand grains. The clasts are general granite and sandstone and not show any preferred long-axis orientation. The basal contacts of the sequences are either sharp or gradual. Two boundaries are identified in distinctly sharp and erosional contacts between diamictites and underlying sandstone (Figs. 3(b), (c)). In some cases, the basal contact appears to be transitional, implying the progressive change in either the number or the size of clast grains in comparison with adjacent units. A slightly stratified diamiactite appears in the middle part, where we observed a clast-cluster composed of material wholly coarser than the surrounding sediment (Figs. 3(d), (e)). The clast cluster occurs in isolation and is 12 m in length, 20 cm in height. Clasts in the cluster show a weakly preferred long-axis orientation.

None of the diamictites in the Nantuo Fm. in Three Gorges area exhibits the diagnostic glacial features in the section, e.g., gravel pavement, striated surfaces, glacially induced deformation, which indicates that they precipitated in a glaciomarine environment (Eyles et al., 1985; Hart and Roberts, 1994). However, a 10 cm-thick mixing zone was found in the boundary between Nantuo diamictites and underlying delta-facies Liantuo sandstones, showing a sharp downward change but a gradual upward change in lithology (Fig. 3(b)). Below the mixing zone, there are some isolated clasts obviously separated from the surrounding sediment which may be caused by subglacial processes (Piotrowski et al., 2001). Massive diamictites within a glaciomarine setting may be the rainout sediments and further reworked by sedimentary gravity flows (Eyles et al., 1985). Weakly stratification is defined by the occurrence of laterally discontinuous sandstone lens and clast-rich layers (< 10 cm thick) which may be a dump structure by sudden break-up and overturning of floating icebergs (Eyles et al., 1985; Thomas and Connell, 1985), which suggests that floating ice was present at that time. The preferred long-axis orientation of clasts in the clast cluster and fine sandstone lens also indicate a reworked process by high bottom current activity (Figs. 3(d), (e)). Besides, the granite and sandstone-rich textures in diamictite facies implied that substances in texture might be originated from the nearby Huangling granite batholith and Liantuo sandstone in Three Gorges area. Some carbonate clasts found in this facies suggest these carbonates should deposit prior to the diamictites and would be most likely from the Datangpo Fm. dominated in carbonates in Three Gorges area. Therefore, the coarse massive diamictites might represent the predominately ice-proximal and ice-contact deposits including rainout of ice-rafted debris and melt-out of materials from the base of the glacier near the grounding line, all of which contributes to the formation of this facies (Eyles et al., 1985). The clast-poor, finer-grained diamictite and weakly stratified diamictite are mainly inferred as ice-rafted debris (Eyles et al., 1985; Miall, 1985). Accordingly, the gradual transition from clast-poor diamictite to overlying sandstone and siltstone is in agreement with such interpretation (Evans and Pudsey, 2002). Variable clast concentrations in massive diamictites facies reflect a change in supply rate of the ice-rafted debris, and the absence of textural sorting in massive diamictites facies is probably due to their relatively rapid accumulation under quiet water conditions (Visser, 1994).

3.2 Sandstone facies

Two types of sandstone facies have been distinguished, i.e., fine-medium horizontally laminated gravelly sandstone with decimeter-scale silt stringers and massive fine sandstones with minor quantities of gravel, and upward into massive siltstones or diamictites (Figs. 4(a)–(e)). The gravelly sandstone displays rhythmically internal stratification, exhibiting systematic normal grading. Rhythmites are graded beds characterized by the alternating of the thin beds between fine and coarse gravelly sandstone lamination (Fig. 4(c)). Besides, silt stringers interlaminated with coarse gravelly sandstone exhibit asymmetric ripple and have small amplitudes of approximately 2 cm (Fig. 4(d)). Laminations are clearly subaqueous in origin and are not of direct glacial origin. Accordingly, the presence of silt stringers also reflects a high current activity (Eyles et al., 1987).

The massive gravelly sandstones occur as 3 m thick units, interbedded with diamictites or siltstones, and the

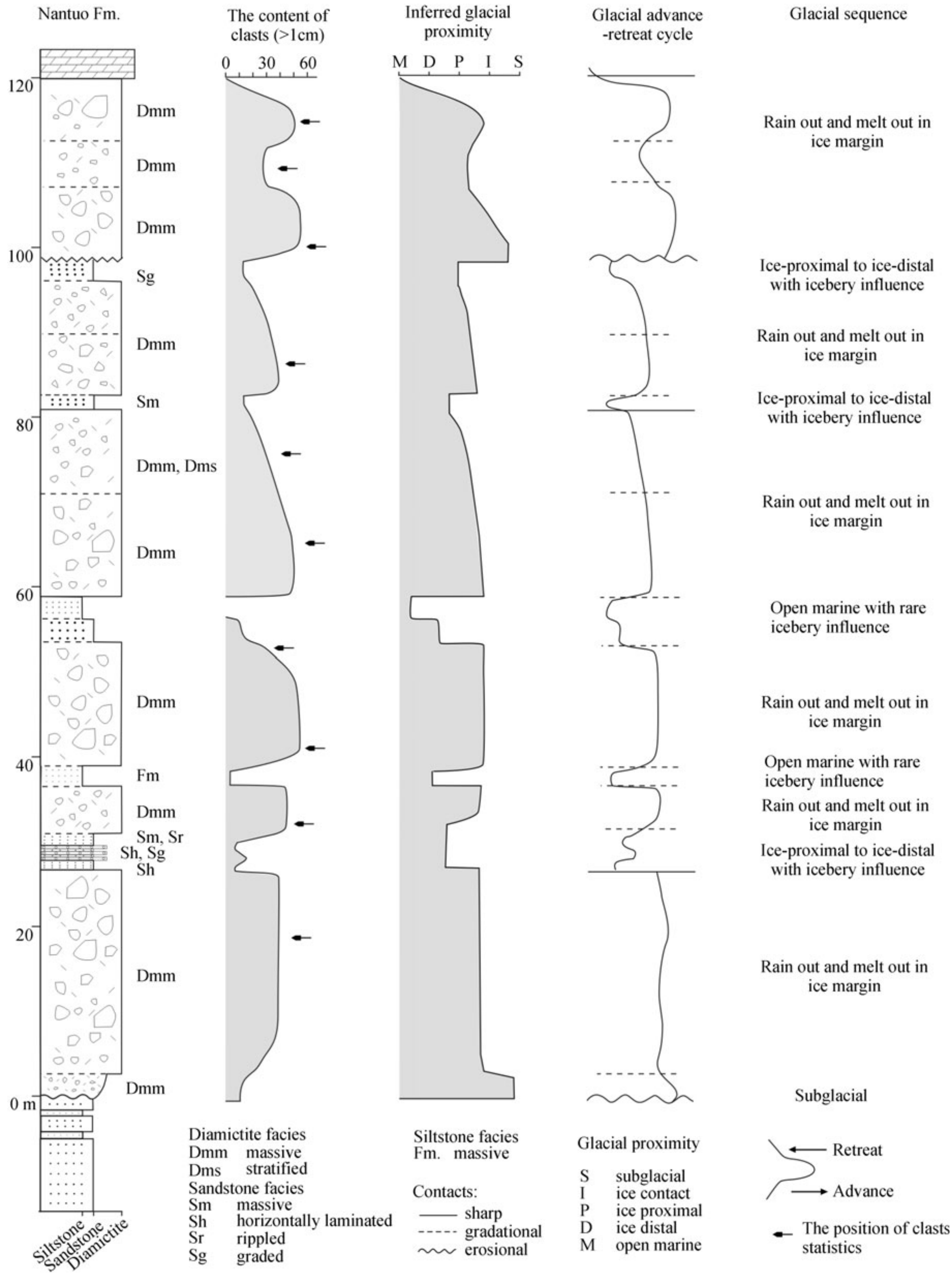

Fig. 2 Stratigraphic log of Nantuo Fm. in Jiulongwan section of Three Gorges area. The content of the clasts based on the field excursions and statistics in 1 m^2. The glacial advance and retreat interpretation is based upon facies sequence and sedimentological criteria discussed in the text

Fig. 3 (a) Clast-rich massive diamictites. The diameter of the coin is 2 cm; (b) sharp and unconformable basal contact of Nantuo Fm. with underlying Liantuo Fm. Hammer handle for scale is 29 cm long; (c) sharp and irregular contact between underlying massive gravelly sandstone and massive diamictite; (d) stacked clast-cluster show preferred long-axis orientation of clasts; (e) weakly stratified diamictite with discontinuous sandstone unit and stacked clasts cluster. Hammer handle for scale is 29 cm long

gravels in this facie decrease in quantity gradually upward. The lowest boundary of this facies is gradual with clast-poor diamictite (Fig. 4(e)), and the upper boundary of this facie is variable, either with a sharp or gradual contact with overlying diamictite and siltstone. The gradual upward decrease in the gravel amount in gravelly sandstone may show a decreased influence of ice-rafting. The sandstone facies could thus be interpreted by the rainout of clay, silt, and sand from melt water plumes emanated from the glacier terminus having clasts in ice-raft (Eyles et al., 1985).

Fig. 4 (a) Sandstone deposit directly above the diamictite with a sharp contact. The diameter of the coin is 2 cm; (b) sandstone lens within the weakly stratified diamictite with some lone stones; (c) sandstone with asymmetric rippled silt stringers; (d) graded bedding within sandstones; (e) massive sandstone gradationally contact with adjacent units; (f) massive siltstone with rare lone stone

3.3 Siltstone facies

These facies are greenish black, poorly sorted, and dominated by silt and mud (Fig. 4(f)). The fine-grained siltstones lack obvious outsized clasts. Visual examination reveals no lamination and a gradation into adjacent clast-poor diamictites. The lack of graded beds rules out a typical turbidite deposition. This facies could thus be interpreted as the suspension settling with clay and silt from the melt water plumes in a relatively quiescent marine environment (Visser, 1991). The minor presence of small lone stones is interpreted as drop stones, although the lithologies do not allow the preservation of perfect drop stone structures (Thomas and Connell, 1985). Therefore, the siltstone facies is proposed to be a distal glaciomarine environment, and the glacial influence is restricted to the deposition of the suspended sediment but not the ice-rafted debris (Eyles et al., 1985; Eyles et al., 1987; Evans and Pudsey, 2002).

4 Glacier advance-retreat cycles

The nature of beds and sequences is particularly important for the interpretation of glacier advance and retreat, especially the contacts between different lithofacies (Miller, 1989). An advance sequence of subaerial or ground ice could be easily recognized by the diamictites abruptly overlying non-glaciogenic rocks and the basal contact is generally sharp with erosional and deforming contact (Miller, 1989; Hart and Roberts, 1994). Subaqueous advance sequence is characterized by gradual contacts between shale and overlying diamictite or a gradual change in diamictite character (e.g. clast content, and/or color) (Miller, 1989). There are two obviously sharp and erosional contacts identified in our sections which represent two large-scale glacier advances (Fig. 2). The first one is the boundary between the underlying delta-facies Liantuo sandstones and the overlying Nantuo diamictite which may indicate a subaerial ice advance. It has been suggested that the shear stress distribution under a glacier moving over a deforming bed is non-uniform, leading to a gradient in the intensity of deformation (van der Wateren, 1995). High strain in the top part of Liantuo sandstones results in the strongest mixing, so that the original laminated structures disappear into a homogenized matrix with some far-transported clasts (Fig. 3(b)). The mixing zone identified is interpreted as lodgement till deposited by grounded ice advancing across underlying Liantuo sandstones. The second one is recognized in the upper part of Nantuo Fm. featured by massive diamicetites abruptly overlying gravelly sandstones (Fig. 3(c)). This contact boundary is generally sharp with erosional relief but no glacial deformation bed, which may be contributed by a large-scale subaqueous glacier advance. Besides, subaqueous advance is characterized by the siltstones and sandstones facies gradually into overlying diamictite facies. In some cases, the gradual increase in the number and size of clasts within the diamictite facies may indicate a smaller glacier advance.

It is well known that the erosive processes rather than the depositional processes are dominated during glacier advance. As a result, the stratigraphic record may mainly reflect a sedimentary accumulation during glacier retreat (Miall, 1985). In diamictite successions, discrete sandstone and siltstone intervals may attribute to multiple glacier retreat process, and the gradual decrease of the number and size of clasts within one diamictite bed possibly reflects a small-scale glacier retreat.

Nantuo glacial sequences in Three Gorges area consist of a series of sequences including ice-contact massive diamictite, ice-proximal massive and weakly stratified diamictite, ice-proximal laminated sandstone and massive sandstone, and ice-distal massive siltstone. The presence of graded and planar-stratified sandstone, silt stringers and dump structure supports an environment of periodic open water conditions, although a large portion of the section are diamictite facies. The diamictite facies may attribute to glacial rain-out and melt-out processes. Sandstone and siltstone intervals in diamictite succession and the changes of clasts in diamictite are the evidences for significant environment fluctuations and multiple glacier advance-retreat cycles.

5 Conclusions

The Nantuo glacial strata may deposit at the end of the Marinoan glaciation, as supported by the previous dating data from the fallout tuff within the basal layer of the Nantuo Fm. This is especially true in Three Gorges area where Gucheng/Jiangkou Fm. and Datangpo Fm. have not recorded. Multiple glacier advance-retreat cycles in the Nantuo Fm. are indicated by the deposits. Our studies on sedimentary successions of the Nantuo Formation convince the stepwise termination rather than a catastrophic end of Marinoan glaciation, consistent with the recent related investigations.

Acknowledgements We thank so much to Prof. Shucheng Xie and two anonymous reviewers for their great constructive comments and corrections to our manuscript. This research was financially supported by the National Basic Research Program of China (Nos. 2011CB808805 and 2009CB21950605), the National Natural Science Foundation of China (Grant Nos. 41172102 and 40772073), SinoPec project (G0800-06-ZS-319) and 111 Project (B08030).

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