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Stratigraphical and $\delta^{13}C$ records of Permo-Carboniferous platform carbonates, South China: Responses to late Paleozoic icehouse climate and icehouse–greenhouse transition

Chao Liu [a,b,c], Emilia Jarochowska [c], Yuansheng Du [a,*], Daniel Vachard [d], Axel Munnecke [c]

[a] State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Wuhan 430074, China
[b] Faculty of Earth Science, China University of Geosciences, Wuhan 430074, China
[c] GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen-Nürnberg, Loewenichstrasse 28, 91054 Erlangen, Germany
[d] 1 rue des Tilleuls, 59152 Gruson, France

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ABSTRACT

Little attention has been focused on the stratigraphical imprints of the Late Paleozoic Ice Age on the equatorial eastern Paleo-Tethys. An integrated study of biostratigraphy, microfacies, and stable carbon isotope stratigraphy was carried out on Pennsylvanian–middle Guadalupian carbonates of the Gongchuan section in the Bama Platform, South China. It records seven cooling and two warming pulses in the pre-Kungurian interval, comparing with ice-proximal stratigraphical records and far-field indirect proxies in lower latitudes. A Kungurian negative $\delta^{13}C$ excursion (from +4.4‰ at the base of the Kungurian to +1.6‰) recorded only in the subequatorial belt is documented here. It is followed by a global positive $\delta^{13}C$ trend reaching +5.3‰ near the Cisuralian–Guadalupian boundary. Seven third-order shallowing–upward cycles are reported for the first time from the Kungurian succession. The duration of each cycle is estimated to ca. 1 myr. These cycles are interpreted as being of glacioeustatic origin and mainly driven by long-period modulations of obliquity (~1.2 myr) under major pCO_2 decreasing condition. This interpretation is supported by recent climate–ice sheet modeling and Cenozoic glaciation studies, which argue that astronomical forcing will be amplified by large-magnitude perturbations in the carbon cycle, when only localized ice-centers persist. Our results emphasize the need for integration of sedimentological and paleoclimatological proxies in elucidating the dynamics of the deglacial phases of the Late Paleozoic Ice Age.

1. Introduction

The Late Paleozoic Ice Age (LPIA; ca. 332–260 Ma ago) is the most severe glaciation in the Phanerozoic, comparable with the Last Glacial Maximum (Raymond and Metz, 2004). Its onset, development and demise have been proposed to be associated with the reconfiguration of Pangea (Saltzman, 2003), atmospheric pCO_2 variations (Royer, 2006; Montañez et al., 2007; Birgenheier et al., 2010), as well as vegetation dynamics (DiMichele et al., 2001; Cleal and Thomas, 2005; Horton et al., 2010; DiMichele, 2014). Multiple discrete pulses of glacial and non-glacial intervals, corresponding to the waxing and waning of ice-sheets in high-latitude Gondwana, rather than a prolonged icehouse period, have been recognized in recent ice-proximal stratigraphical studies (Isbell, 2003; Fielding et al., 2008a, 2008b, 2008c; Shi and Waterhouse, 2010). Although the precise timing is constantly being improved, it is widely accepted that the LPIA had its acme at the Pennsylvanian–Permian transition (Koch and Frank, 2011; Isbell et al., 2012; Montañez and Poulsen, 2013), which was followed by a major deglaciation on Gondwana during the Sakmarian (Isbell, 2003; Montañez et al., 2007). Subsequently, only small persistent ice-centers existed in western and eastern Australia and Africa until the late Guadalupian (Fielding et al., 2008a, 2008b; Mory et al., 2008; Frank et al., 2015).

Great efforts have been made to reconstruct the history of the LPIA by investigating the direct glacial deposits (e.g. Isbell, 2003), it is however difficult to obtain reliable ages as a result of their typically poor preservation (Smith and Read, 2000). Far-field indirect proxies, such as stable isotopes and sedimentary cyclothems from lower-latitude successions have been suggested to faithfully reflect the LPIA (Smith and Read, 2000; Frank et al., 2008; Heckel, 2008). For instance, stable isotopic compositions are extensively utilized as indicators of seawater temperature (Mii et al., 1999; Grossman et al., 2008; Korte et al., 2008), ice volume (e.g. Joachimski et al., 2006; Chen et al., 2013), and pCO_2 levels (e.g. Montañez et al., 2007). The classical Pennsylvanian cyclothems in the tropical area of Pangea are hypothesized as being of glacioeustatic origin, resulting from Milankovitch-driven waxing and

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* Corresponding author.
E-mail address: duyuansheng126@126.com (Y. Du).

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waning of the ice-sheets on Gondwana (Heckel, 1986, 2008; Stemmerik, 2008). Nevertheless, most of such investigations came solely from circum-Euramerica subtropical/tropical regions (e.g. North America, UK, Italy, and Austria) and isolated islands in Panthalassa (e.g. Japan). Less has been focused on the stratigraphical imprints of the LPIA on the equatorial eastern Paleo-Tethys (South China) (Liu et al., 1994; Chen et al., 1998; Izart et al., 2003; Shi and Chen, 2006).

In addition, two significant questions are still pending and need to be answered. Firstly, the interpretation for the classical Pennsylvanian cyclothems has been challenged by recent climate–ice sheet models, which indicate that atmospheric pCO_2 played a key role in determining LPIA dynamics and low-latitude climate variability (Horton et al., 2007; Horton et al., 2012). The models indicate that orbital forcing alone cannot bring about glacioeustatic fluctuations of such magnitude as previously calculated for the LPIA (100–200 m; Joachimski et al., 2006; Rygel et al., 2008) without major perturbations in carbon cycle (Horton and Poulsen, 2009). In contrast, localized ice-centers are more sensitive to orbital forcing (Zachos et al., 2001; Horton and Poulsen, 2009). Therefore, what was the sea-level response to orbital forcing and major pCO_2 fluctuations during the icehouse to greenhouse transition when only localized glaciers grew in Australia? Secondly, the global sea-level curve indicates glacioeustasy-related high-frequency cycles from the Sakmarian to the Capitanian (Haq and Schutter, 2008), i.e. after the collapses of major ice sheets on Gondwana (e.g. Isbell, 2003). High-frequency cyclicity in geochemical, sedimentological and geophysical proxies have been documented in the Sakmarian, Wordian, and Capitanian (Fang et al., 2015; Tierney Cramer and Bostic, 2015; Yao et al., 2015; Shi et al., 2016), yet no specific studies refer to the Kungurian. Was such glacioeustatic high-frequency cyclicity also present in the Kungurian?

Here, we present a Pennsylvanian through middle Guadalupian carbon isotope stratigraphy and a relative sea-level curve based on biostratigraphical and microfacies analyses of the Gongchuan section in the Bama Platform, South China (Fig. 1). Thus, this paper aims to (1) establish high-resolution foraminiferal zonation, (2) test the stratigraphical imprints of the late Paleozoic icehouse climate in the equatorial Bama Platform, (3) highlight the shallowing–upward cycles in the Kungurian, and (4) discuss their glacioeustatic origin and both orbital forcing and major pCO_2 fluctuations as their potential drivers during the icehouse to greenhouse transition.

2. Geological and stratigraphical settings

Throughout the Permo-Carboniferous interval the South China Block was located in an equatorial or subequatorial position (Fig. 1A; Blakey, 2011). The paleogeographic distribution of emerged areas, such as the Upper Yangtze Land, and epicontinental shallow carbonate and basin facies within the block were essentially inherited from the Mississippian outlines (Fig. 1B; Liu and Xu, 1994). The Youjiang Basin was a large basin developed on a passive continental margin during the Late Paleozoic. It was bordered to the west and north by the Upper Yangtze Land, and faced the Paleo-Tethys to the east and south (Fig. 1B) (Lehrmann, 1999). Isolated platforms, including the Bama Platform studied here, developed on tectonic elevations surrounded by deep-basin facies (Du et al., 2013).

The Gongchuan section (N 23°40′38.00″, E 107°53′07.22″) is located in the southern margin of the Bama Platform (Fig. 1C; Liu et al., 2015). About 1400-m-thick Mississippian to lower Guadalupian carbonate succession is continuously exposed in the Gongchuan outcrop. The Mississippian strata in the section have been previously documented

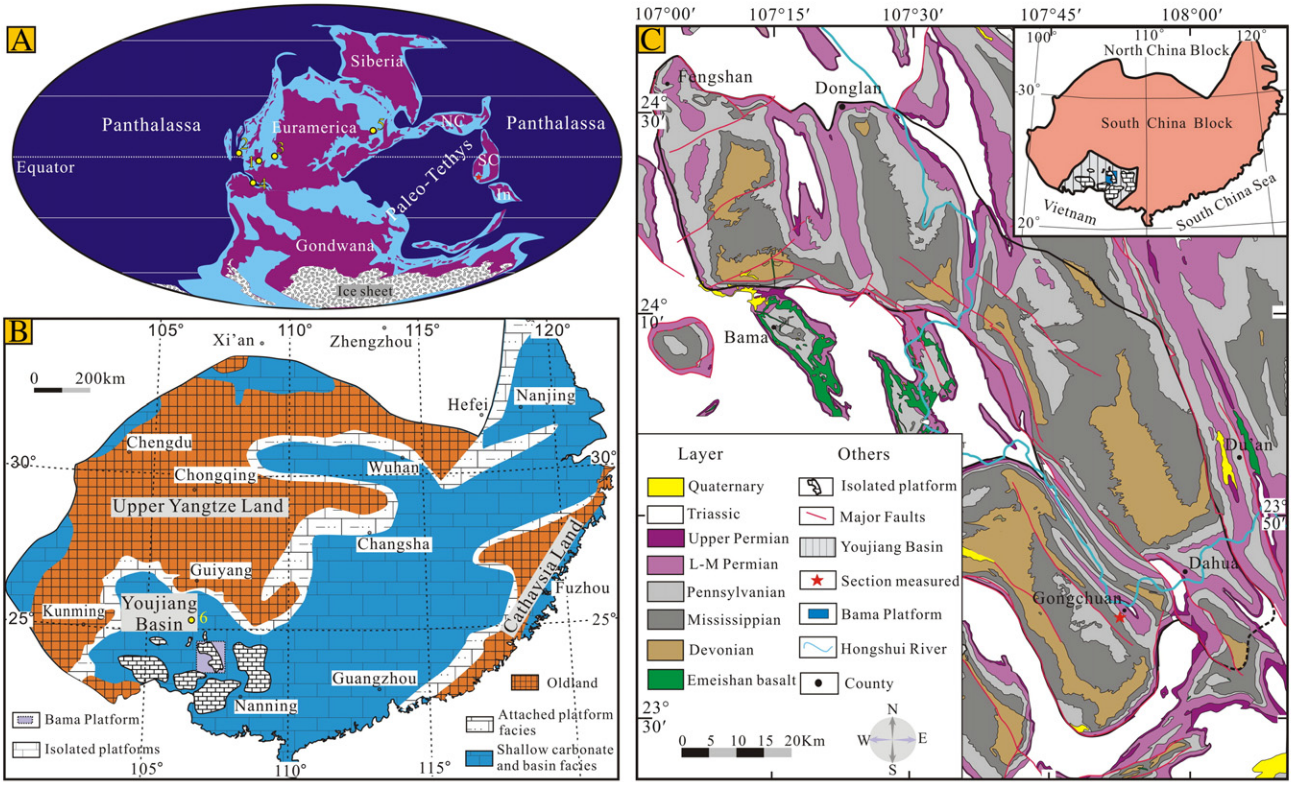

Fig. 1. Location map of the Bama Platform and the studied Gongchuan section, Youjiang Basin, South China. A: Global paleogeographic reconstruction for the Carboniferous–Permian transition; NC — North China, SC — South China, In — Indochina, 1 — Orogrande Basin, 2 — Rockland Section, northeastern Nevada, 3 — Newby 2-28R Core, US Midcontinent, 4 — Venezuelan Andes, 5 — Donets Basin, Ukraine; the red star represents the Gongchuan Section. B: Paleogeographic map of South China and location of the Youjiang Basin and the Bama Platform; 6 — Naqing Section. C: Geological map of the Bama Platform showing location of the studied Gongchuan Section. The borders of the Youjiang Basin are marked as major faults (except for the national boundary in the southwestern Youjiang Basin).
Panel A is modified from Blakey (2011). Panel B is from Liu and Xu (1994). Panel C is compiled from Liu et al. (2015).