



CHRONOLOGY OF NEOPROTEROZOIC ICE AGES IN CENTRAL BRAZIL

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Keywords: Neoproterozoic glaciations, U-Pb and Pb-Pb geochronology, cap carbonates, ash beds, Brazil

INTRODUCTION

The end of the Precambrian Eon is punctuated by glacial events rapidly followed by widespread carbonate sedimentation (cap carbonates) with negative carbon isotopic signatures (Hoffman and Schrag, 2002). Paleomagnetic data show low-inclination magnetization in some glacial deposits suggesting ice-caps have reached the Equator during these times (Sohl et al., 1999). These data suggest that the Neoproterozoic might have experienced the most severe climatic changes in Earth's history, which could have been the evolutionary bottlenecks for the Cambrian "life-explosion" (Knoll et al., 2004).

Several models have been proposed to account for the sedimentological, paleomagnetic and isotopic data, including Phanerozoic-like scenarios, the "snowball earth" hypothesis and its softer variants (slushball earth) as well as the high-obliquity hypothesis. Advocates of uniformitarian models have questioned the sedimentological and paleomagnetic data and suggest the Neoproterozoic ice ages do not differ from those in Phanerozoic times (Eyles and Januszczak, 2004). The snowball earth hypothesis implies synchronous glacial deposition worldwide, with ice-ages lasting for at least tens of millions of years in order to provide the build-up of atmospheric CO₂ necessary for the snowball thaw (Hoffman et al., 1998). The slushball scenario is less stringent in terms of ice-age duration (Hyde et al., 2000). The high-obliquity hypothesis implies non-synchronous glacial events and strong climate variability due to the inversion of temperatures in Earth's surface due the increase in planet's obliquity to more than 54° (Williams, 1993; Williams et al., 1998).

None of the models above fully explain the available data. Field evidence and isotopic data have been used to infirm or negate the contemporaneity of glacial deposits and the cap carbonates. Thus, reliable ages on these rocks are of utmost importance in discriminating between these scenarios. However, the limited number of radiometric ages and their associated errors makes it difficult to test global correlation of glacial units, so that the geochronological record may be explained in terms of limited diachronous glacial episodes, global scale glacial episodes or both.

GLACIAL EPISODES IN CENTRAL BRAZIL

Glacial deposits conformably covered by carbonate rocks have been described in Central Brazil since the 1930's (Figure 1). In the São Francisco craton and surrounding fold belts they correspond to the diamictites of the Jequitai Formation and Macaúbas Group (glacial) and the carbonates of the Bambuí Group, in Minas Gerais, and Bebedouro (glacial) and Salitre (carbonates) Formations in Bahia. Along the southern border of the Amazon craton and the Northern Paraguay fold-belt, these successions are grouped into the Puga Formation (diamictites) and the Araras Group (carbonates). To the south, along the Southern Paraguay belt, the Puga Formation diamictites are covered by carbonates of the Corumbá Group. The Araras and Corumbá Groups have been traditionally correlated, despite the lack of age constraints in both units and the presence of metazoan fossils *Cloudina* and *Corumbella* restricted to the upper part of Corumbá Group (Tamengo Formation). Aiming to better understand the stratigraphic relationship among these units, we here review the geochronological survey performed during the last decade on carbonates found above Neoproterozoic glacial deposits in central Brazil.

ANALYTICAL PROCEDURES

The Pb isotope analyses on carbonates from the Bambuí e Araras groups were carried out at the Geochronological Research Center, at the University of São Paulo, following the analytical procedures of Babinski et al. (1999). Pb isotopic compositions were corrected for a mass fractionation factor of 0.12‰ amu⁻¹ determined based on analyses of common Pb standard NBS 981. Pb blanks were 30-50 pg and have negligible effect on the Pb measured isotopic compositions. Pb-Pb isochron ages were determined using the Model 1 regression of Isoplot (Ludwig, 1999). Errors are reported at the 95% confidence level.

Zircon crystals from two ash beds intercalated in the Tamengo Formation were separated for CL imaging and U-Pb dating. The CL imaging was carried out at the Institute of Mineral Resource, Chinese Academy of Geological Sciences at Beijing. Zircon U-Pb isotope dating was done in the SHRIMP II at the Beijing SHRIMP Laboratory, Beijing. The U-Pb isotope data were collected in sets of five scans throughout the masses

and a reference zircon TEM (417 Ma) was analyzed every fourth analysis. The measured U, Th and Pb abundances as well as Pb isotope ratios were normalized using the reference zircon SL13 (572 Ma) values. Common Pb for the samples was corrected using the measured ^{204}Pb , and errors are reported with 1σ errors. The data were treated following Compston et al. (1992) with the ISOPLOT program of Ludwig (2001).

RESULTS

In the São Francisco Craton we have dated the lowermost carbonates of the Sete Lagoas Formation (Bambuí Group). These deep platform deposits are 90 m thick and contain, in their first ten meters, calcite crystal-fans (aragonite-pseudomorphs). They are characterized by negative $\delta^{13}\text{C}$ values, which increase to values towards 0‰ accompanying the vanishing of sea-floor precipitates upward. Eight carbonate samples from the Sambra quarry were selected for the geochronology study; six from the base of the quarry, corresponding to the deep-platform crystal-rich sediments, and two from the upper part of the quarry, which includes storm-wave crystalline limestones. Samples from the lower Sambra quarry yielded variably radiogenic Pb isotopic compositions with $^{206}\text{Pb}/^{204}\text{Pb}$ ratios ranging from 19.1 to 32.8, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.68 to 16.56, and $^{208}\text{Pb}/^{204}\text{Pb}$ from 38.1 to 39.0. The fibrous precipitates preserved the most radiogenic Pb ratios. Samples from the upper part of the quarry revealed uniform and non-radiogenic Pb ratios ($^{206}\text{Pb}/^{204}\text{Pb} = 18.8$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.65$), and the results of these two samples were not used for regression. The Pb ratios obtained from the lower part of the succession yielded a Pb-Pb isochron age of 740 ± 22 Ma (95% confidence level) (Babinski and Kaufman, 2003). Because the rocks of this outcrop are extremely well preserved and undeformed, suggesting that the Pb isotopic system was not disturbed by later events, that data have been interpreted as the depositional age for this cap carbonate.

In the Northern Paraguay belt we have dated the cap carbonates of the Mirassol d'Oeste Formation (Araras Group), which directly overlies the diamictites of the Puga Formation. They have been studied in detail by Nogueira et al. (2003) and Alvarenga et al. (2004). The carbonate section comprises a lower unit of ca. 22 m thickness, composed of laminated pink dolostones containing tepee-like structures, tubestones and stromatolites. The upper part of the section (ca. 23 m thick) is characterized by intercalation of homogeneous and laminated fine-grained limestone and laminated mudstone; calcite crystal-fans (aragonite-pseudomorphs) can be found in this section. Twelve samples (six from each part to the section) were selected for the geochronology study. The $^{206}\text{Pb}/^{204}\text{Pb}$ ratios range from 18.5 to 65.2, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.72 to 18.56, and $^{208}\text{Pb}/^{204}\text{Pb}$ from 38.3 to 52.7 and yielded a Pb-Pb isochron age of 627 ± 32 Ma (95% confidence level), which is interpreted as the depositional age of this cap carbonate.

In the Southern Paraguay Belt, we have studied the fossil-bearing Tamengo Formation, upper Corumbá Group (Gaucher *et al.*, 2003). Twelve ash beds intercalated with three levels of *Cloudina* were found

within a 15-m thick limestone section of the lower part of the Tamengo Formation at the Corcal quarry east of Corumbá city. Two 10-cm thick ash beds were collected for geochronological analysis, placed about 30 cm below (CTUF-6) and 15 cm above (CTUF-9) the lowest occurrence of *Cloudina*. Standard separation procedures yielded a small amount of zircon crystals for each sample. The U-Pb analyses from both samples presented complex results (Boggiani et al., 2005). Sample CTUF-6 contains euhedral crystals that exhibit oscillatory zoning and range in length from 80 to more than 200 μm . Most of the crystals separated from sample CTUF-9 are euhedral and about 200 μm long but do not exhibit oscillatory zoning. Cathodoluminescence images reveal crystals with relatively dark cores and bright rims.

Three grains of sample CTUF-6 yielded Paleoproterozoic ages (ca. 1.9 Ga); other grains (14 spots) produced very discordant data. However, the least discordant data (6 spots in 3 grains) gave a weighted-mean $^{238}\text{U}/^{206}\text{Pb}$ age of 545 ± 6 Ma, which could indicate the zircon crystallization age of this volcanic tuff. The data obtained on sample CTUF-9 do not permit a straightforward interpretation. Seven spot analyses from five grains of the upper sample (CTUF-9) yielded a weighted-mean $^{238}\text{U}/^{208}\text{Pb}$ age of 570 ± 11 Ma, which cannot be reconciled with the younger age (545 ± 6 Ma) obtained for the lower ash bed (CTUF-6). Considering the complexity of the results prevents any conclusive interpretation and these data should be regarded with caution. Hence, more data are still necessary to define the age of these rocks.

DISCUSSION AND CONCLUSIONS

Three glacial intervals have been recently proposed for the Neoproterozoic: Sturtian, Marinoan and Gaskiers (Halverson et al., 2005). The age of the older one, the Sturtian glacials, is controversial. Ages varying within the wide range of 750 to 680 Ma were attributed to purported Sturtian glacial rocks or the associated carbonates. This distribution could indicate diachronous glacial deposition at the beginning of the Neoproterozoic. Our age obtained on cap carbonates from the Sete Lagoas Formation fits to the older 'Sturtian' ages obtained in Namibia (741 ± 6 Ma in Rosh Pinah Formation volcanic rocks; Frimmel et al., 1996), Zambia (735 ± 5 Ma in Grand Conglomerat; Key et al., 2001) and Oman (723 ± 16 –10 Ma in Ghubrah Formation; Brasier et al., 2000). The Marinoan successions yield consistent ages at ca. 635 Ma for Namibia and China (Hoffmann et al., 2004; Condon et al. 2005). The age obtained for the base of the Araras Group fits well these ages suggesting that Marinoan Glaciation represents a global and synchronous event. Finally, the ages obtained on ash beds in the Southern Paraguay belt, although promising, show a very complex behavior and are difficult to interpret. If the ca. 545 Ma age holds true for the limestone that contains *Cloudina* fossil (Tamengo Formation), the post-Marinoan Araras Group and the upper part (Tamengo Fm.) of the Corumbá Group (north and south Paraguay belt, respectively) cannot be correlated.

ACKNOWLEDGMENTS

The authors thank CNPq for their research fellowships and grants. Financial support for this research has been given by FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and Ministry of Science and Technology (PRONEX Project).

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RESUMO

O final do Precambriano é caracterizado pela abundância de depósitos glaciais, comumente sobrepostos por carbonatos com valores de $\delta^{13}\text{C}$ negativos (cap carbonates). Estes depósitos estão possivelmente relacionados aos episódios glaciais mais extremos ocorridos na história do planeta, precedendo a radiação dos metazoários. O ainda limitado conjunto de dados geocronológicos para estas unidades sugere três eventos glaciais durante o Neoproterozóico: Sturtiano, com idades variando entre 740 e 680 Ma, Marinoano, com idade em torno de 635 Ma, e Gaskierano, datado precisamente em 582 Ma. Nessa contribuição são apresentados dados geocronológicos obtidos em três unidades, na porção central do Brasil. Uma idade isocrônica Pb-Pb de 740 ± 20 Ma foi obtida para carbonatos da Formação Sete Lagoas, porção basal do Grupo Bambuí, Cráton do São Francisco. Uma idade Pb-Pb de 627 ± 32 Ma foi obtida para carbonatos de capa da Formação Mirassol d'Oeste, base do Grupo Araras, na porção sudeste do Cráton Amazônico. Na porção sul da Faixa Paraguai foram datados zircões, pelo método U-Pb (SHRIMP), extraídos de camadas de tufos intercaladas em carbonatos contendo fósseis de *Cloudina*. Apesar do comportamento complexo apresentado por estas amostras, uma idade de 545 ± 6 Ma obtida em alguns zircões analisados é interpretada, preliminarmente, como a idade dos carbonatos da Formação Tamengo. As idades obtidas nos grupos Bambuí e Araras correspondem, respectivamente, aos intervalos comumente atribuídos aos episódios Sturtiano e Marinoano. A idade obtida na Formação Tamengo, permite calibrar a idade de aparecimento da *Cloudina*, após os eventos glaciais.

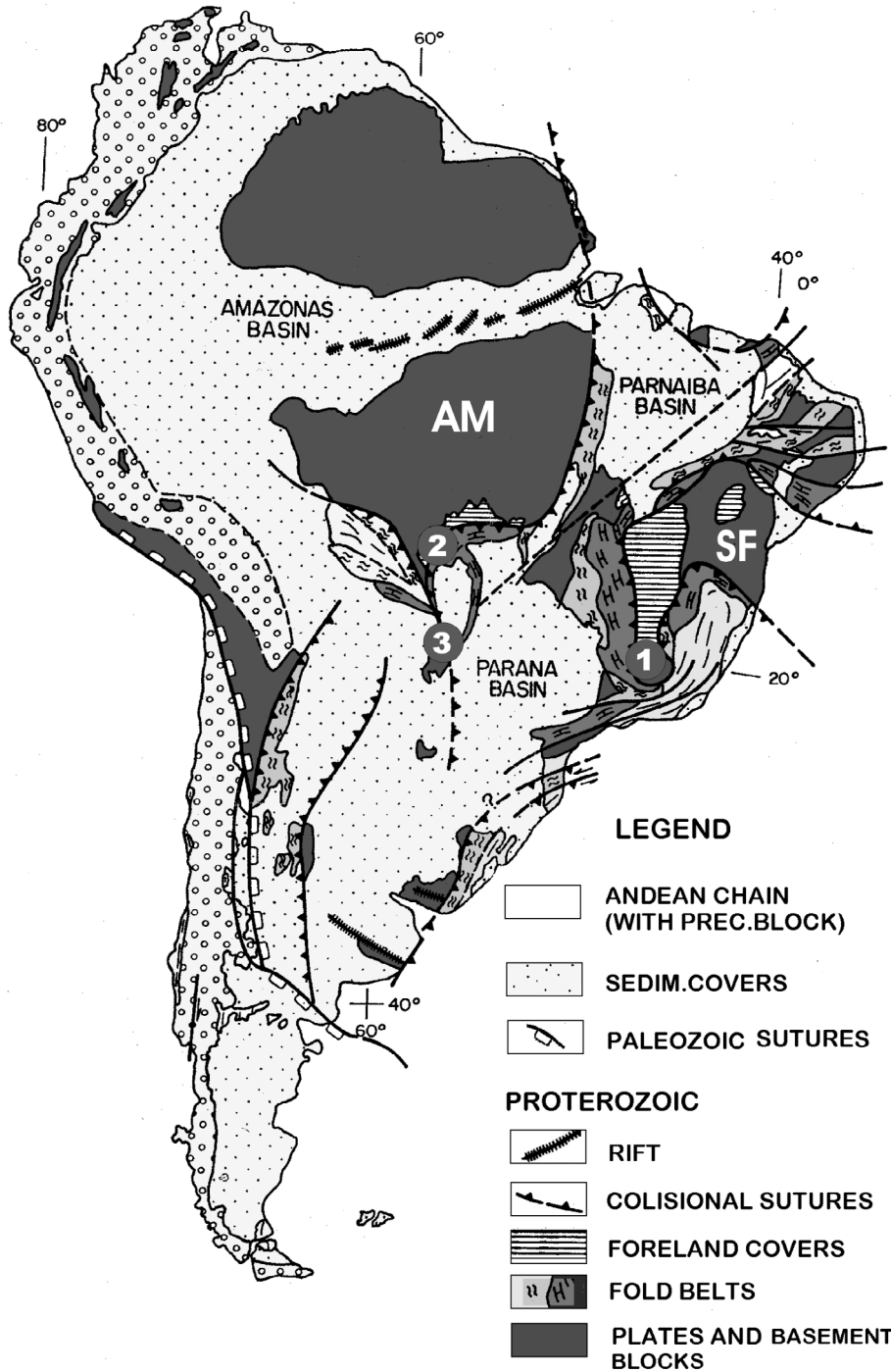


Figure1. Simplified geological map of South America showing the location of the geological units dated in this study (numbered circles): 1 = cap carbonates from the Sete Lagoas Formation, Bambuí Group; 2 = cap carbonates from the Mirassol d'Oeste Formation, Araras Group; 3 = ash beds intercalated in Cloudina-bearing carbonates of the Tamengo Formation. AM = Amazon Craton; SF = São Francisco Craton.