A pre-Sturtian depositional age of the lower Paraguay Belt, Western Brazil, and its relationship to western Gondwana magmatism

Talitta Nunes Manoel[1*]; David Selby[2,3]; Matthieu Emmanuel Galvez[4]; Jayme Alfredo Dexheimer Leite[5]; Luan Nonato Figueiredo[5]

[1]*Rio de janeiro State University, Programa de pós-graduação. Faculdade de Geologia (FGEL)- UERJ. São Francisco Xavier street, 524- Maracanã, Rio de Janeiro. E-mail: nunestalitta@gmail.com*

[2]*Department of Earth Sciences, Durham University, Durham, England, UK, DH1 3LE.*

[3]*State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Resources, China University of Geoscience Wuhan, Hubei Province, 430074, China.*

[4]*Swiss Federal Institute of Technology, Zurich Institute of Geochemistry and Petrology NO E 53.2 Sonneggstrasse 5 CH 8092 Zurich, Switzerland.E-mail: matthieu.galvez@erdw.ethz.ch*

[5]*Federal University of Mato Grosso, Programa de pós-graduação, Faculdade de Geociências (FAGEO), UFMT, Cuiabá, Brazil.*

**corresponding author.*

Abstract

The Neoproterozoic Paraguay Belt in mid-eastern Mato Grosso, western Brazil, records the geological evolution of the margins of western Gondwana. The lack of absolute geochronology for the Paraguay Belt has hampered both regional and global stratigraphic correlations. Here we determine the depositional age for the Peresopolis black slate that belongs to the base of the Cuiabá Group in the Paraguay Belt using Re-Os geochronometry. We obtain a narrow Re-Os age interval of 784 ± 8 Ma and a juvenile initial $^{187}Os/^{188}Os$ composition (Os_i) of 0.15 ± 0.03. These data indicate that the Peresopolis black slate is Tonian in age and was deposited in a basin strongly influenced by the weathering of juvenile material, and potentially linked to the early rifting of Rodinia on western Gondwana. These slates record a time interval that is poorly represented in Brazil and with few counterparts in other Neoproterozoic basins globally. As such, our work is a foundation for future geochemical correlations and paleoenvironmental reconstructions of this critical transition of Earth history in Brazil and elsewhere.

Keywords: Re-Os geochronology; Tonian; Rodinia; Organic-rich slate; Paraguay Belt.

1. Introduction

The geological record indicates that dramatic environmental changes occurred in the late Neoproterozoic. These events, which included tectonic reorganization, diversification of life and periodic swings between climatic extremes (Shields-Zhou and Och, 2011; Sahoo et al. 2012; Lyons et al. 2014; Knoll and Nowak, 2017; Halverson et al. 2018), are so profound that they mark the end of an Eon. However, limited chronostratigraphic constraints hamper our ability to reconstruct the complex paleoenvironmental changes that occur during this period of Earth history (Halverson et al. 2018).

Existing temporal constraints show that the emplacement of large igneous provinces in the Neoproterozoic between 825 and 717 million years ago (Ma) coincide with the breakup of the Rodinia supercontinent (Evans, 2009) and global rift-related volcanism (Li et al. 2003; Knoll et al. 2006; Li et al. 2008; Halverson et al. 2009; Cohen and Macdonald, 2015; Porter, 2016; Cox et al., 2016). This tectonic reorganization enhanced sedimentation in several nearby marine basins, in particular along the western margin of Gondwana (Brito Neves, 1999). It is thought that the shallow marine sediments in the Paraguay Belt in Brazil record this major geodynamic transition.

Although the consensus holds that these sequences were deposited on the southern edge of the Amazonian Craton, their depositional age remains unclear, hindering their use in worldwide paleoenvironmental cross-correlations. Detrital zircon U-Pb chronology bracket a maximum possible age of the source materials between 927 and 653 Ma (Batalha, 2017; Babinski et al. 2018). However, such a range in ages are problematic because many large isotopic swings and two major glaciations (Halverson et al. 2005) occurred in this period of the Neoproterozoic Earth.

A prerequisite for the reconstruction of the Neoproterozoic Earth by global correlation of geological strata is precise age dating. Calibrating the Proterozoic Eon (2500 - 541 Ma) can be challenging given that there are significant gaps, primarily due to the limitations of the biostratigraphic record, and the fragmentary and consistently deformed sedimentary strata (Knoll and Nowak, 2017; Halverson et al. 2018). Therefore, the goal of this study is to provide robust age constraints for the Cuiabá Group, and with this, explore the potential future use of the Peresopolis slate as an indicator of paleoenvironmental conditions for the Tonian period. Here we show the application of the rhenium-osmium (Re-Os) isotope geochronometer to the Peresopolis black slates of the Cuiabá Group.

2. Geological background

2.1. The Paraguay Belt

The Paraguay Belt lies in the heart of South America, at the southeastern edge of the Amazon Craton (Fig. 1). It consists of a sequence of metasedimentary rocks associated with the collision and post-collision stages of the Brasiliano/Pan-African Orogeny (Alvarenga, 1990; Trompette, 1994; Pimentel et al. 1996; Trindade et al. 2003; Tohver et al.2006). The waning stages of this orogeny are recorded by a series of granitic intrusions between 540 and 518 ± 4 Ma in the older units of the Paraguay Belt (Almeida and Mantovani, 1975; McGee et al. 2012).

The Paraguay Belt (Fig. 1) is composed of the following stratigraphic units. The Nova Xavantina unit, at the basement of the Cuiabá Group, records the initial stages of sedimentation and the following metasedimentary units. It is directly overlain by the carbonate sequence of the Araras Group and of the upper siliciclastic rocks from Alto Paraguai Group in the north. The Nova Xavantina unit comprises a basal unit of mafic metavolcanic rocks that are overlain by a banded iron formation, carbon-rich pelites, and covered by metasiltites and quartzites (Martinelli and Batista, 2003) (Fig. 2). The basal volcano-sedimentary succession is interpreted to record initial seafloor spreading or a retro-arc basin (Pinho, 1990; Lacerda Filho et al. 2004). Despite few chronological constraints, the volcano-sedimentary succession of the Nova Xavantina unit is thought to form the base of the Cuiabá Group (e.g., Saes et al. 2008) (See section 2.4).

The northwestern Amazonian Craton and the northeastern Brasilia Belt provided the main sediment source for the Paraguay Belt units, with a minor component considered to have been derived from the intraoceanic Goiás arc to the east (Pimentel et al. 1991, 1997, 2000, Dantas et al. 2009, Batalha, 2017; McGee et al. 2014; Babinski et al., 2018; Pelosi et al. 2017). Deformation and metamorphism intensity of the belt decreases toward the southern margin of the Amazon Craton (Alvarenga, 1988, 1990), with peak metamorphism (greenschist facies) being reached during the waning stages Brasiliano/Pan-African orogeny (e.g., Manoel and Leite, 2018 and references therein). Coincident with the late stages of the Brasiliano/Pan-African orogeny are a series of granitic intrusions (540 - 518 Ma; Almeida and Mantovani, 1975; McGee et al. 2012; McGee et al. 2015).

2.2. The Cuiabá Group

The Cuiabá Group (Fig.2) is composed of metasedimentary rocks deposited under extensional conditions leading to the development of a passive margin on southeastern Amazonian Craton (Lacerda Filho et al. 2004; McGee et al. 2015; Trindade et al. 2006). It is divided into three formations: the basal Campina de Pedras, the Acorizal, and the upper Coxipó (Tokashiki and Saes, 2008). The base of the Campina de Pedras Formation is dominantly carbon-rich pelites that are overlain by metarenites, calcitic marbles, and feldspathic metagraywacke. This lithologic association suggests a deposition in a deep lake system in tropical to semi-arid climate conditions related to the rifting and break-up of Rodinia (Tokashiki and Saes, 2008; Beal, 2013). These rocks are covered by the younger glacio-marine and turbiditic sediments of the upper units (Alvarenga et al. 2004). The Acorizal Formation comprises massive diamictites, metaconglomerates, metarenites, and metapelites that are interpreted to represent a glacial-marine sedimentary succession deposited proximal to the Amazonian Craton. The Coxipó Formation is characterized by greenish-pinkish metadiamictites with faceted and striated pebbles intercalated with metaturbidites of a postglacial sequence (Tokashiki and Saes, 2008; Beal, 2013; Batalha, 2017).

2.3. The Peresopolis slate

The Peresopolis black slate was first recognized during a drilling campaign in mid-2014. It is composed of a 65 m-thick fine-grained carbonaceous slate located at the northern limit of the exposed Cuiabá Group (Fig.1). Within the current geological and stratigraphic subdivisions, the Peresopolis black slates lies below the Coxipó Fm. (cf section 2.2). The slate trends E-W and crops out as a slightly folded tabular layer ca. 1,800 m long and 100 m wide. It sits in the northern flank of a regional anticline conformably overlying carbon-poor slates (Fig. 3), and it is conformably overlain by fine-grained metarenites. Raman spectroscopy on organic matter has shown that the unit was metamorphosed to low-greenschist facies conditions, with peak metamorphic temperatures not exceeding ca. 300°C (Manoel and Leite, 2018). The mineral assemblage includes quartz, muscovite and sulfides like pyrite and sphalerite. The deposition of these slates may have occurred in a deep marine basin distant from the cratonic area, probably associated with the E-W extension that started the sedimentation of the oldest sequences of Nova Xavantina, at northeast of the Paraguay Belt (Dantas et al. 2007).

2.4. Lower Paraguay Belt Age constraints

Several U-Pb detrital zircon provenance studies of the Cuiabá Group present ages that range between 652 ± 5 Ma and 2 Ga (Batalha, 2017; Babinski et al. 2018). The Campina de Pedras and Acorizal formations of the Cuiabá Group contain detrital zircons with a predominance of Mesoproterozoic (1200 - 1250 Ma) ages. They are thought to reflect an Amazonian Craton provenance. The youngest detrital zircon with a U-Pb age of 652 ± 5 Ma was obtained from a diamictite within the Marzagão Member of the Coxipó Formation which has been used to infer a post-Sturtian age for this unit (Fig.2) (e.g., Babinski et al.2018).

Zircons from metavolcanic rocks of the Nova Xavantina yield Tonian U-Pb ages of 822, 771 and 750 Ma (Dantas et al. 2007, Silva, 2018), with the oldest being attributed to volcanism related to E-W rifting that predated the Cuiabá basin (Dantas et al. 2007). The latter was followed by seafloor spreading that triggered the deposition of the first sediments of the Paraguay Belt (Silva, 2018). Recent U-Pb detrital zircon ages of 721 ± 20 have been reported for a CIF (clastic iron formation) layer belonging to a diamictite facies that lie stratigraphically below the banded iron formation of the Nova Xavantina unit (Oliveira, 2018).

3. Methods

3.1. Sampling

The Peresopolis black slate is intersected by the drill core Ben03A at 100 m depth (latitude 14°40’49.17’’S, longitude 54°58’26.14’’W) (Fig. 1). We selected thirty-six samples for TOC measurements, with twelve samples between 8 to 40 m, each of approximately 20g, selected for Re and Os abundance and isotope composition determinations (Fig. 3). The core samples are fresh and show no evidence of weathering, veining, or secondary (diagenetic) pyrite. This supports that the organic carbon present in the unit is composed of a mixture of hydrocarbons generated *in-situ* by maturation of the original algal and/or planktonic organic macromolecules, and of macromolecular kerogen (Vandenbroucke and Largeau, 2007). It means that that the fossil organic materials that contain the Re and Os have not been remobilized from another, potentially much younger or older, unit. Hence, our Re-Os dating of organic material provides a robust assessment for the age of the unit. We note that the organic carbon isotopic data for the Peresopolis black slate is homogeneous, with $\delta^{13}C$ values between -28 and -29 ‰ (Manoel and Leite, 2018), which are typical for Neoproterozoic organic matter.

3.2. Total Organic Carbon (TOC)

Samples (n = 36) selected for TOC analysis from the core Ben03A (Fig. 3) were powdered using an agate mortar at Laboratório Multi-Usuário em Técnicas Analíticas (LAMUTA), Federal University of Mato Grosso (UFMT). The weight percent of TOC content for the slates were determined from the combustion of powdered samples previously treated by hydrochloric acid using a Leco carbon-sulphur analyzer at Bureau Veritas Commodities, Canada.

3.3. Re-Os analysis

Twelve samples, ~20g each (> 5cm), were polished using a diamond polishing wheel to eliminate contamination from cutting and drilling marks. The samples were rinsed with MQ and then air dried at 60°C for ~12 hours, broken into chips with no metal contact. Samples were crushed to a fine powder (~30 µm) in an agate mortar at Laboratório Multi-Usuário em Técnicas Analíticas (LAMUTA), Federal University of Mato Grosso (UFMT). The Re-Os isotope analysis was carried out at the Durham Geochemistry Centre (Laboratory for Sulphide and Source Rock Geochronology and Geochemistry) at Durham University. For sample digestion, a $Cr^{VI}–H_2SO_4$ solution was employed to preferentially dissolve the organic fraction of the samples and thus liberate hydrogenous Re and Os, avoiding the contamination from detrital Re and Os (Selby and Creaser, 2003). About 0.5 g sample powder with a known amount of a mixed $^{190}Os + ^{185}Re$ tracer (spike) solution and 8 ml of 0.25 g/g $Cr^{VI}–H_2SO_4$ (4N) solution was digested in a sealed Carius tube for 48 h at 220°C. Osmium was purified using solvent extraction ($CHCl_3$) and micro-distillation methods. Rhenium was isolated from the osmium purified acid solution using NaOH-C_3H_6O solvent extraction (Cumming et al., 2013) and anion bead chromatography (Selby and Creaser, 2003). The purified Re and Os fractions were loaded onto Ni and Pt filaments, respectively (Selby et al., 2007). We measured Rhenium and Os isotopic composition by negative thermal ionization mass spectrometry (N-TIMS) (Creaser et al. 1991; Völkening et al., 1991) in the Arthur Holmes Laboratory at Durham University. Total procedural blanks during this study were 18.0 ± 2.5 pg and 0.12 ± 0.05 pg (1σ S.D., n = 3) for Re and Os, respectively, with an average $^{187}Os/^{188}Os$ value of 0.20 ± 0.03 (n = 3). The $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ uncertainties are determined through full propagation of uncertainties, including those in weighing, mass spectrometer measurements, spike calibrations, blank abundances and reproducibility of standard values.

3.3.1. The Monte Carlo Simulation

The Isoplot program calculates an age through the regression of all the Re-Os isotopic data together with the error correlation, rho (Table 2) (Ludwig, 2012). Applying the Isoplot approach, when the probability of fit is lower than 15 %, a Model 3 age solution is automatically used and assumes that the degree of scattering of the data about a line of best-fit cannot solely be attributed to by the assigned analytical uncertainties. In such case, a best-fit of the data is achieved by accounting for an unknown but normally distributed variation in the initial $^{187}Os/^{188}Os$ composition of the sample set.

An alternative method used to assess the Re-Os data is a Monte Carlo simulation, whereby without assuming the sources of scatter, the method not only propagates the analytical uncertainties, but also uncertainties arising from model uncertainties (i.e., difference in initial isotope composition, varying ages, and/or isotopic disturbance within the sample/sample set) (Li et al. 2019). This method critically avoids subjectively utilizing a cut-off value for the probability of data fit that is the fundamental underlying approach of Isoplot Model 1 versus Model 3 methods (Ludwig, 2012), and notably distinguishes between analytical and model uncertainties (Li et al. 2019).

4. Results – TOC and Re-Os data of the Peresopolis slate

The TOC of the sample set ranges between 0.3 and 16 wt%, with the upper 60 m of the Peresopolis slate possessing > 8 wt% TOC (Table 1; Fig. 3). The twelve samples analyzed for Re-Os geochronology possess 78 - 121 ppb Re, 1671 - 4113 ppt Os_{total} and 442 – 1328 ppt ^{192}Os (best estimate of hydrogenous Os) (Table 2). The $^{187}Re/^{188}Os$ values range between 160 and 436, which exhibit a positive correlation with the $^{187}Os/^{188}Os$ compositions (2.26 - 5.90; Table 2). The regression of all the Re-Os isotopic data together with the error correlation, rho (Table 2) yields an Isoplot Model 3 (see section 3.3.1) Re-Os date of 783 ± 10 Ma (2 sigma, n = 12, MSWD = 10.5), with an initial $^{187}Os/^{188}Os$ isotopic ratio (Os_i) of 0.16 ± 0.04. When applying the Monte Carlo approach both date and its uncertainty (783 ± 10 Ma) as well as the initial $^{187}Os/^{188}Os$ composition (0.16 ± 0.04) (Fig. 4b) are identical to those derived using the Isoplot v. 4.15 (Fig. 4a), which should be the case when the scatter about the best-fit line of the data is significantly large (see table 2) (MSWD >>2.5; Li et al. 2019).

5. Discussion and Implications

5.1 Sources of age and $^{187}Os/^{188}Os$ composition uncertainties

The samples were selected to avoid any visible aspects that could lead to disturbance of the Re-Os systematics (e.g., alteration, veining, etc.), although this cannot be entirely ruled out. We note that sample BEN03CX08 at ~25 m yields a slightly more radiogenic initial $^{187}Os/^{188}Os$ composition calculated at 783 Ma (0.21 ± 0.01) and exhibits almost double the maximum deviation from the linear best-fit of the entire data set (1.57; Table 2). Removing this sample yields a much better fit for the Re-Os data (n = 11; Isoplot Model 3 – 784 ± 7 Ma, initial $^{187}Os/^{188}Os$ of 0.15 ± 0.03; MSWD = 4.4, n = 11; Monte Carlo simulation – 784 ± 8 Ma; initial $^{187}Os/^{188}Os$ of 0.15 ± 0.03), and suggest that the uncertainty in the date is mostly caused by analytical (68 %) uncertainties rather than by model uncertainties (Fig. 5c).

Both analytical and model uncertainties may be present despite refined measurements and careful sample selection. A last critical issue is how isochronous the sample set is given that it encompasses ~32 m. For example, if a duration of 1 Myr is considered between each sample then the 32 m of the sampled stratigraphy would represent ~11 Myrs. Calculating the initial $^{187}Os/^{188}Os$ values for each sample according to a possible 1 Myr duration between samples, the initial $^{187}Os/^{188}Os$ values show greater variation than the initial $^{187}Os/^{188}Os$ at 783 Ma and exhibit a slight increase to more radiogenic compositions stratigraphically (Table 1). Also, there is no positive relationship between the $^{187}Re/^{188}Os$ with the initial $^{187}Os/^{188}Os$, implying that the determined Re-Os age is not a function of mixing samples with different ages and Os_i (see table 2). The latter is further illustrated by the Re-Os data of the stratigraphically youngest (CX3 and Ben04) and oldest (Ben03CX14 and Ben03CX10 – stratigraphically highest samples with distinct $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ values) samples that independently yield Re-Os ages that are identical within uncertainty (785.8 ± 7.3 Ma and 782 ± 8.2 Ma, respectively). Therefore, considering all sources of analytical, model and sample uncertainties, we consider the best estimate of the depositional age of the Peresopolis black slate is 784 ± 8 Ma [9 including the decay constant uncertainty of Smoliar et al. 1996], with an initial $^{187}Os/^{188}Os$ composition of 0.15 ± 0.03 (Fig. 5b).

5.2 A pre-Sturtian age

To date, the uppermost unit of Cuiabá Group, the Coxipó Formation, is thought to represent a postglacial sequence associated with turbidite deposition in a passive margin setting (e.g., Alvarenga and Trompette, 1992; Batalha, 2017). Previous constraints from detrital zircon in a diamictite in the upper Coxipó Formation yields a maximum depositional age of ca. 652 Ma (e.g., Alvarenga and Trompette, 1992; Batalha, 2017; Babinski et al. 2018), i.e., post-Sturtian (<660 Ma, Rooney et al. 2015).

Our pre-Sturtian depositional age of ca. 784 Ma (Fig. 5b) for the Peresopolis black slate suggests that the unit may either be an extension of the stratigraphically lowest unit of the Cuiabá Group, i.e. the Campina de Pedras Formation (cf section 2.2), or that it sits below the Cuiabá Group altogether. However, our data does not permit the further evaluation of the potential stratigraphic position of the Peresopolis slate. Regardless, the pre-Sturtian age of the unit offers a unique window into the Tonian period and the pre-glacial Neoproterozoic Earth. Indeed, climate modelling suggests that global temperatures decreased by ca. 4°C between 780 - 720 Ma (Goddéris et al. 2017), and this global climatic event has been causally linked to the breakup of Rodinia and associated drawdown of CO_2 by basalt weathering at low latitudes (Goddéris et al. 2017). The Sturtian glaciation (717 - 660 Ma, Rooney et al. 2015) marks the apex of this long-term cooling event. The Peresopolis black slate is a direct witness for this transient period to a Snowball Earth system. Other rocks of the Cuiabá Group such as the BIFs of

Nova Xavantina unit may also be representative of the Sturtian glacial pericontinental sedimentary environment.

5.3 Initial $^{187}Os/^{188}Os$ (Osi) composition and depositional environment

Our data provide additional insights into the depositional environment of the Peresopolis slate which were not available before. The inferred $^{187}Os/^{188}Os$ values for Neoproterozoic seawater derived from the initial $^{187}Os/^{188}Os$ (Osi) compositions of organic-rich sedimentary rocks exhibit considerable variability (0.12-1.44; Fig. 6). Post-Sturtian and Marinoan glacial deposits immediately following deglaciation are typically characterized by radiogenic Os_i values (ca. 1.0 and 1.2, respectively) in response to extensive continental erosion during deglaciation (Fig. 5; Rooney et al. 2014, 2015, 2016). Elevated Osi values may also reflect a decline in a juvenile mantle-like source and/or an increase in continental input. For example, the moderately radiogenic Os_i values (ca. 0.67) for the ca. 890 Ma Shaler Supergroup, NW Canada, are attributed to continental erosion during amalgamation of Rodinia (vanAcken et al. 2013). Radiogenic Os_i values may also reflect specific basin conditions, such as spatial restriction and/or a transition of non-marine (lacustrine) to marine settings (e.g., ca. 757 Ma Chuar Group, North America, $Os_i = 1.13$; Rooney et al. 2018).

In contrast, the non-radiogenic Os_i values for the Peresopolis black slate (0.15 ± 0.03) are more typical of the Neoproterozoic pre-glacial values and notably similar to the low Os_i values from the pre-Sturtian Coppercap Formation (ca. 732 Ma; $Os_i = 0.15 \pm 0.002$; Rooney et al. 2014) (Fig. 6). As such, the non-radiogenic Os_i composition of the Peresopolis black slate suggests that a significant fraction of the continental crust being eroded was mafic in composition. Although, the nature of this source can be debated, the breakup of Rodinia was associated with intense mafic volcanism and the emplacement of large igneous provinces (LIP) at low latitudes between 850 - 717 Ma. The major mid-Proterozoic LIP's are the Arabian-Nubian (ca. 850 Ma, Ernst et al. 2008), Guibei and Willouran (ca. 830 Ma, Ernst et al. 2008) and Gunbarrel (ca. 780 Ma, Harlan et al. 2003). Although weathering of all these LIPs could have provided non-radiogenic Os to neighboring oceanic basins (e.g., Li et al. 2003; Halverson et al. 2007b; Goddéris et al. 2003, 2017; Rooney et al. 2014, 2015, 2016; Cox et al., 2016), the Gunbarrel LIP is more relevant as the source of non-radiogenic osmium given its geographic location and that it is broadly contemporaneous with the deposition of the Peresopolis black slate. An additional source of non-radiogenic osmium could also be the mafic lithologies of the Nova Xavantina Sequence (ca. 822, 771 and 750 Ma, Dantas et al. 2007; Silva et al. 2018) or the juvenile intraoceanic Goiás arc (ca. 900 – 800 Ma Pimentel and Fuck, 1992). However, the latter is considered to have only played a minor role in the supply of detritus to the basin (Pimentel et al. 1991, 1997, 2000, Dantas et al. 2009, Batalha, 2017; McGee et al. 2014; Babinski et al. 2018; Pelosi et al. 2017).

6. Conclusion

Our work provides the first direct age for sedimentation on a segment of the Paraguay Belt. A Re-Os age of 784 ± 8 [9] Ma for the Peresopolis black slate (Cuiabá Group, Paraguay Belt, western Brazil) suggests that these rocks formed during the Tonian period of the early Neoproterozoic. It also indicates that the deposition of the Peresopolis black slate coincided with the onset of a long-term global cooling transition that ultimately led to the Sturtian glaciation (ca. 717 - 660 Ma), the first major global glaciation of the Neoproterozoic.

The pre-Sturtian age and non-radiogenic $^{187}Os/^{188}Os$ compositions (0.15 ± 0.03) of the Peresopolis black slate suggest that the slate was deposited in a marine basin associated with rifting of the supercontinent Rodinia, with the non-radiogenic osmium isotope composition most likely inherited from weathered LIPs nearby: the Gunbarrel LIP, and/or the mafic lithologies of the Nova Xavantina unit, and to a lesser extent the Goiás arc. However, our data cannot discriminate between these potential sources.

Finally, our work improves the existing chronostratigraphic constraints for the timing of continental breakup on the western margin of Gondwana and further provides insight into the pre-Cryogenian osmium isotope seawater record. As a geological and paleoenvironmental archive, the Paraguay Belt provides insight into a poorly understood, but critical transition of Neoproterozoic Earth history that predates the major glaciations. Based on our new Re-Os age constraints, further geochemical study and global correlations will be explored.

Acknowledgments. We thank Moisés Sachetti for the core Ben03A and all the support during this study. TM acknowledges the Mato Grosso Federal University for the facilities. We are grateful to Elton

Dantas, from Universidade de Brasília, for helpful discussions, and to Swapan Sahoo for bringing to our attention the work by Diamond and Lyons (2014). DS acknowledges technical support from Geoff Nowell, Antonia Hoffman, and Chris Ottley, and the Total Endowment Fund and Dida Scholarship of CUG Wuhan.

References

Almeida, F. D., Mantovani, M. S. M., 1975. Geologia e geocronologia do granito de São Vicente, Mato Grosso. Anais da Academia Brasileira de Ciências, 47, 451-458.

Alvarenga, C.J.S., 1988. Turbiditos e a Glaciação do Final do Proterozóico Superior no Cinturão Dobrado Paraguai, Mato Grosso. Rev. Bras. Geociências, São Paulo 18 (3), 323–327.

Alvarenga, C.J.S., 1990. Phénomenes sedimentaires, structuraux et circulation de fluides à la transition Chaine-Craton: Example de la cote Paraguai dáge Proterozoique Supérieur. PhD thesis. University of Marseille 3, Mato Grosso, Brésil.

Alvarenga, C. J., Trompette, R., 1992. Glacially influenced sedimentation in the later Proterozoic of the Paraguay Belt (Mato Grosso, Brazil). Palaeogeography, Palaeoclimatology, Palaeoecology, 92(1-2), 85-105.

Alvarenga, C.J.S., Santos, R.V., Dantas, E.L., 2004. C–O–Sr isotopic stratigraphy of cap carbonates overlying Marinoan-age glacial diamictites in the Paraguay Belt, Brazil. Precambrian Res. 131, 1–21.

Babinski, M., McGee, B., do Couto Tokashiki, C., Tassinari, C. C., Saes, G. S., Pinho, F. E. C., 2018. Comparing two arms of an orogenic belt during Gondwana amalgamation: Age and provenance of the Cuiabá Group, northern Paraguay Belt, Brazil. Journal of South American Earth Sciences, 85, 6-42.

Batalha, R.S., 2017. Estudos de Minerais Pesados, Análise Morfológica e Datação U-Pb por ICP-MS-LA de Zircões Detríticos – Proveniências dos Metassedimentos do Grupo Cuiabá, Faixa Paraguai Norte – MT. Dissertação de Mestrado. Universidade Federal de Mato Grosso.

Beal, V., 2013. Estratigrafia de Sequência do Grupo Cuiabá, Criogeniano/Neoproterozoico III (850-650MA) Da Faixa Paraguai Norte, Mato Grosso. PhD thesis, Dissertação de Mestrado, Instituto de Ciências Exatas e da Terra, Universidade Federal de Mato Grosso.

Bertoni, M. E., Rooney, A. D., Selby, D., Alkmim, F. F., Le Heron, D. P., 2014. Neoproterozoic Re–Os systematics of organic-rich rocks in the São Francisco Basin, Brazil and implications for hydrocarbon exploration. Precambrian Research, 255, 355-366.

Brito Neves, B. B. D., Campos Neto, M. D. C., Fuck, R. A., 1999. From Rodinia to Western Gondwana: an approach to the Brasiliano-Pan African Cycle and orogenic collage. Episodes-Newsmagazine of the International Union of Geological Sciences, 22(3), 155-166.

Cohen, P.A., Macdonald, F.A., 2015, The Proterozoic record of eukaryotes: Paleobiology, v. 41, p. 610–632.

Cohen, P. A., Strauss, J. V., Rooney, A. D., Sharma, M., Tosca, N., 2017. Controlled hydroxyapatite biomineralization in an ~ 810 million-year-old unicellular eukaryote. Science Advances, 3(6), e1700095.

Cox, G. M., Halverson, G. P., Stevenson, R. K., Vokaty, M., Poirier, A., Kunzmann, M., Li, Z. X., Denyszyn, S. W., Strauss, J.V., Macdonald, F. A., 2016. Continental flood basalt weathering as a trigger for Neoproterozoic Snowball Earth. Earth and Planetary Science Letters, 446, 89-99.

Creaser, R. A., Papanastassiou, D. A., Wasserburg, G. J., 1991. Negative thermal ion mass spectrometry of osmium, rhenium and iridium. Geochimica et Cosmochimica Acta, 55(1), 397-401.

Cumming, V.M., Poulton, S.W., Rooney, AD., Selby, D., 2013. Anoxia in the terrestrial environment during the Late Mesoproterozoic. Geology*,* doi:10.1130/G34299.1.

Dantas, E.L., Armstrong, R., Pimentel, M.M., Fuck, R.A., Martinelli, C.D., Silva, M.F., Laux, J.H., 2007. 800 Ma rifting in the Paraguay Belt, central Brazil: U-Pb SHRIMP age determination, Rodinia break-up and implications for a connection with Avalonian peri-Gondwana terranes. In: Geological Society of America Annual Meeting.

Dantas, E.L., Alvarenga, C.J.S., Santos, R.V., Pimentel, M.M., 2009. Using Nd isotopes to understand the provenance of sedimentary rocks from a continental margin to a foreland basin in the Neoproterozoic Paraguay Belt, Central Brazil. Precambrian Res. 170, 1–12.

Ernst, R.E., Wingate, M.T.D., Buchan, K.L., Li, Z.X., 2008. Global record of 1600–700 Ma Large Igneous Provinces (LIPs): implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents. Precambrian Research 160, 159–178.

Evans, D.A.D., 2009. The palaeomagnetically viable, long-lived and all-inclusive Rodinia supercontinent reconstruction. In: Murphy J.B., Keppie J.D. & Hynes A.J. (eds) Ancient Orogens and Modern Analogues. Geological Society, London, Special Publications, 327, 371–404.

Gibson, T. M., Shih, P. M., Cumming, V. M., Fischer, W. W., Crockford, P. W., Hodgskiss, M. S., and Halverson, G. P., 2017. Precise age of Bangiomorpha pubescens dates the origin of eukaryotic photosynthesis. Geology, 46(2), 135-138.

Goddéris, Y., Donnadieu, Y., Nédélec, A., Dupré, B., Dessert, C., Grard, A., Ramstein, G., François, L.M., 2003. The Sturtian “snowball” glaciation: fire and ice. Earth and Planetary Science Letters 211, 1–12.

Goddéris Y, Le Hir G, Macouin M, Donnadieu Y, Hubert-Théou L, Dera G, Aretz M, Fluteau F, Li ZX, Halverson GP., 2017. Paleogeographic forcing of the strontium isotopic cycle in the Neoproterozoic. Gondwana Research. Feb 1; 42:151-62.

Halverson, G. P., Hoffman, P. F., Schrag, D. P., Maloof, A. C., Rice, A. H. N., 2005. Toward a Neoproterozoic composite carbon-isotope record. GSA Bulletin, 117(9-10), 1181-1207.

Halverson, G.P., Dudás, F.Ö., Maloof, A.C., Bowring, S.A., 2007b. Evolution of the $^{87}Sr/^{86}Sr$ composition of Neoproterozoic seawater. Palaeogeography, Palaeoclimatology, Palaeoecology 256, 103–129.

Halverson, G.P., Hurtgen, M.T., Porter, S.M., Collins, A.S., 2009. Neoproterozoic–Cambrian biogeochemical evolution, in Gaucher, C., Sial, A., Halverson, G., and Frimmel, H., eds., Neoproterozoic–Cambrian Tectonics, Global Change and Evolution: a focus on southwestern Gondwana: Developments in Precambrian Geology 16: Amsterdam, Elsevier, p. 351–365.

Halverson, G. P., Porter, S. M., Gibson, T. M., 2018. Dating the late Proterozoic stratigraphic record. Emerging Topics in Life Sciences, 2(2), 137-147.

Harlan, S.S., Heaman, L.M., LeCheminant, A.N., Premo, W.R., 2003. Gunbarrel mafic magmatic event: a key 780 Ma time marker for Rodinia plate reconstructions. Geology 31, 1053–1056.

Kendall, B. S., Creaser, R. A., Ross, G. M., Selby, D., 2004. Constraints on the timing of Marinoan "Snowball Earth" glaciation by 187Re–187Os dating of a Neoproterozoic, post-glacial black shale in Western Canada. Earth and Planetary Science Letters, 222(3-4), 729-740.

Kendall, B., Creaser, R. A., & Selby, D., 2006. Re-Os geochronology of postglacial black shales in Australia: Constraints on the timing of "Sturtian" glaciation. Geology, 34(9), 729-732.

Kendall, B., Creaser, R. A., Selby, D., 2009. ^{187}Re-^{187}Os geochronology of Precambrian organic-rich sedimentary rocks. Geological Society, London, Special Publications, 326(1), 85-107.

Knoll, A.H., Javaux, E., Hewitt, D., Cohen, P., 2006, Eukaryotic organisms in Proterozoic oceans: Philosophical Transactions of the Royal Society of London, ser. B, Biological Sciences, v. 361, p. 1023–1038.

Knoll, A. H., Nowak, M. A. 2017. The timetable of evolution. Science Advances, 3(5), e1603076.

Lacerda Filho, J.V., Valente, C.R., Bahia, R.B.C., Lopes, R.C., Romanini, S.J., Oliveira, I.W.B., Oliveira, C.C., Sachs, L.L.B., Silva, V.A., Batista, I.H., 2004. Carta Geológica do Brasil ao Milionésimo, Sistema de Informações Geográficas.

Li, Z.X., Li, X.H., Kinny, P.D., Wang, J., Zhang, S., Zhou, H., 2003, Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze craton, South China, and correlations with other continents: Evidence for a ju superplume that broke up Rodinia: Precambrian Research, v. 122, p. 85–109.

Li, Z., Bogdanova, S., Collins, A., Davidson, A., De Waele, B., Ernst, R., Fitzsimmons, I., Fuck, R., Gladkochub, D., Jacobs, J., Karlstrom, K., Lu, S., Natapov, L., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: Precambrian Research, v. 160, p. 179–210.

Li, Y., Zhang, S., Hobbs, R., Caiado, C., Sproson, A. D., Selby, D., Rooney, A. D., 2019. Monte Carlo sampling for error propagation in linear regression and applications in isochron geochronology. Science Bulletin, 64(3), 189-197.

Ludwig, K.R., 2012. Isoplot, version 3.75: A geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication No. 5.

Luz et al., 1980 J.S. Luz, A.M. Oliveira, J.O. Souza, J.J.I.M. Motta, L.C. Tanno, L.S. Carmo, N.B. Souza. Projeto Coxipó. Relatório Final. Companhia de Pesquisa de Recursos Minerais, Superintendência Regional de Goiânia, DNPM/ CPRM, 1 (1980), p. 136.

Lyons, T. W., Reinhard, C. T., Planavsky, N. J., 2014. The rise of oxygen in Earth's early ocean and atmosphere. Nature, 506(7488), 307.

Manoel, T. N., Leite, J. A. D., 2018. On the origin of the Neoproterozoic Peresopolis graphite deposit, Paraguay Belt, Brazil. Journal of South American Earth Sciences, 84, 104-112.

Martinelli, C.D., Batista, J.J., 2003. Estratigrafia da seqüência metavulcanossedimentar dos Araés: Grupo Cuiabá? In: Simpósio de Geologia do Centro-Oeste, 8, pp. 124–125, Cuiabá, Anais.

McGee, B., Collins, A.S., Trindade, R.I.F., 2012. Gday Gondwana — the final accretion of a supercontinent: U–Pb ages from the post-orogenic São Vicente Granite, northern Paraguay Belt, Brazil. Gondwana Res. 21, 316–322.

McGee, B., Collins, A.S., Trindade, R.I.F., Payne, J., 2014. Age and provenance of the Cryogenian to Cambrian passive margin to foreland basin sequence of the northern Paraguay Belt, Brazil. Geol. Soc. Am. Bull. 127, 76–86.

McGee, B., Collins, A.S., Trindade, R.I.F., Jourdan, F., 2015. Investigating mid-Ediacaran glaciation and final Gondwana amalgamation using coupled sedimentology and 40Ar/39Ar detrital muscovite provenance from the Paraguay Belt, Brazil. Sedimentology 62, 130–154.

Oliveira, J. A., 2018. Proveniência e geoquímica isotópica das formações ferríferas do norte da faixa Paraguay. 2018. 112 f., il. Dissertação (Mestrado em Geologia). Universidade de Brasília.

Pelosi, G.F.F., 2017. Age, Provenance and Tectonic Setting from Southern Portion of the Cuiabá Group: Implications for the Evolution of the Paraguai Belt. Doctoral dissertation, Universidade Federal de Mato Grosso.

Pimentel, M.M., Heaman, L., Fuck, R.A., 1991. Zircon and sphene U-Pb geochronology of Upper Proterozoic volcanic-arc rock units from southwestern Goiás, central Brazil. J. S. Am. Earth Sci. 4, 295–305.

Pimentel, M. M., Fuck, R. A., 1992. Neoproterozoic crustal accretion in central Brazil. Geology, 20(4), 375-379.

Pimentel, M. M., Fuck, R. A., Alvarenga, C. J. S., 1996. Post- Brasiliano (Pan-African) high-K granitic magmatism in central Brazil: the role of late Precambrian–early Paleozoic extension. Precambrian Research, 80, 217–238.

Pimentel, M.M., Whitehouse, M.J., Viana, M.G., Fuck, R.A., Machado, N., 1997. The Mara Rosa Arc in the Tocantins Province: further evidence for Neoproterozoic crustal accretion in central Brazil. Precambrian Research 81, 299–310.

Pimentel, M.M., Fuck, A.R., Jost, H., Ferreira Filho, C.F., Araújo, C.M., 2000. The basement of the Brasília Fold Belt and Goiás Magmatic Arc. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds.), Tectonic Evolution of South America, Rio de Janeiro, 31 International Geological Congress, pp. 195–229.

Pinho, F.E.C., 1990. Estudo das rochas encaixantes e veios mineralizados a ouro do Grupo Cuiabá, na região denominada "Garimpo dos Araés" Nova Xavantina, estado de Mato Grosso. PhD thesis. Universidade Federal do Rio Grande do Sul, Porto Alegre.

Porter, S., 2016. Tiny vampires in ancient seas: Evidence for predation via perforation in fossils from the 780–740 million-year- old Chuar Group, Grand Canyon, USA: Proceedings of the Royal Society, ser. B, Biological Sciences, v. 283, p. 20160221.

Rooney, A. D., Selby, D., Houzay, J. P., Renne, P. R., 2010. Re–Os geochronology of Mesoproterozoic sedimentary succession, Taoudeni basin, Mauritania: Implications for basin-wide correlations and Re–Os organic-rich sediments systematics. Earth and Planetary Science Letters, 289(3-4), 486-496.

Rooney, A. D., Chew, D. M., Selby, D., 2011. Re–Os geochronology of the Neoproterozoic–Cambrian Dalradian Supergroup of Scotland and Ireland: implications for Neoproterozoic stratigraphy, glaciations and Re–Os systematics. Precambrian Research, 185(3-4), 202-214.

Rooney, A.D., Macdonald, F.A., Strauss, J.V., Dudás, F.Ö., Hallmann, C., Selby, D., 2014. Re-Os geochronology and coupled Os-Sr isotope constraints on the Sturtian snowball Earth:

Proceedings of the National Academy of Sciences of the United States of America, v. 111, p. 51–56.

Rooney, A.D., Strauss, J.V., Brandon, A.D., Macdonald, F.A., 2015. A Cryogenian chronology: Two long-lasting synchronous Neoproterozoic glaciations: Geology, v. 43, p. 459–462.

Rooney, A. D., Selby, D., Lloyd, J. M., Roberts, D. H., Lückge, A., Sageman, B. B., Prouty, N. G., 2016. Tracking millennial- scale Holocene glacial advance and retreat using osmium isotopes: Insights from the Greenland ice sheet. Quaternary Science Reviews, 138, 49-61.

Rooney, A. D., Austermann, J., Smith, E. F., Li, Y., Selby, D., Dehler, C. M., ... & Macdonald, F. A., 2018. Coupled Re-Os and U-Pb geochronology of the Tonian Chuar Group, Grand Canyon. GSA Bulletin, 130(7-8), 1085-1098.

Saes, G.S., Santos, A.A., Santos Júnior, W.A., Gomes, L.P., Silva, S.N., 2008. Projeto Avaliação de Rochas Calcárias e Fosfatadas para Insumos Agrícolas do Estado do Mato Grosso. CPRM, p.21-33.

Sahoo, S. K., Planavsky, N. J., Kendall, B., Wang, X., Shi, X., Scott, C., Anbar, A.D., Lyons, T.W., Jiang, G, 2012. Ocean oxygenation in the wake of the Marinoan glaciation. Nature, 489 (7417), 546.

Selby, D., Creaser, R. A., 2003. Re-Os geochronology of organic rich sediments: an evaluation of organic matter analysis methods: Chemical Geology, v. 200, no. 3-4, p. 225-240.

Selby, D., 2007. Direct Rhenium–Osmium age of the Oxfordian-Kimmeridgian boundary, Staffin bay, Isle of Skye, UK, and the Late Jurassic time scale. Norsk Geologisk Tidsskrift 87 (3), 291–299.

Shields-Zhou, G.A; Och, L., 2011. The case for a Neoproterozoic oxygenation event: geochemical evidence and biological consequences. GSa Today, v. 21, n. 3, p. 4-11.

Silva, M. F.., 2018. Evolução Tectônica de Rift para Margem Passiva da Faixa Paraguai-Mato Grosso, Brasil Central. Instituto de Geociências. Universidade de Brasília. Tese de Doutorado N°144, 1v.198p.

Smoliar, M. I., Walker, R. J., Morgan, J. W., 1996. Re-Os ages of group IIA, IIIA, IVA, and IVB iron meteorites. Science, 271(5252), 1099-1102.

Tohver, E., D'Agrella-Filho, M. S., Trindade, R. I. F., 2006. Paleomagnetic record of Africa and South America for the 1200–500 Ma interval, and evaluation of Rodinia and Gondwana assemblies. Precambrian Research, 147, 193–222.

Tokashiki, C.C., Saes, G.S., 2008. Revisão estratigráfica e faciologia do Grupo Cuiabá no alinhamento Cangas-Poconé, Baixada Cuiabana, Mato Grosso. Rev. Bras. Geociencias 38, 661–675.

Trindade, R. I. F., Font, E., D'Agrella Filho, M.S., Nogueira, A.C.R., Riccomini, C., 2003. Low-latitude and multiple geomagnetic reversals in the Neoproterozoic Puga cap carbonate, Amazon craton. Terra. Nova 15, 441–446.

Trindade, R.I.F., D'Agrella-Filho, M.S., Epof, I., Brito Neves, B.B., 2006. Paleomagnetism of early cambrian itabaiana mafic dikes (NE Brazil) and the final assembly of Gondwana. Earth Planet Sci. Lett. 244, 361–377.

Trompette, R., 1994. Geology of western Gondwana (2000-500 Ma): Pan-Africa-Brasiliano aggregation of South America and Africa (No. 55 (215-13) TRO).

vanAcken, D., Thomson, D., Rainbird, R.H., Creaser, R.A., 2013. Constraining the depositional history of the Neoproterozoic Shaler Supergroup, Amundsen Basin, NW Canada: Rhenium–osmium dating of black shales from the Wynniatt and Boot Inlet Formations. Precambrian Res. 236, 124–131.

Vandenbroucke, M., Largeau, C., 2007. Kerogen origin, evolution and structure. Organic Geochemistry 38, 719-833.

Völkening, J., Walczyk, T., Heumann, K.G., 1991. Osmium isotope ratio determinations by negative thermal ion mass spectrometry. Int. J. Mass Spectrom. Ion Process. 105, 147–159.

Zhu, B., Becker, H., Jiang, S. Y., Pi, D. H., Fischer-Gödde, M., Yang, J. H., 2013. Re–Os geochronology of black shales from the Neoproterozoic Doushantuo Formation, Yangtze platform, South China. Precambrian Research, 225, 67-76.

Figure Legends.

Fig. 1. Geological map of the Paraguay Belt with the main divisions based on geochronology and lithostratigraphy. The yellow star represents the location of the core Ben03. Modified after McGee et

al. (2015). Units 1 and 2: intercalated pelites and carbon-rich pelites, marbles and metagreywacke; Unit 3 and 5: meta-conglomerates, metarenites and graded phyllites, meta-arkose and quartzite; Unit 4: metadiamictites (Engenho Facies) and arenitic to pelitic meta rhythmites with dropstones (Cangas Facies); Units 6, 7 and 8: phyllites, metadiamictites, quartzites (Mata-Mata Facies) and marbles (Guia Facies). Undivided unit: quartzites, phyllites and metarenites.

Fig. 2. Possible stratigraphic column for the northern segment of the Cuiabá Group, modified after Beal (2013). The unit numbers correspond to the subunits of Luz et al. (1980). Units 1 and 2: intercalated pelites and carbon-rich pelites, marbles and metagreywacke; Unit 3 and 5: metaconglomerates, metarenites and graded phyllites, meta-arkose and quartzite; Unit 4: metadiamictites (Engenho Facies) and arenitic to pelitic meta rhythmites with dropstones (Cangas Facies); Units 6, 7 and 8: phyllites, metadiamictites, quartzites (Mata-Mata Facies) and marbles (Guia Facies). The red star represents horizons possessing U-Pb detrital zircon ages, with the youngest concordant age interpreted as maximum depositional age: (1) Babinski et al. 2018. (2) Batalha, 2017. The yellow star represents the Re-Os age (3) This work.

Fig. 3. Stratigraphic interval of the Peresopolis slate in the drillhole Ben03A showing the TOC values and the sampled areas for Re-Os analysis and initial $^{187}Os/^{188}Os$ (Osi) composition of the analyzed samples.

Fig. 4. Re-Os chronology results of the 12 samples using the Monte Carlo based method and the Isoplot program. (a) traditional isochron diagram using the algorithm of the Isoplot Program; (b) Monte Carlo age simulation contour plot. (c) Monte Carlo results illustrating the analytical only and analytical + model uncertainties contribution to the calculated age uncertainty at the 2-sigma level. See text for discussion.

Fig. 5. Re-Os chronology results of the 11 samples using the Monte Carlo based method and the Isoplot program. (a) traditional isochron diagram using the algorithm of the Isoplot Program; (b) Monte Carlo age simulation contour plot. (c) Monte Carlo results illustrating the analytical only and analytical +

model uncertainties contribution to the calculated age uncertainty at the 2-sigma level. See text for discussion.

Fig. 6. Compilation of the Neoproterozoic seawater $^{187}Os/^{188}Os$ composition derived from organic-rich sedimentary rock analysis. References: (1) Rooney et al. 2010; (2) Gibson et al. 2017; (3) Bertoni et al. 2014; (4) vanAcken et al. 2013; (5) Cohen et al. 2017; (6) This study (0.15± 0.03); (7) Rooney et al. 2018; (8) Rooney et al. 2015; (9) Rooney et al. 2014; (10); Rooney et al. 2011; (11) Kendall et al. 2006; (12) Zhu et al. 2013; (13) Kendall et al. 2004; (14) Kendall et al. 2009. The red bars illustrate the major Neoproterozoic LIP's and their relative magnitude: ca. 850 Ma Arabian/Nubian (A-N); ca. 830 Guibei and Willouran (G-W); ca. 780 Ma Gunbarrel (G). The blue stripes represent the majors Neoproterozoic glaciation: Sturtian (717 - 660 Ma), Marinoan (650 - 635 Ma) and Gaskiers (ca. 579 Ma). See text for discussion.