From Snowball Earth to the Cambrian Explosion: an Ediacaran Subcommission field trip to Brazil

Marc Laflamme[1], Lucas Veríssimo Warren[2], Fabrício de Andrade Caxito[3], Tara Selly[4,5], Alan J. Kaufman[6], Graham A. Shields[7], Shuhai Xiao[8], and Maoyan Zhu[9]*

[1]Department of Chemical and Physical Sciences, University of Toronto Mississauga, Canada. E-mail: marc.laflamme@utoronto.ca

[2]Department of Geology, São Paulo State University, Brazil. E-mail: lucas.warren@unesp.br

[3]Departamento de Geologia, Universidade Federal de Minas Gerais, Brazil. E-mail: caxito@ufmg.br

[4]Department of Geological Sciences, University of Missouri, USA. E-mail: sellyt@missouri.edu

[5]X-ray Microanalysis Laboratory, University of Missouri, USA. E-mail: sellyt@missouri.edu

[6]Department of Geology and Earth System Science Interdisciplinary Center, University of Maryland, USA. E-mail: kaufman@umd.edu

[7]Department of Earth Sciences, University College London, UK. E-mail: g.shields@ucl.ac.uk

[8]Department of Geosciences, Virginia Tech, USA. E-mail: xiao@vt.edu

[9]Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, China. E-mail: myzhu@nigpas.ac.cn

* Corresponding author: Department of Chemical and Physical Sciences, University of Toronto Mississauga, Canada. E-mail: marc.laflamme@utoronto.ca, Tel., 01-647-999-3589

Abstract

We report the findings from our International Subcommission on Ediacaran Stratigraphy (ISCS) trip to the Neoproterozoic to Cambrian Bambuí Group in Brazil. Important geochemical markers, glacial diamictites, and possible calcifying fossils have previously been reported from the Bambuí Group, which represent important criteria to be considered in subdividing the Ediacaran Period into meaningful Series and Stages.

Introduction and background

In late November 2023, the Ediacaran Subcommission, together with members of the Cryogenian and Cambrian subcommissions, held a field meeting to explore the Neoproterozoic to Cambrian Bambuí Group in Minas Gerais, Brazil. In our continued endeavour to subdivide the nearly 100 million years (635–539 Ma) of Ediacaran time into meaningful windows, Xiao et al. (2016) outlined the potential geological, geochemical, and paleontological observations that could be used as temporal markers. Chief amongst these are the identification of key geochemical events—especially the profound negative carbon isotope anomaly known as the Shuram Excursion as well as the first and last occurrence of Ediacara biotas and the stratigraphic position of a glacial diamictites like the one that corresponds to the ca. 579 Ma 'Gaskiers' ice age (Pu et al., 2016). This five-day field excursion included important stops to investigate a large-scale glacial unit of debatable Neoproterozoic age and to search for important Ediacaran biostratigraphic markers, especially the calcified funnel-in-funnel tubes of *Cloudina*—the first known animal to create a carbonate shell. As such, the Bambuí Group represents a key section that potentially provides insight into the selection of GSSPs (Global Boundary Stratotype Section and Point) to subdivide the Ediacaran System. In this report, we highlight the important localities visited by voting and corresponding members of both subcommissions and discuss some outstanding questions concerning the Bambuí Group of Brazil.

The Bambuí Group is a Neoproterozoic to Cambrian mixed carbonate-siliciclastic unit that outcrops over 350,000 km^2 of the Archean/Proterozoic São Francisco Craton in east central Brazil (Caxito et al., 2012; Reis et al., 2017; and references therein). The Bambuí Group comprises six major units (in ascending order): (1) The Jequitaí Formation, a diamictite that represents a Neoproterozoic glacial deposit of debatable age; (2) The Sete Lagoas Formation, which is divided into the basal Pedro Leopoldo Member (LSL) that contains originally aragonite crystal fans and a strong negative $\delta^{13}C$ anomaly representing a post-glacial cap carbonate, and the Lagoa Santa Member (MSL and USL), comprising organic-rich limestone and dolomitic limestone with laminar and columnar stromatolites and thrombolites, in addition to the report of *Cloudina*, *Corumbella*, and putative trace fossils (Warren et al., 2014); (3) The overlying siltstone and mudstone of the Serra de Santa Helena Formation likely represents a basin-wide transgression. The occurrence of heterolithic facies associated with occasional salt pseudomorphs and mud cracks in this interval suggests deposition in inter- to subtidal settings under episodic evaporitic conditions (Uhlein et al., 2019). Abundant microbial surface textures, pustular structures, and possible simple traces (Okubo et al., 2023) indicate extensive distribution of mat grounds in this shallow marine environment; (4) The overlying Lagoa do Jacaré Formation is composed of dark oolitic to muddy limestone and microbialites; (5) The Serra da Saudade Formation consisting of green siltstone, shale, and sandstone, and finally (6) The Três Marias Formation, a coarse siliciclastic molasse deposit, composed of sandstone, conglomerate, and shale, with potential trace fossils, as well as detrital zircons as young as ca. 527 Ma, indicating a Cambrian age (Tavares et al., 2020). Bambuí strata are divided by at least five distinct sequence boundaries, including a major regional unconformity between the Serra da Saudade and Três Marias formations (DaSilva et al., 2022).

Out on the rocks

Our first day began with a visit to the Brazilian Geological Survey's core facility in Caeté. There we investigated two cores (PSB13 and PSB14, Figs. 1, 2) drilled through the São Francisco Craton (henceforth SFC) near Januária. These rock libraries gave delegates unimpeded access to the Bambuí stratigraphy that formed the basis of our trip and allowed the trip leaders to guide us through the complex geochemical signals that have been recovered from the cores (Fig. 3). Both cores contain diamictite of glacial origin that are overlain by post-glacial cap carbonate with characteristically negative $\delta^{13}C$ values. These are disconformably followed by limestone and dolomitic limestone in an 80+ meter interval of near 0‰ values in which the putative cloudinomorphs were reported (Warren et al., 2014), and then an interval spanning three formations of >350 meter with profoundly positive values ranging from +5 up to +14‰.

The Ediacaran age assignment for the Bambuí Group relies on the presence of cloudinomorphs in the Lagoa Santa Member, which was a primary target of the Subcommission field workshop. If the biomineralized fossils are verified at this level, they would represent the oldest known cloudinomorphs given their stratigraphic position below the Middle Bambuí Excursion (MIBE), which based on the stratigraphic architecture of the Windermere Supergroup would underly the Shuram—constrained by Re-Os ages between 564 and 579 Ma (Rooney et al., 2020)—that is preserved in the Gametrail Formation (Macdonald et al., 2013). At present, the oldest known cloudinomorph fossils are found near the end of the Shuram in the lower Nama

Group of Namibia (Kaufman et al., 2019). Unfortunately, the Shuram is missing in the Bambuí stratigraphy, which might be due to basin restriction (Uhlein et al., 2019; contra Moynihan et al., 2019 and DaSilva et al., 2022), in addition to the fossil impressions of the soft-bodied Ediacara biotas.

Our second day focused on examining outcrops and quarries exposing Sete Lagoas Formation carbonates as we travelled over 400 km north from Belo Horizonte to Montes Claros. Along the way we stopped at several localities, including those where tubular columnar stromatolites (Fig. 4 left panel) and calcite (ex-aragonite) crystal fans were documented (Figs. 4 right panel, 5). On day three we continued our travels north towards Januária and observed spectacular outcrops of the Jequitaí Formation showcasing glacially striated pavements characterised by U-shaped grooves with internal striae (Fig. 6). These are interpreted as slumped plow ridges caused by saltation of grounded glacial ice. We visited additional sites where the Jequitaí diamictite included large dropstones and striated clasts. On day four we explored the Januária area in the northern Minas Gerais State. In addition to spectacular bladed barite ($BaSO_4$) crystal fans (Fig. 7) from an outcrop at Riacho da Cruz, delegates searched the Barreiro Quarry from where thrombolites with chert nodules and the Ediacaran biomineralized macrofossil *Cloudina* have been reported (Warren et al., 2014). On day five, members explored several outcrops of the Serra de Santa Helena, Lagoa do Jacaré and Serra da Saudade formations in the Januária-Lontra section. Examples of microbially induced sedimentary structures (MISS) and putative Cambrian trace fossils were found in very fine-grained sandstone of the Serra de Santa Helena Formation. In the afternoon we moved to the Sapé section, where peritidal to subtidal carbonates of the Sete Lagoas Formation crop out. At this location, samples of possible fragments of skeletal organisms were collected. Our final field day was spent visiting the spectacular Janelões cave system (Fig. 8) of the Peruaçu National Park, which formed by karstification of the Sete Lagoas Formation carbonates.

Outstanding questions

As with all good field trips, exciting discussions took place on the outcrops and during evening meals. One of the topics that got a lot of us thinking was the age of the Bambuí Group, given the continuing debates in the literature. For example, the basal Pedro Leopoldo Member ex-aragonite crystal fans at Sambra Quarry have been dated by the Pb-Pb carbonate technique at 720 ± 22 Ma (Babinski et al., 2007), which, at the time argued for a Sturtian age for the underlying diamictite. However, both high-resolution U-Pb and Re-Os acquired in the last decade indicate that the Sturtian glaciation lasted from ca. 717 to 660 Ma (Hoffman et al., 2017, and references therein), which would make the Pb-Pb age not compatible with a cap carbonate to that specific glaciation. Recently, in-situ LA-ICP-MS U-Pb dating of the same ex-aragonite fans at Sambra Quarry yielded lower intercept dates of 615 ± 6 Ma and 608 ± 5 Ma (Caxito et al., 2021) consistent with a Marinoan age for the Jequitaí diamictite. Using the same technique, crystal fans from the upper Lagoa Santa Member (separated by a sequence boundary from the Pedro Leopoldo Member according to DaSilva et al., 2022) at Tatiana Quarry yielded an age of 573 ± 11 Ma, while stromatolites at the top of the unit provided an age of 566 ± 15 Ma, which was interpreted as early diagenetic in origin (Caxito et al., 2021).

Similarly, detrital zircons from the Lagoa Santa Member yielded a weighted mean $^{206}Pb/^{238}U$ age of 571 ± 3 Ma, interpreted as a maximum depositional age for this unit (recalculated by Caxito et al., 2021 from Paula-Santos and Babinski, 2018; Paula-Santos et al., 2015). The age estimate supports the Ediacaran designation for the entire succession (Paula-Santos et al., 2015). Additionally, both SHRIMP and LA-ICPMS detrital zircon data from the Bambuí Group support derivation of most of the stratigraphic package from the erosion of Ediacaran sources located on the surrounding Brasiliano mountain belts, including samples from the upper Sete Lagoas Formation (Pimentel et al., 2011; Dias et al., 2024), conglomerate wedges on the western portion of the basin (Uhlein et al., 2017), and samples from the Serra da Saudade Formation (Paula-Santos and Babinski, 2018; Kuchenbecker et al., 2020)—all indicating original provenance in the ca. 635–

560 Ma age range. Samples from the overlying Serra da Saudade and Três Marias Formations show even younger detrital zircons, as young as ca. 555–520 Ma (Tavares et al., 2020; Moreira et al., 2020; Rossi et al., 2020; Dias et al., 2024).

If these ages are correct, they suggest instead that the glacial units of the Jequitaí Formation were potentially co-eval with the Gaskiers glaciation at ~579 Ma (Pu et al., 2016), or perhaps even one of the less well characterized post-Gaskiers Ediacaran glaciations (e.g. Xiao et al., 2004; Hebert et al., 2010; Le Heron et al., 2019; Linnemann et al., 2021). However, it must be noted that no Ediacaran detrital zircons have been found in either the Pedro Leopoldo member cap carbonate or in the underlying Jequitaí Formation diamictites, with the main younger zircon peak at ca. 900 Ma and sparse Cryogenian zircons (see compilation in Caxito et al., 2021). This supports the interpretation of deposition in distinct basinal settings with distinct provenances (cratonic versus mountain belts) for the glacial-related basal part of the Bambuí Group (diamictite + cap carbonate) in contrast to the upper part of the succession (Lagoa Santa member upwards) and leaves the question of the age of the glaciation open for debate. Further up section in a possible ash fall tuff breccia of the Serra da Saudade Formation, LA-ICPMS U-Pb ages for the youngest population (10 out of 107) of detrital zircons yield an age of 520.2 ± 5.3 Ma (Moreira et al., 2020; although see DaSilva et al., 2022 for an alternative view) suggesting that the upper Bambuí Group may be Cambrian in age. The full range of U-Pb ages span from ca. 520 to nearly 2800 Ma indicating a significant admixture of inherited grains. While this minimum age is likely to be robust, the igneous horizon lies over 100 meters above carbonates that are highly ^{13}C enriched as discussed above and sit below carbonates of the Jaíba Member that have $\delta^{13}C$ values between 1 and 3.5‰, as well as a tight distribution of $^{87}Sr/^{86}Sr$ values near 0.7080. Strontium isotope age models are consistent with these carbonates being deposited either before or after Marinoan aged glacial deposits in South China and elsewhere (e.g. Cui et al., 2015; Lau et al., 2017: see Fig. 1, left panel), or terminal Ediacaran strata in Arctic Siberia (Vishnevskaya et al., 2013; Kaufman et al., 2019), but not with those from the basal Cambrian interval (cf. Kaufman et al., 1996). Thus, at present, conflicting data make the age significance of the Serra da Saudade siltstone unclear; there is always the possibility of an unknown unconformity between the highly positive $\delta^{13}C$ interval and the volcaniclastic horizon.

Considering that Ediacaran carbonates with such positive extremes are rare (see Moynihan et al., 2019 for the highest recorded Ediacaran values of ca. +12‰ in a 5 meter interval within carbonate deep marine turbidites of the Nadaleen Formation of the Windermere Supergroup: Fig. 1, right panel), the extended Middle Bambuí Excursion might relate to basin restriction associated with the closing of the Goiás-Brasilides and Adamastor oceans (Uhlein et al., 2019; Caetano-Filho et al., 2020; Cui et al., 2020; Caxito et al., 2021). However, physical evidence of restriction is lacking, and a recent sequence stratigraphic analysis suggests continuous connection with the open ocean (DaSilva et al., 2022). The presumed Ediacaran equivalent in northern Canada would be the Nadaleen Formation where regional mapping reveals no evidence of basinal restriction. Alternatively, the positive carbon isotope anomaly coupled with non-radiogenic $^{87}Sr/^{86}Sr$ values (<0.7075) might be Cryogenian in age (see Kaufman et al., 2009 for an extended discussion and Fig. 9, left panel for an example from Mongolia) and hence predate the Marinoan ice age (**M** in Fig. 9) of Snowball Earth renown. In this case, the basal Bambuí diamictite might be related to Sturtian (**S** in Fig. 9) glaciation instead. Notice, however, that this interpretation is not supported by the available geochronological (detrital zircon, U-Pb in carbonate), chemostratigraphic and paleontological data available as discussed above. Thus, more detailed work is necessary to better constrain the age of both the glacial record and the extreme carbon isotope fluctuations recorded in the Bambuí Group.

The difficulties associated with the age dating of Bambui Group sedimentary rocks has important ramifications on our continued development of the Terminal Ediacaran Stage (Xiao et al., 2016). Despite a spirited search by the field trip members, except for possible fossil fragments, no new specimens of *Cloudina* were found at either Barreiros Quarry or the Sapé section where they have been previously reported (Warren et al., 2014). Further study of the fragmentary remains that have been described are warranted but lacking more robust fossil evidence and more clarity about age constraints and isotope age models, it remains unclear whether the Jequitaí glacial diamictite and the Bambuí Group containing the MIBE is Ediacaran or Cryogenian in age. As mentioned above, if cloudinomorphs are confirmed in the Lagoa Santa Member and it is Ediacaran (but pre-Shuram) in age, then the first appearance of these early experiments in biomineralization would be 10s of millions of years older than previously known. This finding would thus play an important role in subdividing the Ediacaran Period.

Moving Forward:

Overall, the success of the Neoproterozoic Bambuí Group field trip marks an important return to Subcommission activities (Fig. 10) following the difficulties associated with the global pandemic. Considering that this trip was originally scheduled for Spring 2020, our division is excited to renew the process of defining the "Terminal Ediacaran Series" (Xiao et al., 2016) to which the Bambuí Group will feature prominently in the debate.

Acknowledgments:

We thank Jonathan Rojas and all the staff of the Brazilian Geological Survey drillcore facility at Caeté, Brazil, for allowing access to the drillcores and for the hospitality in receiving our Subcommission members.

References:

Babinski, M., Vieira, L.C., and Trindade, R.I. 2007. Direct dating of the Sete Lagoas cap carbonate (Bambuí Group, Brazil) and implications for the Neoproterozoic glacial events. Terra Nova, 19(6), 401–406.

Caetano-Filho, S., Sansjofre, P., Ader, M., Paula-Santos, G., Babinski, M., Bedoya-Rueda, C., and Kuchenbecker, M., 2020, A large epeiric methanogenic Bambuí sea in the core of Gondwana supercontinent? Geoscience Frontiers, v. 12, pp. 203–218.

Caxito, F., Halverson, G.P., A., Uhlein, A., Stevenson, R., Dias, T.G., and Uhlein, G.J., 2012, Marinoan glaciation in east central Brazil: Precambrian Research, v. 200, pp.38–58.

Caxito, F., Lana, C., Frei, R., Uhlein, G.J., Sial, A.N., Dantas, E.L., Pinto, A.G., Campos, F.C., Galvão, P., Warren, L. V., Okubo, J., and Ganade, C.E., 2021, Goldilocks at the dawn of complex life: mountains might have damaged Ediacaran–Cambrian ecosystems and prompted an early Cambrian greenhouse world. Scientific Reports, v. 11, pp. 1–15.

Cui, H., Kaufman, A.J., Xiao, S., Zhu, M., Zhou, C., and Liu, X.M. 2015. Redox architecture of an Ediacaran ocean margin: Integrated chemostratigraphic (δ13C–δ34S–87Sr/86Sr–Ce/Ce*) correlation of the Doushantuo Formation, South China. Chemical Geology, 405, 48–62.

Cui, H., Warren, L.V., Uhlein, G.J., Okubo, J., Liu, X.M., Plummer, R.E., Baele, J.M., Goderis, S., Claeys, P., and Li, F., 2020, Global or regional? Constraining the origins of the middle Bambuí carbon cycle anomaly in Brazil. Precambrian Research, v. 348, pp 105861.

DaSilva, L.G., Pufahl, P.K., James, N.P., Guimaraes, E.M. and Reis, C., 2022, Sequence stratigraphy and paleoenvironmental significance of the Neoproterozoic Bambui Group, Central Brazil. Precambrian Research, v. 379, pp. 106710.

Dias A.N.C., Martins-Ferreira M.A.C., Pereira V.Q., Sales A.S.W., Chemale Jr. F.; Insights into the Phanerozoic evolution of the São Francisco Craton based on detrital zircon thermochronology and U-Pb-Hf geochronology. GSA Bulletin 2024; doi: https://doi.org/10.1130/B37281.1

Hebert, C.L., Kaufman, A.J., Penniston-Dorland, S.C. and Martin, A.J., 2010, Radiometric and stratigraphic constraints on terminal Ediacaran (post-Gaskiers) glaciation and metazoan evolution. Precambrian Research, v. 182, pp. 402-412.

Hoffman, P.F., Abbot, D.S., Ashkenazy, Y., Benn, D.I., Brocks, J.J., Cohen, P.A., Cox, G.M., Creveling, J.R., Donnadieu, Y., Erwin, D.H., and Fairchild, I.J. 2017. Snowball Earth climate dynamics and Cryogenian geology-geobiology. Science Advances, 3(11), e1600983.

Kaufman, A.J., Knoll, A.H., Semikhatov, M.A., Grotzinger, J.P., Jacobsen, S.B., and Adams, W. 1996. Integrated chronostratigraphy of Proterozoic–Cambrian boundary beds in the western Anabar region, northern Siberia. Geological Magazine, 133(5), 509–533.

Kaufman et al., 2009

Kaufman et al., 2019

Kuchenbecker, M., Pedrosa-Soares, A. C., Babinski, M., Reis, H. L. S., Atman, D., & da Costa, R. D. (2020). Towards an integrated tectonic model for the interaction between the Bambuí basin and the adjoining orogenic belts: Evidences from the detrital zircon record of syn-orogenic units. Journal of South American Earth Sciences, 104, 102831.

Lau, K.V., Macdonald, F.A., Maher, K., and Payne, J.L. 2017. Uranium isotope evidence for temporary ocean oxygenation in the aftermath of the Sturtian Snowball Earth. Earth and Planetary Science Letters, 458, 282–292.

Le Heron, D.P., Vandyk, T.M., Kuang, H., Liu, Y., Chen, X., Wang, Y., Yang, Z., Scharfenberg, L., Davies, B. and Shields, G., 2019, Bird's-eye view of an Ediacaran subglacial landscape. Geology, v. 47, pp.705-709.

Linnemann, U., Hofmann, M., Gärtner, A., Gärtner, J., Zieger, J., Krause, R., Haenel, R., Mende, K., Ovtcharova, M., Schaltegger, U. and Vickers-Rich, P., 2022, An Upper Ediacaran Glacial

Period in Cadomia: the Granville tillite (Armorican Massif)–sedimentology, geochronology and provenance. Geological Magazine, v. 159, pp.999-1013.

Macdonald, F.A., Strauss, J.V., Sperling, E.A., Halverson, G.P., Narbonne, G.M., Johnston, D.T., Kunzmann, M., Schrag, D.P., and Higgins, J.A. 2013. The stratigraphic relationship between the Shuram carbon isotope excursion, the oxygenation of Neoproterozoic oceans, and the first appearance of the Ediacara biota and bilaterian trace fossils in northwestern Canada. Chemical Geology, 362, 250–272.

Moreira, D.S., Uhlein, A., Dussin, I.A., Uhlein, G.J., and Misuzaki, A.M.P., 2020, A Cambrian age for the upper Bambuí Group, Brazil, supported by the first U-Pb dating of volcanoclastic bed. Journal of South American Earth Sciences, v. 99, pp. 102503.

Moynihan, D.P., Strauss, J.V., Nelson, L.L., and Padget, C.D. 2019. Upper Windermere Supergroup and the transition from rifting to continent-margin sedimentation, Nadaleen River area, northern Canadian Cordillera. GSA Bulletin, 131(9-10), 1673–1701.

Okubo, J., Inglez, L., Uhlein, G.J., Warren, L. V, Xiao, S., 2023, Simple structures and complex stories: potential microbially induced sedimentary structures in the Ediacaran Serra De Santa Helena Formation, Bambuí Group, eastern Brazil. Palaios, v. 38, pp. 188–209.

Paula-Santos, G.M., Babinski, M., Kuchenbecker, M., Caetano-Filho, S., Trindade, R.I., and Pedrosa-Soares, A.C., 2015, New evidence of an Ediacaran age for the Bambuí Group in southern São Francisco craton (eastern Brazil) from zircon U-Pb data and isotope chemostratigraphy. Gondwana Research, v. 28, pp. 702–720.

Paula-Santos, G.M., and Babinski, M., 2018, Sedimentary provenance in the southern sector of the São Francisco Basin, SE Brazil. Brazilian Journal of Geology, v. 48, pp. 51–74.

Pimentel, M. M., Rodrigues, J. B., DellaGiustina, M. E. S., Junges, S., Matteini, M., & Armstrong, R. (2011). The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil, based on SHRIMP and LA-ICPMS U–Pb sedimentary provenance data: a review. Journal of South American Earth Sciences, 31(4), 345-357.

Pu, J.P., Bowring, S.A., Ramezani, J., Myrow, P., Raub, T.D., Landing, E., Mills, A., Hodgin, E. and Macdonald, F.A., 2016, Dodging snowballs: Geochronology of the Gaskiers glaciation and the first appearance of the Ediacaran biota. Geology, v. 44, pp. 955–958.

Reis, H.L.S., Alkmim, F.F., Fonseca, R.C.S., Nascimento, T.C., Suss, J.F., and Prevatti, L.D., 2017, The São Francisco Basin. Regional Geology Reviews. Springer, Cham., pp. 117–143.

Rooney, A.D., Cantine, M.D., Bergmann, K.D., Gómez-Pérez, I., Baloushi, B.A., Boag, T.H., Busch, J.F., Sperling, E.A., and Strauss, J.V., 2020, Calibrating the coevolution of Ediacaran life and environment. Earth, Atmospheric, And Planetary Sciences, v. 117, pp. 16824–16830.

Rossi, A. V., Danderfer Filho, A., Bersan, S. M., Kelmer, L. R., Tavares, T. D., & de Carvalho Lana, C. (2020). Stratigraphic, isotopic, and geochronological record of a superposed pro-foreland basin in the eastern São Francisco craton during west Gondwana amalgamation. Journal of South American Earth Sciences, 97, 102406.

Tavares, T.D., Martins, M. De S., Alkmim, F.F., and Lana, C., 2020, Detrital zircons from the Upper Três Marias Formation, São Francisco basin, SE Brazil: record of foreland deposition during the Cambrian? Journal of South American Earth Sciences, v. 97, pp. 102395.

Uhlein, G. J., Uhlein, A., Stevenson, R., Halverson, G. P., Caxito, F. A., & Cox, G. M. (2017). Early to late Ediacaran conglomeratic wedges from a complete foreland basin cycle in the southwest São Francisco Craton, Bambuí Group, Brazil. Precambrian Research, 299, 101-116.

Uhlein, G.J., Uhlein, A., Pereira, E., Caxito, F.A., Okubo, J., Warren, L.V., and Sial, A.N., 2019, Ediacaran paleoenvironmental changes recorded in the mixed carbonate/siliciclastic Bambuí Basin, Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 517 pp. 39–51.

Vishnevskaya et al., 2013

Warren, L.V., Quaglio, F., Riccomini, C., Simões, M.G., Poire, D.G., Strikis, N.M., Anelli, L.E., Strikis, P.C., 2014, The puzzle assembled: Ediacaran guide fossil *Cloudina* reveals an old proto-Gondwana seaway. Geology, v. 42, pp. 391–394.

Xiao, S., Bao, H., Wang, H., Kaufman, A.J., Zhou, C., Li, G., Yuan, X. and Ling, H., 2004, The Neoproterozoic Quruqtagh Group in eastern Chinese Tianshan: evidence for a post-Marinoan glaciation. Precambrian Research, v. 130, pp. 1–26.

Xiao, S., Narbonne, G.M., Zhou, C., Laflamme, M., Grazhdankin, D.V., Moczydlowska-Vidal, M., and Cui, H., 2016, Towards an Ediacaran time scale: problems, protocols, and prospects. Episodes, v. 39, pp. 540–555.

Figure Captions

Figure 1. Members of the Cryogenian and Ediacaran subcommittees analyzing Bambuí Basin drill cores. From left clockwise: Huan Cui, Xiao-Dong Shang, Ying Zhou, Jay Kaufman, Graham Shields, Erik Sperling, Fabricio Caxito, Gabriel Correa Antunes, and Brandt Gibson. Photo from Huan Cui.

Figure 2. Members of the Ediacaran subcommission discussing the origin of the diamictite from the Jequitaí Fm. From left: Marc Laflamme, Shuhai Xiao, and Juliana Okubo. Photo from Huan Cui.

Figure 3. Simplified stratigraphic column and compilation of carbon isotopic data for the Bambuí Group (Caxito et al., 2021 and references therein)

Figure 4. Black columnar stromatolites (left) and aragonite fans (right) of the uppermost Sete Lagoas Formation (Lagoa Santa Member). Photo from Huan Cui.

Figure 5. Exposure of carbonates from the Sete Lagoas Formation (Lagoa Santa Member) at the Tatiana Quarry. In this section there are several intervals of dolomite fans a few meters below the upper contact with the Serra de Santa Helena Formation. Photo from Marc Laflamme.

Figure 6. Striated pavements from Jequitaí Formation. In this outcrop, tillites occur directly on the glacial surface. Photo from Marc Laflamme.

Figure 7. Aragonite (left) and barite (right) fans from the base of the Sete Lagoas Formation. Photo from Marc Laflamme.

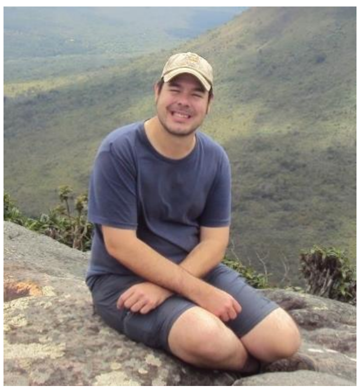
Figure 8. Sunlight inside the Janelões cave. Photo from Marc Laflamme.

Figure 9. Comparative Cryogenian and Ediacaran Earth history based on the presence of Sturtian (S) and Marinoan (M) aged diamictites, presumptive fossils of biomineralized Ediacaran

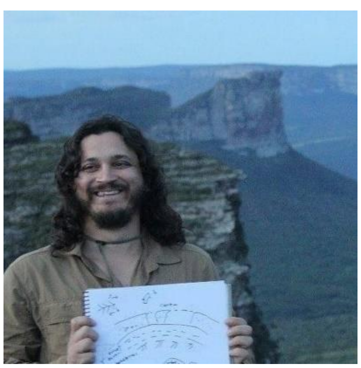
Period cloudinomorphs, and chemostratigraphic trends in both carbon and strontium isotopes. (Left panel) Cryogenian Taishir Formation of Mongolia (see Bold et al., 2015 and Lau et al., 2017), which lies between Sturtian and Marinoan glacial deposits and preserves a profound positive carbon isotope anomaly (up to +12‰) and uniformly non-radiogenic $^{87}Sr/^{86}Sr$ compositions over a 400 m interval. (Center panel) Cryogenian or Ediacaran Bambuí Group of Brazil (see Misi et al., 2007; Babinski et al., 2007; Caxito et al., 2012; 2021; Cui et al., 2020; Uhlein et al., 2019 for lowest $^{87}Sr/^{86}Sr$ values in each interval) overlying the Jequitai glacial diamictite of debatable Sturtian or Marinoan age. The stratigraphic position of the putative cloudinomorph fossils are illustrated below the >350 m of the Middle Bambui Excursion (MIBE). (Right panel) If the Bambui Group sedimentary rocks are correlative with the Ediacaran succession in northern Canada (Right panel) based on the positive d13C compositions of the Nadaleen Formation (Moynihan et al., 2019) the presumptive cloudinomorphs in Brazil would represent an earlier FAD for the biomineralized remains. At present the oldest known cloudinomorphs have been identified in the uppermost Mara Member in the Nama Group of Namibia (Kaufman et al., 2019) occurring at the end of the Shuram Excursion, which is notably missing in the Brazilian Bambui Group.

Figure 10. Members of the Ediacaran and Cryogenian subcommissions at the end of a working day. From left to right, Chuan Yang, Ben Yang, Graham Shields-Zhou, Maoyan Zhu, Huan Cui, Tara Selly, Casey Bennett, Carolina Reis, Fabrício Caxito, Ying Zhou, Gabriel Uhlein, Juliana Okubo, Johannes Zieger, Gabriel Antunes, Mandy Zieger-Hofmann, Shuhai Xiao, Erik Sperling, Lucas Warren, Marc Laflamme, Brandt Gibson, Ulf Linneman, Xiao-Dong Shang.

Marc Laflamme is a professor of paleontology at the University of Toronto Mississauga. His research examines the origins, evolution, function, and preservation of the Ediacara biota. He is the current Chair of the International Subcommission on Ediacaran Stratigraphy of the International Commission of Stratigraphy in the International Union of Geological Sciences.



Lucas Veríssimo Warren Lucas Veríssimo Warren is an associate professor of sedimentology and biostratigraphy at the São Paulo State University, Brazil. Lucas focuses his research on basin analysis with an emphasis on sedimentology, sequence stratigraphy and Precambrian biostratigraphy mainly in Ediacaran successions in South America and Africa. He co-led the joint subcommission field trip to Brazil in 2023 and is currently secretary of the International Subcommission on Ediacaran Stratigraphy.



Fabrício de Andrade Caxito is a professor of geology at Universidade Federal de Minas Gerais, Brazil. His research is focused on applying field and geochemical tools to understand the interlinked evolution of the solid Earth and life that thrives on it. He is a voting member of the International Subcommission on Cryogenian Stratigraphy and co-led the joint subcommission field trip to Brazil in 2023.

Tara Selly's is a Research Assistant Professor and Assistant Director of the X-ray Microanalysis Lab at the University of Missouri. Her research utilizes modern microscopic techniques to answer questions about the origins of macroscopic life on Earth. Through this work, she explores how late Ediacaran (~550 million-year-old) organisms became incorporated into the fossil record and how their preservation influences paleontologists' ability to interpret their original biology.

Alan J. Kaufman is a Professor at the University of Maryland. His research has focused on the determination of changes in the isotopic composition of the oceans through time, by the analysis of stragraphic suites of little-altered carbonate rocks. Thus far, most of these studies have centered around Neoproterozoic (ca. 1000-544 million-year-old) sedimentary successions in Svalbard/East Greenland, Namibia, arctic Canada and Alaska, India, and the western USA.

Graham A. Shields is a Professor from the University College London. His research utilizes geochemical and isotopic tracers to study the composition of past oceans and atmosphere, and the coevolution with life through crucial junctures in Earth history. His research group develops proxies to trace biogeochemical fluxes and related feedbacks that govern oxygen, carbon dioxide and nutrient budgets on Earth.

Shuhai Xiao is a professor of geobiology at Virginia Tech. He integrates paleobiological, sedimentological, and geochemical data to investigate the Precambrian Earth history, with a focus on the Ediacaran Period. In 2012–2020, he served as the Chair of the International Subcommission on Ediacaran Stratigraphy of the

International Commission of Stratigraphy in the International Union of Geological Sciences.

Maoyan Zhu is a research professor of geology and paleontology at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. His research focuses on early evolution of multicellular organisms and animals, Neoproterozoic-Cambrian stratigraphy and palaeo-environmental changes. He is the current Chair of the International Subcommission on Cryogenian Stratigraphy of the International Commission of Stratigraphy in the International Union of Geological Sciences.

Figure 1

Figure 1. Members of the Cryogenian and Ediacaran subcommittees analyzing Bambuí Basin drill cores. From left clockwise: Huan Cui, Xiao-Dong Shang, Ying Zhou, Jay Kaufman, Graham Shields, Erik Sperling, Fabricio Caxito, Gabriel Correa Antunes, and Brandt Gibson. Photo from Huan Cui.

Figure 2

Figure 2. Members of the Ediacaran subcommission discussing the origin of the diamictite from the Jequitaí Fm. From left: Marc Laflamme, Shuhai Xiao, and Juliana Okubo. Photo from Huan Cui.

Figure 3

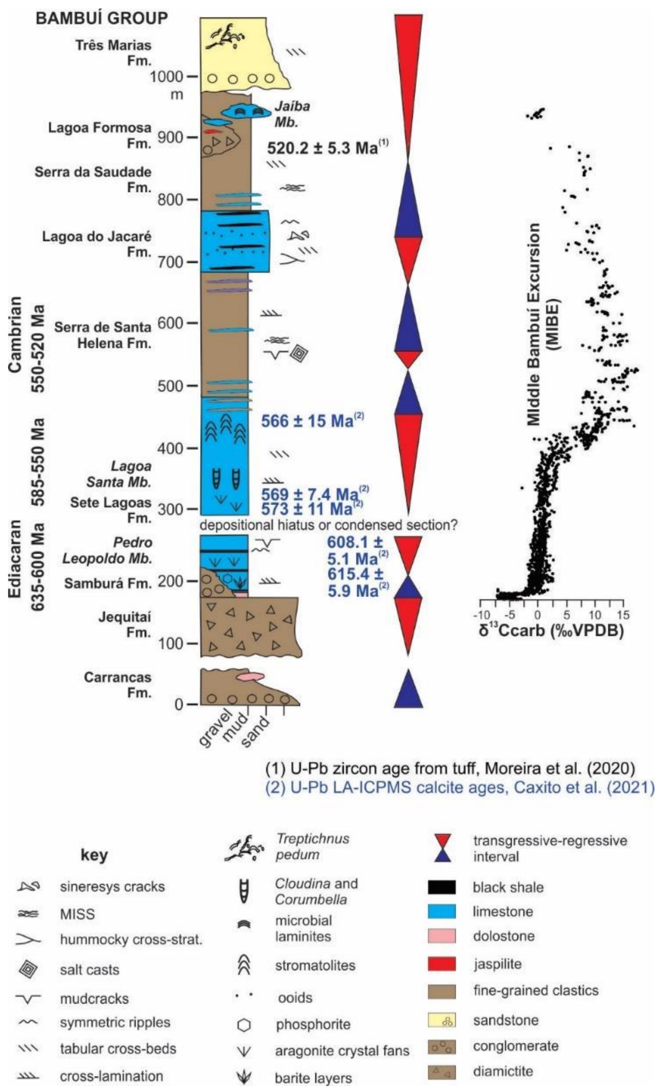


Figure 3 - Simplified stratigraphic column and compilation of carbon isotopic data for the Bambuí Group (Caxito et al., 2021 and references therein)

Figure 4

Figure 4. Black columnar stromatolites (left) and aragonite fans (right) of the uppermost Sete Lagoas Formation (Lagoa Santa Member). Photo from Huan Cui.

Figure 5

Figure 5. Exposure of carbonates from the Sete Lagoas Formation (Lagoa Santa Member) at the Tatiana Quarry. In this section there are several intervals of dolomite fans a few meters below the upper contact with the Serra de Santa Helena Formation. Photo from Marc Laflamme.

Figure 6

Figure 6. Striated pavements from Jequitaí Formation. In this outcrop, tillites occur directly on the glacial surface. Photo from Marc Laflamme.

Figure 7

Figure 7. Aragonite (left) and barite (right) fans from the base of the Sete Lagoas Formation. Photo from Marc Laflamme.

Figure 8

Figure 8. Sunlight inside the Janelões cave. Photo from Marc Laflamme.

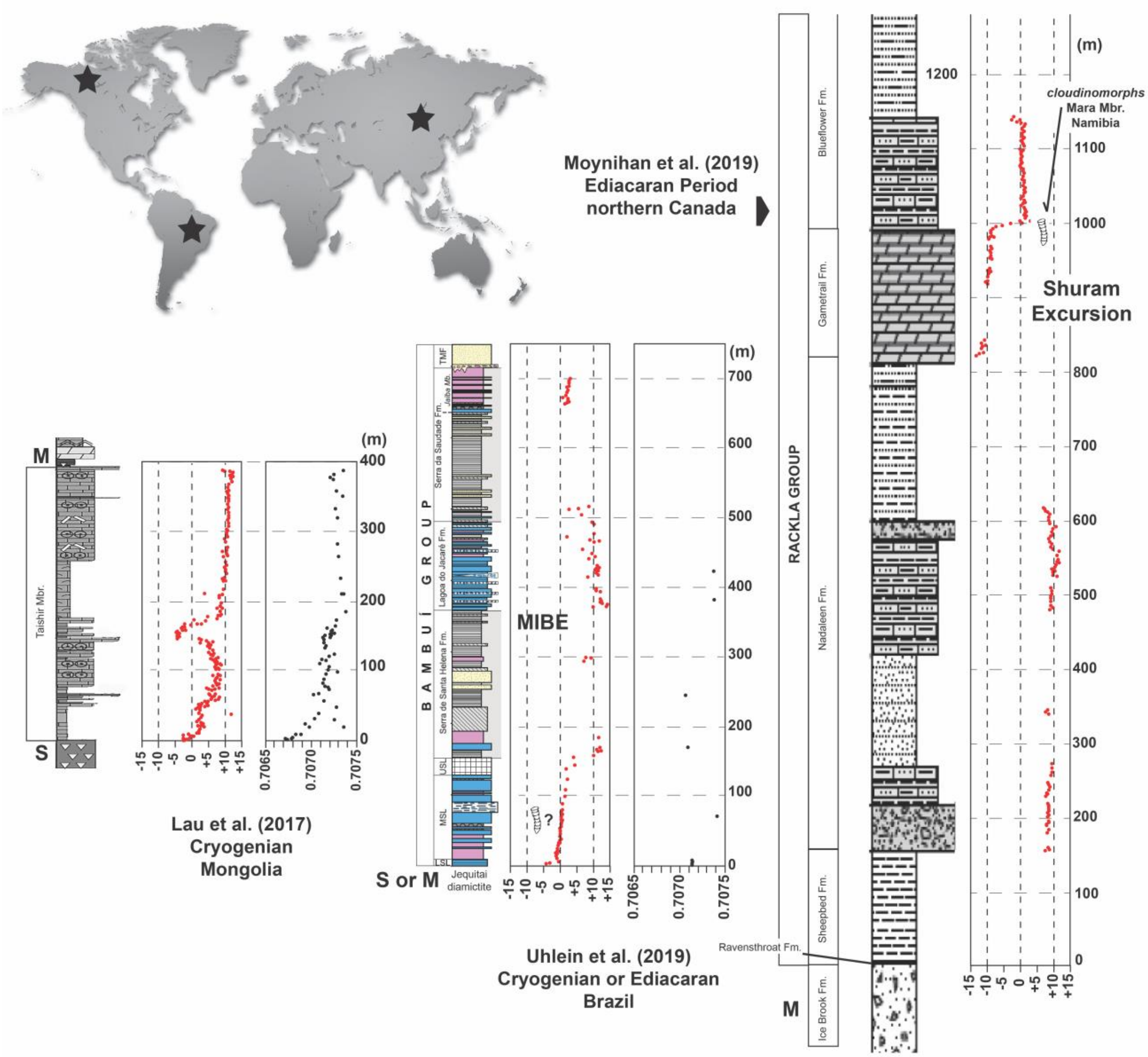


Figure 9. Comparative Cryogenian and Ediacaran Earth history based on the presence of Sturtian (S) and Marinoan (M) aged diamictites, presumptive fossils of biomineralized Ediacaran Period cloudinomorphs, and chemostratigraphic trends in both carbon and strontium isotopes. (Left panel) Cryogenian Taishir Formation of Mongolia (see Bold et al., 2015 and Lau et al., 2017), which lies between Sturtian and Marinoan glacial deposits and preserves a profound positive carbon isotope anomaly (up to +12‰) and uniformly non-radiogenic $^{87}Sr/^{86}Sr$ compositions over a 400 m interval. (Center panel) Cryogenian or Ediacaran Bambuí Group of Brazil (see Misi et al., 2007; Babinski et al., 2007; Caxito et al., 2012; 2021; Cui et al., 2020; Uhlein et al., 2019 for lowest $^{87}Sr/^{86}Sr$ values in each interval) overlying the Jequitai glacial diamictite of debatable

Sturtian or Marinoan age. The stratigraphic position of the putative cloudinomorph fossils are illustrated below the >350 m of the Middle Bambui Excursion (MIBE). (Right panel) If the Bambui Group sedimentary rocks are correlative with the Ediacaran succession in northern Canada (Right panel) based on the positive d13C compositions of the Nadaleen Formation (Moynihan et al., 2019) the presumptive cloudinomorphs in Brazil would represent an earlier FAD for the biomineralized remains. At present the oldest known cloudinomorphs have been identified in the uppermost Mara Member in the Nama Group of Namibia (Kaufman et al., 2019) occurring at the end of the Shuram Excursion, which is notably missing in the Brazilian Bambui Group.

Figure 10

Figure 10. Members of the Ediacaran and Cryogenian subcommissions at the end of a working day. From left to right, Chuan Yang, Ben Yang, Graham Shields-Zhou, Maoyan Zhu, Huan Cui, Tara Selly, Casey Bennett, Carolina Reis, Fabrício Caxito, Ying Zhou, Gabriel Uhlein, Juliana Okubo, Johannes Zieger, Gabriel Antunes, Mandy Zieger-Hofmann, Shuhai Xiao, Erik Sperling, Lucas Warren, Marc Laflamme, Brandt Gibson, Ulf Linneman, Xiao-Dong Shang. Photo from Huan Cui.