

Recurrent emplacement of non-glacial diamictite during the late Paleozoic ice age

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ABSTRACT

Most ice-age diamictites were emplaced in basinal settings by non-subglacial processes. Nonetheless, the occurrence of diamictite in rock successions is widely employed to estimate ice extent and delimit glacial growth-decay cycles that serve as background for paleoclimate modeling. We report a cyclic diamictite-mudstone succession from the Bashkirian-Moscovian Campo do Tenente Formation in southern Brazil to investigate the timing of diamictite emplacement with respect to glaciation. Glacial cycles can be recognized, in which mudstones with ice-rafted debris record deposition in a marine-influenced water body during intervals of maximum ice advance. Diamictites, on the other hand, lack striated and faceted clasts, have deformed blocks of sandstones, and are enveloped by IRD-free mudstones. They are interpreted as non-glacial mass-transport deposits derived from delta collapse during intervals of maximum ice retreat, in which dispersed gravel derives from block assimilation and not from ice rafting.

INTRODUCTION

Discriminating subglacial diamictites (tillites) from those formed in glacioaquatic settings or via non-glacial landslides is an old, but still controversial, issue on the reconstruction of deep-time glaciations (e.g., Deynoux, 1985; Eyles and Januszczak, 2007). Glacially related and non-glacial diamictites may intercalate in the same succession (e.g., Le Heron et al., 2017), which may lead to overestimations of glacial extent based on diamictite distribution (e.g., González-Bonorino and Eyles, 1995). Diverse interpretations of diamictite can result in discrepant ice-volume calculations ranging from supercontinent-scale ice sheets up to 3×10^7 km² large (e.g., Cao et al., 2018), to isolated ice centers on highlands that together are one order of magnitude smaller (e.g., Isbell et al., 2012).

It has been long recognized that most ice-age diamictites accumulated in basinal settings via non-subglacial processes (Eyles, 1993). Evidence includes their association with turbidites, ice-rafted debris (IRD), and slump-generated structures. Nonetheless, diamictite is often taken as a paleoclimate proxy, and its recurrence in rock successions is widely used to delimit cycles of ice-sheet growth and decay (e.g., Fielding et al., 2008). Concerning mass-transport diamictites, these assumptions are problematic because previously inferred glacial influence on mass flows vary from strong (e.g., Visser, 1997) to absent (e.g., Eyles and Januszczak, 2007), which unfortunately renders these diamictites non-unique within glacialigenic stratigraphic schemes.

In the mid- to high-latitude stratigraphic record of the late Paleozoic ice age, recurrent

diamictite are used to delimit and correlate thick (tens to hundreds of meters) sequences recording glacier advance-retreat cycles (e.g., França and Potter, 1991; Visser, 1997; Fielding et al., 2008). We investigate the timing of diamictite deposition within a higher-resolution (several meters thick) diamictite-mudstone stratigraphy of a Bashkirian-Moscovian succession of the Campo do Tenente Formation (southern Brazil). The Campo do Tenente Formation crops out in the eastern Paraná Basin (Fig. 1A), a region that was glaciated by the presumed westward advance of ice lobes from an ice sheet in southwest Africa (Windhoek Ice Sheet).

DATA DESCRIPTION AND INTERPRETATION

The 140-m-thick Campo do Tenente Formation (lower Itararé Group; Fig. 1B) is considered as the upper half of a long-term (~5 m.y.) glacialigenic sequence (França and Potter, 1991). It covers ~700 km² of the eastern Paraná Basin, onlaps the basement to the east-southeast and drapes a glacially scoured and striated substrate (Barbosa, 1940). Previously reported *Botryococcus* sp., *Tasmanites* spp., and *Leiosphaeridia* spp. (Kipper et al., 2017) indicate a brackish marginal/restricted marine environment for this formation. The unit comprises multiple alternating packages (Fig. 1B) of (1) thick diamictite, and (2) thinly bedded shale/rhythmite/diamictite, which we define as two facies associations (F1 and F2, respectively; Fig. 2). A sedimentological log assembled in the Campo do Tenente municipal quarry (Fig. 3A) allowed a detailed description of the two associations and the identification of six individual facies (F1-A, F1-B,

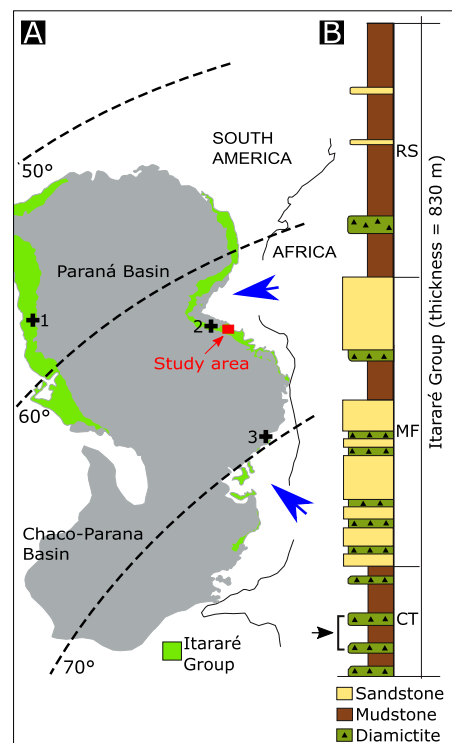


Figure 1. Geological setting. A: Location of the study area in eastern Paraná Basin (southern Brazil) according to its former position during the late Paleozoic, with blue arrows indicating paleo-ice flow directions. Black crosses indicate localities from which subglacial erosional features have been reinterpreted as products of iceberg scouring (1: Rosa et al., 2016; 2: Vesely and Assine, 2014) or sub-aerial erosion (3: Fedorchuk et al., 2018). B: Schematic subdivision of the Itararé Group in the southeast Paraná Basin, with black arrow pointing to the examined interval. Formation names: CT—Campo do Tenente; MF—Mafra; RS—Rio do Sul.

and F2-A–F2-D; see the GSA Data Repository¹). IRD (dropstones and pellets) amount was estimated visually each 10 cm, and thin sections of macroscopically IRD-free intervals were examined to look for finer IRD fractions.

¹GSA Data Repository item 2018211, lithofacies of the Campo do Tenente Formation, is available online at <http://www.geosociety.org/datarepository/2018/> or on request from editing@geosociety.org.

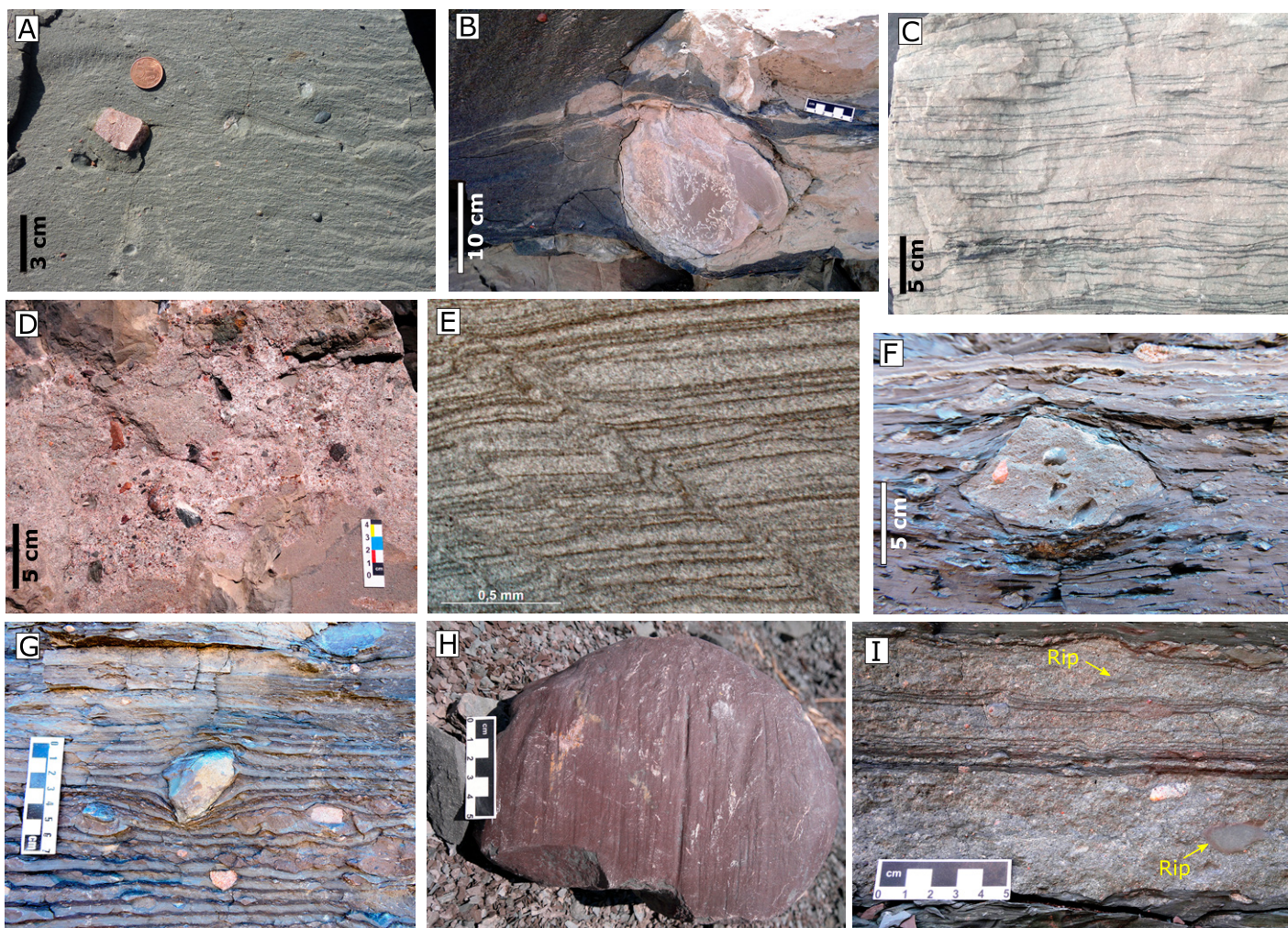


Figure 2. Facies characteristics. Diamictite (facies F1) can be homogeneous (A) or with bands derived from sandstone block assimilation (B). Blocks exhibit original sedimentary structures (C) and gravel-rich layers (D). E: Photomicrograph of thinly laminated mudstone (F2-D) lacking ice-rafted debris (IRD) (note small-scale soft-sediment deformation). F–H: F2-B rhythmites full of IRD in the form of poorly sorted sediment pellets (F) and dropstones (G); the latter often striated (H). I: Stratified diamictite (F2-C) with shale interbeds and imbricated rip-up clasts (Rip).

Thick Diamictite Facies Association (F1)

Description

F1 diamictites are sheet-like, 8-m-thick, sandy-muddy and clast-poor facies (Fig. 2A) containing less than 5% gravel, with a maximum size of 7 cm. They lack faceted/polished/striated clasts. Heterogeneous (F1-B) diamictites show up as meter-scale blocks of fine to gravelly sandstones (Figs. 2B–2D). Blocks are plastically deformed and disrupted, and primary sedimentary structures are often preserved (Fig. 2C).

Interpretation

A subaquatic origin for F1 is suggested by its intercalation with shale and rhythmite facies. The presence of allochthonous blocks and the strongly aligned magnetic fabrics reported by Gravenor and Von Brunn (1987) and Amato (2017) favors mobilization by slumps and debris flows, denoting a mass-flow origin for these diamictites. Allochthonous blocks are interpreted as from proximal, shallower depositional

settings due to current-generated sedimentary structures and heterolithic bedding characteristic of fluvial or tide-influenced environments. The absence of these facies in underlying strata rules out block incorporation by basal plucking and, instead, indicates entrainment via collapse from areas upslope (e.g., Nemec et al., 1988). The fact that all grain sizes in F1-A (mud to pebbles) were also observed in blocks suggests that the matrix is a product of disintegration and homogenization of a protolith (e.g., Eyles and Eyles, 2000) and that gravel in the diamictite is derived from block assimilation. The absence of faceted/striated/oversized clasts precludes interpreting F1 as re-sedimented IRD or glacial debris, and points to a non-glacial origin.

Thinly-Bedded Rhythmite-Shale-Diamictite Facies Association (F2)

Description

The base of F2 includes a 20-cm-thick, sand-mud, IRD-free rhythmite (F2-A). Sand content

decreases upward giving rise to a silt-mud rhythmite (F2-B). Within F2-B, the amount of IRD increases from near zero at the base to an interval full of IRD in which rhythmicity is hardly recognizable. IRD increase-decrease cycles repeat several times upsection (Fig. 3A). The uppermost interval is a 2-m-thick shale lacking IRD (Fig. 2E). When present, IRD is in both dark and pale layers, and comprise extrabasinal limestones and sediment pellets (Figs. 2F and 2G). Limestones are up to 40 cm in diameter, commonly striated (Fig. 2H), often bend and penetrate subjacent layers, and are onlapped by overlying beds, suggesting deposition by floating ice (dropstones; Thomas and Connell, 1984). Pellets are more abundant and comprise aggregates (from a few millimeters to 5 cm) of mud, sand, and gravel (Fig. 2F). Some are stretched parallel to bedding and partially disrupted, giving rise to nodular layers of poorly sorted sediment.

The F2 succession is punctuated by discrete beds of crudely stratified, clast-poor, sandy

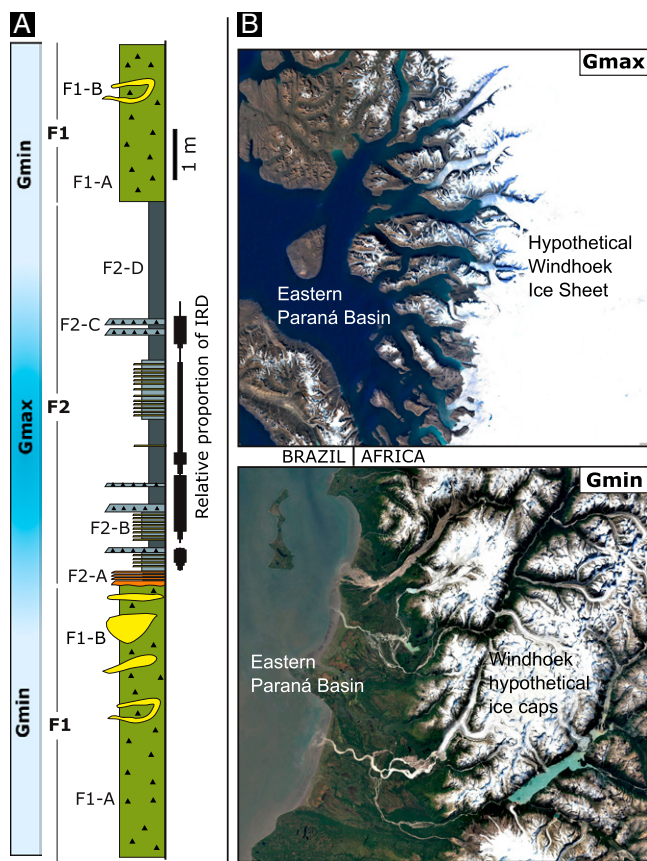


Figure 3. Sedimentological profile (A) and Google Earth™ modern analogs (B) for intervals of maximum ice advance (Gmax; Greenland) and intervals of maximum ice retreat (Gmin; southern Alaska) stages of the Campo do Tenente Formation (southern Brazil; see the Data Repository [see footnote 1] for facies description). At Gmax, deposition took place in a water body fringed by calving glaciers flowing from the Windhoek Ice Sheet (southwest Africa). At Gmin, the ice cover, if present, was limited to small ice caps on the highland, and sediment was transferred to the basin through fluvio-deltaic systems that were subject to slope instability and mass flow activity.

diamictites (F2-C; Fig. 2I) whose upper limits are gradational into shale (F2-D). With few exceptions, beds are associated with shale or rhythmites rich in IRD. Internally, this facies exhibits rip-up mudstone clasts (Fig. 2I) indicating erosion of a muddy substrate. The coarse-grained fraction of the matrix has a nodular texture resembling multiple attached sediment pellets that were transported and deformed.

Interpretation

Rhythmites are interpreted as the product of successive, suspended-load-dominated, decelerating flows. A sedimentation rate of ~28 mm/k.y. has been estimated for similar rhythmites in the Itararé Group (Franco and Hinnov, 2012), which, by comparison, would give a time span of ~107 k.y. for the 3 m of rhythmites in the Campo do Tenente quarry. The duration of a whole F2 unit (rhythmite+shale) is thus expected to be ~700 k.y., considering a minimum sedimentation rate of 10 mm/k.y. for laminated mudstones in glaciated environments (e.g., Ó Cofaigh and Dowdeswell, 2001) and not considering loss by compaction. Sediment pellets like those observed (till pellets) originate in glacial environments by processes like infilling of spaces between ice crystals (Ovenshine, 1970), and mechanical shearing of deforming beds beneath ice streams (Cowan et al., 2012). For the crudely stratified diamictite facies (F2-C), a gravity-flow origin is indicated mainly because of the rip-up

mudstone clasts and the sharp-based, fining-upward character of individual beds (Gravenor and Rocha-Campos, 1983). Additionally, we interpret that this facies derives from destabilization and remobilization of IRD-rich sediment accumulations.

DISCUSSION AND CONCLUSIONS

Field observations and literature data on the Campo do Tenente Formation suggest a marine-influenced environment fringed by outlet glaciers or ice streams, comparable to Quaternary embayments or epicontinental seas in which deglaciation commonly includes deposition by turbidity currents and mass flows (e.g., Bellwald et al., 2016). Quaternary IRD has been used to reconstruct past glacier expansion, as it indicates the delivery of icebergs from ice margins in contact with the basin (e.g., Bond et al., 1992). Similarly, IRD-rich layers (Fig. 3A) observed in this study testify to stages of iceberg production from calving ice margins (intervals of maximum ice advance). IRD-free intervals, on the other hand, relate to stages when iceberg input was low or absent because ice margins retreated to land (intervals of maximum ice retreat). During maximum retreats, sediment was supplied by streams from terrestrial ice margins or from deglaciated catchments. As F1 diamictites rest on, and are capped by, IRD-free layers, they are genetically associated with intervals of maximum ice retreat. This is corroborated by facies

in sandstone blocks suggesting cogenetic, non-glaciated fluvio-deltaic and/or estuarine systems located upslope that were subject to downslope re-sedimentation, resulting in mass-transport diamictites.

Our findings match with recent studies that envisaged a significantly smaller volume of ice in different sectors of the Paraná Basin (Fig. 1A) and in other late Paleozoic basins based on the re-interpretation of diamictite facies, soft-sediment grooves, and paleovalleys as non-subglacial products (e.g., Eyles and Eyles, 2000; Vesely and Assine, 2014; Rosa et al., 2016; Fedorchuk et al., 2018). Once indisputable evidence for subglacial erosion/deposition (plowed and glaciotectionized sediments) is also reported in the eastern border of the Paraná Basin (e.g., Vesely et al., 2015; Fallgatter and Paim, 2017), a paleogeography of relatively small (hundreds of meters to a few kilometers wide) and diachronic ice lobes flanked by non-glaciated shorelines (Fig. 3B) seems more likely than that of a huge ice margin up to hundreds of kilometers across (e.g., Gesicki et al., 2002; Stark and del Papa, 2006).

Non-glacial reinterpretations for tectonically related mass-flow diamictites have also resulted in drastic reductions of estimated ice extent in areas formerly considered to be covered by ice sheets during the Neoproterozoic, such as Namibia (Eyles and Januszczak, 2007) and North America (Carto and Eyles, 2012), where evidence for glacial-debris input in diamictite (e.g., faceted/striated clasts) is absent. Mass-transport diamictites are volumetrically important in the geological record of all ice ages, but not all have the same level of glacial affinity. While some reported diamictites show clear evidence of being re-sedimented glacial debris, in other cases a glacial signature cannot be demonstrated and a non-glacial origin is likely. These two emplacement conditions lead to dramatically different paleoclimatic and glacial cyclicity reconstructions.

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