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ARTICLE

A review on late Paleozoic ice-related erosional landforms in the Paraná Basin: origin and paleogeographical implications

Revisão de formas erosivas relacionadas à ação do gelo no Paleozoico superior da Bacia do Paraná: origem e implicações paleogeográficas

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ABSTRACT: The Late Paleozoic Ice Age is recorded in the Paraná Basin as glacial deposits, deformational features and ice-related erosional landforms of the Itararé Group. Erosional landforms are often employed to build paleogeographic models that depict the location of ice masses and paleo ice-flow directions. This paper provides a review of the literature and new data on micro- to meso-scale ice-related, erosional landforms of the Paraná Basin. Examined landforms can be placed into four broad categories based on their mode of origin. Subglacial landforms on rigid substrates occur on the Precambrian basement or on older units in the Paraná Basin. They include streamlined landforms and striated pavements formed by abrasion and/or plucking beneath advancing glaciers. Subglacial landforms on soft beds are intraformational surfaces generated by erosion and deformation of unconsolidated deposits when overridden by glaciers. Ice-keel scour marks are soft-sediment striated/grooved landforms developed by the scouring of free-floating ice masses on underlying sediments. Striated clast pavements are horizons containing aligned clasts that are abraded subglacially due to the advance of glaciers on unconsolidated deposits. Only those erosional landforms formed subglacially can be used as reliable paleo ice-flow indicators. Based on these data, the paleogeography of the Paraná Basin during the Late Paleozoic Ice Age fits into a model of several glacial lobes derived from topographically-controlled ice spreading centers located around the basin instead of a single continental ice sheet.

KEYWORDS: Late Paleozoic Ice Age; Itararé Group; glacial erosion; paleogeography.

RESUMO: *A Era Glacial Neopaleozoica está registrada na Bacia do Paraná através da sucessão sedimentar do Grupo Itararé e unidades correlatas, bem como por feições glaciotectônicas e formas de leito erosivas relacionadas à ação do gelo. Formas de leito erosivas são comumente utilizadas em análises paleogeográficas visando evidenciar o sentido de fluxo de geleiras e localizar antigos centros irradiadores de gelo. Neste trabalho é apresentada uma revisão da literatura e novos dados sobre formas de leito erosivas de micro a mesoescala encontradas na Bacia do Paraná. As formas de leito examinadas podem ser enquadradas em quatro categorias cuja origem está relacionada a diferentes processos. Formas subglaciais sobre substrato rígido são estruturas geradas por abrasão e/ou remoção de blocos sobre substratos litificados do embasamento precambriano ou de unidades mais antigas da bacia. Incluem formas alongadas e pavimentos estriados formados sob geleiras em avanço. Formas subglaciais sobre leitos moles são superfícies intraformacionais geradas por erosão e deformação de depósitos inconsolidados quando da passagem de geleiras. Marcas de arrasto de quilhas de gelo, por outro lado, são superfícies intraformacionais comumente estriadas e sulcadas, formadas pelo arrasto de quilhas de blocos de gelo livremente flutuantes sobre sedimento de fundo. Pavimentos de clastos estriados são horizontes contendo clastos alinhados submetidos à abrasão subglacial pelo avanço de geleiras sobre sedimentos. Dentre as diferentes formas de leito, apenas aquelas formadas sob geleiras em avanço podem ser utilizadas como indicadores confiáveis do paleofluxo glacial. Com base nisso, a paleogeografia da Bacia do Paraná durante a Era Glacial Neopaleozoica se insere em um modelo com vários lobos glaciais derivados de centros glaciais situados sobre altos topográficos ao invés de um único manto de gelo de dimensões continentais.*

PALAVRAS-CHAVE: *Era Glacial Neopaleozoica; Grupo Itararé; erosão glacial; paleogeografia.*

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INTRODUCTION

The Late Paleozoic Ice Age (LPIA) was a period in Earth history during which global temperatures were relatively low and the Gondwana supercontinent was situated in high latitudes of the Southern Hemisphere. By the early 1970's, seminal studies on the LPIA at a global scale were published (Frakes & Crowell 1969, 1970, Frakes *et al*. 1971, Crowell & Frakes 1971, 1972). Since these papers, different studies were performed attempting to determine the extent, timing and paths of LPIA ice-sheets (e.g. Veevers & Powell 1987, Visser 1987, Santos *et al*. 1996, Gesicki *et al*. 2002, Starck & Papa 2006, Isbell *et al*. 2012).

To date, there is no consensus concerning the paleogeographic and chronologic distribution of the late Paleozoic ice masses in Gondwana, which, in part, is due to different scales of approach, the constant improvement in geological dating techniques, and the evolution of knowledge concerning sedimentation in past glacial environments. Hypotheses on LPIA glaciations can be grouped in two main working hypotheses. The traditional one assumes that the LPIA lasted for about 100 Ma as a long, single glacial period dominated by large ice sheets derived from a huge polar ice mass centered over Antarctica (Veevers & Powell 1987, Frakes *et al.* 1992, Scotese *et al.* 1999, Scotese 2014). The other hypothesis suggests several smaller ice masses controlled by the equilibrium-line altitude that expanded and retreated in several glacial-interglacial periods about 1 to 8 Ma-long each, totalizing an ice age of about 72 Ma of duration (e.g. Fielding *et al*. 2008, Isbell *et al*. 2012).

Many workers dealing with both hypotheses infer the extent and paths of former glaciers based on a variety of geological indicators. Most indicators, however, are not diagnostic of paleo ice-flow and, in some cases, not even for the presence of ice, like, for instance, the occurrence of diamictites. The most reliable indicators of paleo ice-flow are elongated subglacial features (including erosional, deformational and depositional landforms) and glaciotectonic deformational structures that are unequivocally generated by the advance of glaciers and that have been used to produce detailed reconstructions of the Pleistocene glaciations in North America and Eurasia (Flint 1957). In the case of LPIA glaciations, on the other hand, the paths of former glaciers have been interpreted mainly based on kinematic indicators found in striated surfaces, once larger landforms are poorly preserved and/or are difficult to map in these older glacial successions. However, it is well known from the Quaternary literature that mechanisms other than glacier advance may produce striated surfaces in glacial environments, as, for instance, floating ice moved by wind and currents (Woodworth-Lynas & Dowdeswell 1994). Moreover, soft-sediment striated surfaces and striated pavements on lithified beds are commonly treated indiscriminately in paleoenviromental interpretations of the late Paleozoic successions.

In this paper, we present a review and a critical reassessment of ice-related erosional landforms of the LPIA reported in the Paraná Basin. As "ice-related erosional landforms" we define landforms (cf. Bennett & Glasser 2009) formed by the action of ice, but not necessarily advancing glaciers (e.g. ice-keel scours). In this study, only micro to mesoscale features are discussed, which excludes larger landforms like glacial valleys and cirques. The main goals of the present paper are:

1. to illustrate the great variety of structures based on published examples plus new localities;
2. to make distinctions between landforms developed on soft sediment (soft-sediment surfaces) and those formed by abrasion of lithified beds;
3. to distinguish subglacial landforms from those generated by floating ice (non-subglacial);
4. to propose alternative interpretations for previously described striated surfaces; and
5. to discuss potential implications for paleogeographic reconstructions in the context of the LPIA.

In the Paraná Basin, LPIA strata are contained in the sedimentary succession of the Itararé Group, as well as in glacial landforms carved on the Precambrian basement and on pre-Carboniferous Paleozoic units (Fig. 1). The Bashkirian to Sakmarian (Holz *et al.* 2010) Itararé Group (Fig. 2) is up to 1,300 m thick and can be divided into three, basin wide stratigraphic units named, from base to top, Lagoa Azul, Campo Mourão and Taciba formations (França & Potter 1988). In the northern, northwestern and western sectors of the basin, the Itararé Group is correlative to the Aquidauana (in Brazil) and Aquidabán (in Paraguay) formations. The first report on ice-related erosive landforms associated with the Itararé Group was published simultaneously by Barbosa (1940) and Carvalho (1940) in Santa Catarina state. Subsequently, several types of landforms were documented (e.g. Almeida 1948, Bigarella *et al.* 1967, Rocha-Campos *et al*. 1988, Gesicki *et al*. 2002, Vesely & Assine 2002) as indicated in Figure 1 and Table 1. Evaluating the various types of landforms associated with strata of the Itararé Group will contribute to better resolve the size and extent of glaciation that influenced deposition in the Paraná Basin during the Carboniferous and Permian.

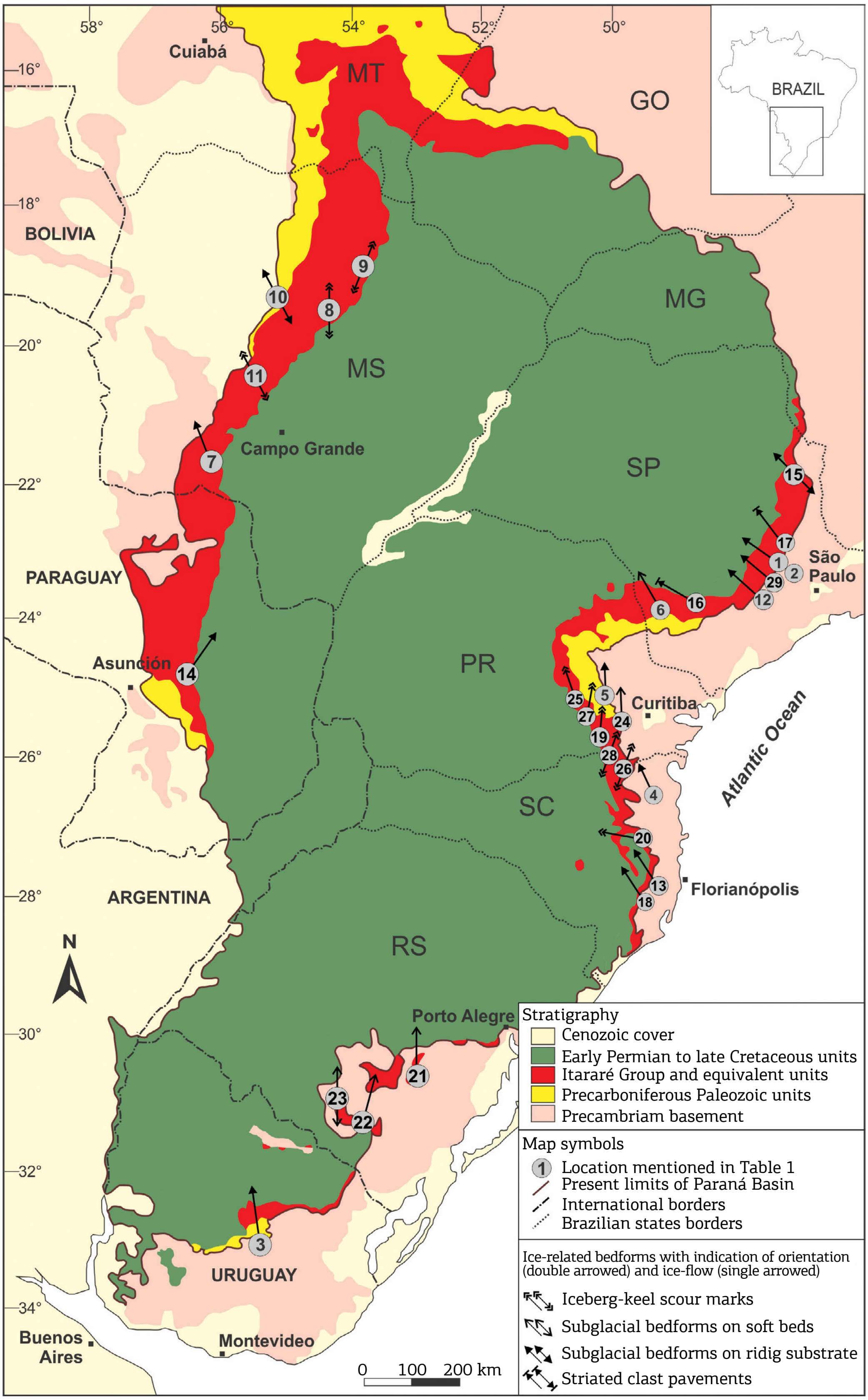

Figure 1. Generalized geological map of the Paraná Basin showing the location and orientation of ice-related landforms discussed in this paper.

DATASET AND METHODS

After an extensive search in the literature, 31 publications that describe ice-related, micro to mesoscale erosional landforms in the Paraná Basin were identified (Fig. 1, Tab. 1). Of these, 29 present kinematic indicators that can be used to determine the direction and/or the sense of the ice flow. The landforms were classified according to the terminology presented in Table 2, which is based on Bennett & Glasser (2009) and Benn & Evans (2010) classifications. An origin was indicated for these features at each locality based on information provided by the original authors, and new interpretations resulted from the present study when possible (Tab. 1).

Data provided by the previous authors and derived from direct field observation were analyzed in order to evaluate the landforms according to the nature of the substrate (soft or lithified), type of structures, stratigraphic setting with respect to underlying and overlying deposits, and state of documentation (in the case of published localities). After that, and taking into consideration the origin of each landform, localities were qualified according to their reliability as paleo ice-flow indicators. Direct field observations from localities 4, 13, 18 and 19 (Tab. 1), and information from published case studies outside the Paraná Basin were also incorporated to support our general interpretations.

MICRO TO MESOSCALE ICE-RELATED EROSIONAL LANDFORMS

A classification of ice-related erosional landforms is illustrated in Table 2, which considers the size, the nature of the substrate (rigid vs. plastic), the origin (subglacial vs. non-subglacial) and the positive or negative relief of the landform. Glaciers flowing on rigid substrates erode through abrasion and plucking (Bennet & Glasser 2009). Abrasion is a process by which particles embedded at the glacier sole (subglacial zone) scratch the underlying rock producing striations, grooves, polished surfaces and associated structures (Flint 1957, Shaw 1985, Miller 1996). This process can operate on preglacial substrates or on clast pavements that take place within sediments (e.g. Rocha-Campos *et al.* 1976). Plucking or quarrying occurs when rock fragments are removed from the substrate as the ice slides onto and over preexistent protuberances. Rock fragments incorporated at the glacier base by plucking act like tools during the abrasion processes (Boulton 1979). The combination of plucking and abrasion generates streamlined, stoss-and-lee features known as *moutonnées*.

When a glacier advance onto soft beds made up of unconsolidated sediments, soft-sediment deformation occurs and erosion is dominated by plowing, generating grooves ridges, flutes and drumlins (e.g. Bennet & Glasser 2009). The ice advance also can produce glaciotectonic features in subglacial to glaciomarginal sediments (e.g. van der Wateren 1994, Roberts & Hart 2005), including folds, faults, boudins and foliation. These structures can also be used to give ice-flow kinematics and are documented in the late Paleozoic succession in Paraná Basin (Vesely *et al.* 2015, Aquino *et al.* 2016), however they are not discussed in the present paper. In glacial marine or lacustrine environments blocks of floating ice (icebergs or sea/lake ice) may scour the bottom sediments producing ice-keel scour

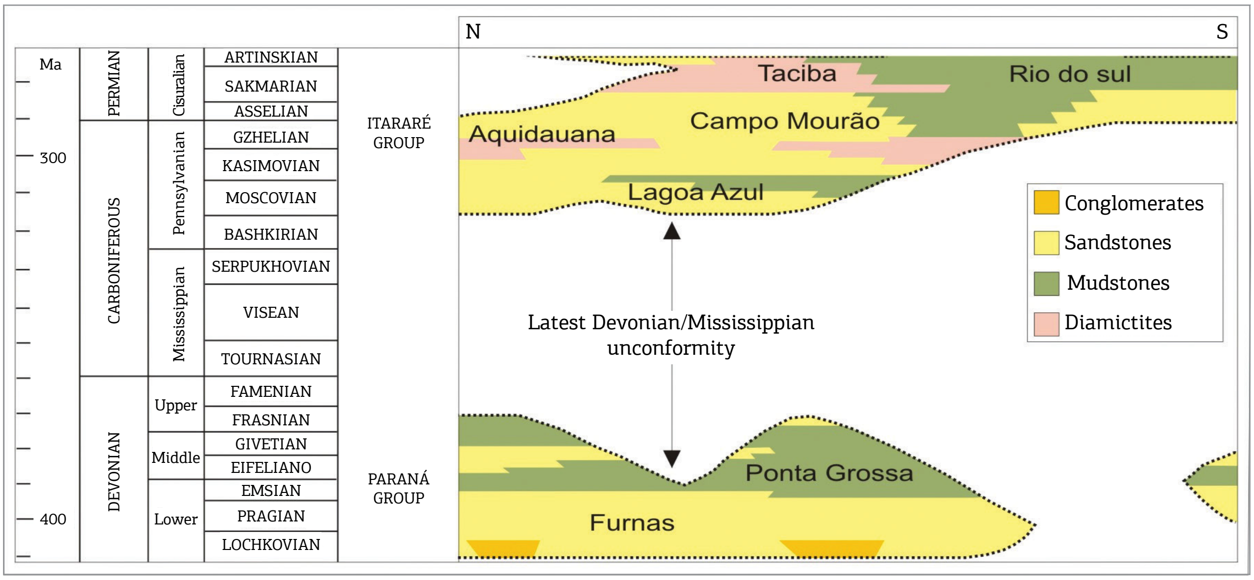

Figure 2. Stratigraphic chart for the Devonian-Early Permian succession of the Paraná Basin (adapted from Milani *et al.* 2007).

marks that are shallow to deep scours containing parallel sets of grooves and ridges (e.g. Woodworth-Lynas & Dowdeswell 1994). These structures are not related to regional glacier flow because floating ice blocks move by forces other than glacier advance, like winds, tides and currents (e.g. Hill *et al.* 2008).

Table 1. Ice-related landforms reported in the Paraná Basin. Numbers indicate their location in Figure 1.

	Reference	Location	Type of bedform	Azimut/direction of ice-flow
1	Almeida (1948)	Salto (SP)	Streamlined bedform	305°
2	Amaral (1965)	Salto (SP)	Streamlined bedform	305°
3	Assine *et al.* (2010)	Estancia de Las Moras (UY)	Streamlined bedform	NNW
4	Barbosa (1940); Carvalho (1940)	São Bento do Sul (SC)	Striated pavement	335°
5	Bigarella *et al.* (1967); Vesely (2006)	Colônia Witmarsum (PR)	Striated pavement	358°
6	Caetano-Chang *et al.* (1990)	Engenheiro Maia (SP)	Subglacial bedform on soft bed	330°
7	Gesicki *et al.* (2002)	Rio Aquidauana (MS)	Ice-keel scour mark	339°
8	Gesicki *et al.* (2002)	Serra Negra I (MS)	Ice-keel scour mark	0–180°
9	Gesicki *et al.* (2002)	Serra Negra II (MS)	Ice-keel scour mark	22–202°
10	Gesicki *et al.* (2002)	Rio Negro (MS)	Striated pavement	152–332°
11	Gesicki *et al.* (2002)	Rio Estrela (MS)	Ice-keel scour mark	152–332°
12	Pérez-Aguilar *et al.* (2009)	Salto (SP)	Striated pavement	312°
13	Puigdomenech *et al.* (2014)	Vidal Ramos (SC)	Striated pavement	NW
14	Riccomini & Velázquez (1999)	Escobar (PY)	Subglacial bedform on soft bed	35°
15	Rocha-Campos *et al.* (1968)	Mococa (SP)	Streamlined bedform	135–315°
16	Rocha-Campos *et al.* (1968, 1969)	Jurumirim (SP)	Striated clast pavement	300°
17	Rocha-Campos *et al.* (1976)	Capivari (SP)	Striated clast pavement	323°
18	Rocha-Campos *et al.* (1988)	Alfredo Wagner (SC)	Striated pavement	327°
19	Rosa (2015)	São Luiz do Purunã (PR)	Ice-keel scour mark	5°
20	Santos *et al.* (1992)	Trombudo Central (SC)	Soft-sediment striated surface	280°
21	Tomazelli & Soliani (1982)	Cachoeira do Sul (RS)	Subglacial bedform on soft bed	360°
22	Tomazelli & Soliani (1982)	Pinheiro Machado (RS)	Subglacial bedform on soft bed	15°
23	Tomazelli & Soliani (1997)	Suspiro (RS)	Subglacial bedform on soft bed	0–180°
24	Trosdtorf *et al.* (2005)	São Luiz do Purunã (PR)	Subglacial bedform on soft bed	2°
25	Vesely & Assine (2002)	Palmeira (PR)	Ice-keel scour mark	341°
26	Vesely & Assine (2014)	Lapa (PR)	Ice-keel scour mark	20–200°
27	Vesely & Assine (2014)	Vila Velha (PR)	Ice-keel scour mark	10°
28	Vesely & Assine (2014)	São Luiz do Purunã (PR)	Ice-keel scour mark	20–200°
29	Viviani & Rocha-Campos (2002)	Rio Tietê valley (SP)	Streamlined bedform	NW

Ice-related, erosional landforms on lithified beds are widely reported from late Paleozoic basins of Gondwana. Striated pavements and streamlined landforms carved on the preglacial basement take place in western Argentina and Bolivia (López-Gamundí & Martínez 2000, Starck *et al.* 1993), Africa (Veatch 1935, Visser & Kingsley 1982, Visser 1985, von Brunn & Marshall 1989, Cole 1991, Bussert 2010) and the Arabian Peninsula (Braakman *et al.* 1982, Kruck & Thiele 1983). As documented by Rosa (2015), soft-sediment striated surfaces are also very common in the late Paleozoic successions of these basins (e.g. Lindsay 1970, Crowell & Frakes 1972, Savage 1972, Visser & Hall 1985, von Brunn & Talbot 1986, Visser 1990, González *et al.* 1995). Their definition as subglacial or non-subglacial has great impact on LPIA paleogeography (e.g. Vesely & Assine 2014).

ICE-RELATED LANDFORMS IN THE PARANÁ BASIN

Examined localities in the Paraná Basin consist of four main categories of ice-related, micro- to meso-scale erosional and forms based on their origin and the nature of the substrate. These incluse:

1. subglacial landforms on lithified beds;
2. subglacial landforms on soft beds;
3. ice-keel scour marks; and
4. striated clast pavements.

These are treated separately in the following subsections.

Subglacial landforms on lithified beds

Subglacial landforms developed by abrasion and plucking of lithified substrates are relatively common in the Paraná Basin. They occur on Precambrian igneous/metamorphic rocks or on lithified Devonian sandstones of the Furnas Formation. These features form beneath flowing, wet-based glaciers that slides on the bed (e.g. Bennet & Glasser 2009) and, thus, are good indicators of paleo ice-flow directions. Dry-based glaciers, on the other hand, move mainly by internal deformation, with insignificant plucking and abrasion resulting in a thin or absent basal debris layer.

According to the classification shown in Table 2, two main types of landforms are described: striated pavements (micro- to meso-scale features) and streamlined landforms (meso-scale features). A combination of both is frequent, in such a way that striated pavements commonly occur superimposed to streamlined landforms.

Striated pavements

The first report on striated pavements in the Paraná Basin was published by Carvalho (1940) and Barbosa

Table 2. Classification of ice-related landforms used in the present paper (based on Bennet & Glasser (2009) and Benn & Evans (2010).

<table>
<tr><th rowspan="3">Process</th><th rowspan="3">Substrate type</th><th rowspan="3">Relief type</th><th colspan="8">Scale</th></tr>
<tr><th colspan="3">Micro</th><th colspan="3">Meso</th><th colspan="2">Macro</th></tr>
<tr><th>0.01</th><th>0.1</th><th>1</th><th>10</th><th>100</th><th>1</th><th>10</th><th>100</th></tr>
<tr><td rowspan="8">Subglacial erosion</td><td rowspan="2">Unconsolidated (plastic)</td><td>Depression</td><td colspan="3">← Striae →</td><td colspan="3">← Groove →</td><td colspan="2"></td></tr>
<tr><td>Eminence</td><td colspan="3">← Flute →</td><td colspan="5"></td></tr>
<tr><td rowspan="6">Consolidated (rigid)</td><td rowspan="4">Depression</td><td colspan="3">← Striae →</td><td colspan="3">← Groove →</td><td colspan="2"></td></tr>
<tr><td colspan="2">← Crescentic gouge →</td><td colspan="6"></td></tr>
<tr><td colspan="2">← Crescentic fracture →</td><td colspan="6"></td></tr>
<tr><td colspan="5"></td><td colspan="3">← Valley →</td></tr>
<tr><td rowspan="2">Eminence</td><td colspan="2"></td><td colspan="3">← Whaleback →</td><td colspan="3"></td></tr>
<tr><td></td><td colspan="6">← Roche moutonnée →</td><td></td></tr>
<tr><td>Iceberg-keel scour</td><td>Unconsolidated (plastic)</td><td>Depression</td><td></td><td colspan="4">← Iceberg-keel scour mark with internal striae and groove →</td><td colspan="3"></td></tr>
</table>

(1940), who described a surface containing parallel striations on crystalline rocks underlying the Itararé Group in São Bento do Sul (Santa Catarina state). The linear features are oriented to the SE-NW and a northwestward paleo ice-flow direction was inferred by the authors based on the provenance of the clasts that occur in an overlying diamictite. Associated with this pavement, the authors recognized a very irregular substrate with troughs several meters deep filled with glacial diamictites. Later, Dequech (1948) questioned the glacial origin of the pavement, arguing that the striations are parallel to the metamorphic foliation of the basement. The main outcrop described by Carvalho (1940) and Barbosa (1940) is no longer available. However, our field observations in this area found evidence that the Precambrian basement was eroded by ice, including delicate striations, scours with few meters of relief filled with clast-rich diamictites contained plucked clasts of local basement rocks and the occurrence of bullet-shaped clasts in the diamictite (Fig. 3). Considering these characteristics and following Rocha-Campos *et al.* (1988), the diamictites can be interpreted as lodgement tillites resting on a subglacially eroded, rigid substrate, corroborating thus the original interpretation of Barbosa (1940).

Still in Santa Catarina, Rocha-Campos *et al.* (1988) documented a striated pavement at Alfredo Wagner, developed on Precambrian granite. The striations on this pavement lie on a gently undulated surface covered by laterally discontinuous, massive and stratified diamictites, the former being confined to narrow depressions (Fig. 4). Black shale with dropstones overlies the diamictite body and laterally, the shales drapes the granitic basement. According to Rocha-Campos *et al.* (1988), crescentic gouges and fractures on the striated pavement allowed them to infer a paleo ice-flow towards the NW. Because of weathering, these features are no longer recognized (Fig. 4B), but are well illustrated by the authors in their Figures 3, 4 and 5.

Equivalent striated pavements can be found in other localities of eastern Santa Catarina, as, for instance, the occurrence noticed by Puigdomenech *et al.* (2014) in Vidal Ramos, where thin striations occur at the bottom and at the sidewall of an elongated groove about 1 m deep carved onto low-grade metamorphic rocks (their Figure 3B). Although these authors did not provide kinematic indicators for paleo ice-flow, new field observations at the same surface found non-striated steps perpendicular to the main striations (Fig. 5A), which allow to interpret that the ice slid on the bed towards the northwest. This paleo ice-flow is coincident with paleocurrents to the NW measured by Puigdomenech *et al.* (2014) in deglacial deposits that are above the striated surface.

In São Paulo state, Pérez-Aguilar *et al.* (2009) recently reported two striated pavements on Precambrian granites in Salto, which are oriented to the NW and display crescentic fractures and gouges indicating a northwestward ice flow. These two surfaces are covered by diamictites that can be interpreted as lodgement tillites deposited by an active glacier that slid across the bed.

Besides the Precambrian basement, subglacial striated pavements also occur on surfaces made up of pre-Carboniferous

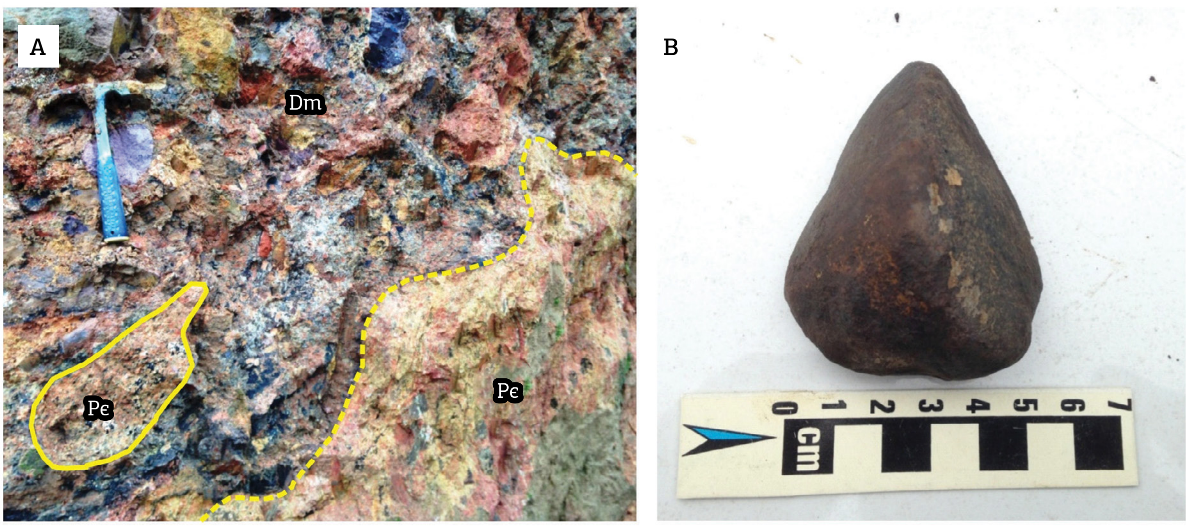

Figure 3. Glacial features observed in São Bento do Sul (Santa Catarina state). (A) Clast-rich diamictite (Dm) with plucked clasts (solid line) overlying an irregular non conformable surface (dashed line) of the Precambrian basement (Pє); (B) Bullet-shaped clast retrieved from diamictite.

units of the Paraná Basin. Bigarella *et al.* (1967) described a series of striated pavements developed in Devonian sandstones of the Furnas Formation in southeastern Paraná State. In the Witmarsum locality, striations, grooves and ridges are on a flat surface (Fig. 5B), oriented towards 358º, and are covered by sand-rich massive diamictites. Crescentic fractures reported by Bigarella *et al.* (1967) indicate paleo ice-flow direction towards the north. Approximately 7 km away from this locality, Vesely (2006) found another striated pavement on the same substrate with the same orientation, which suggest a regional trend of glacier flow in this sector of the basin.

On the western side of the basin Gesicki *et al.* (2002) also reported a striated pavement on sandstones of the Furnas Formation in the Rio Negro locality, Mato Grosso do Sul state. Although kinematic indicators were not observed by the authors in this surface, a northwestward paleo ice-flow was inferred based on indicators found on intraformational striated surfaces that occur higher in the section, within beds of the Aquidauana Formation. A subglacial origin for the Rio Negro surface is reasonable once it has been formed onto a rigid Devonian substrate. However, the NW paleo ice-flow interpreted by Gesicki *et al.* (2002) is uncertain because it is based on intraformational (soft-sediment) erosional features which subglacial nature cannot be assured (see discussion below).

Streamlined landforms

Streamlined landforms are meso-scale, slightly elongated, positive structures generated subglacially on bedrock

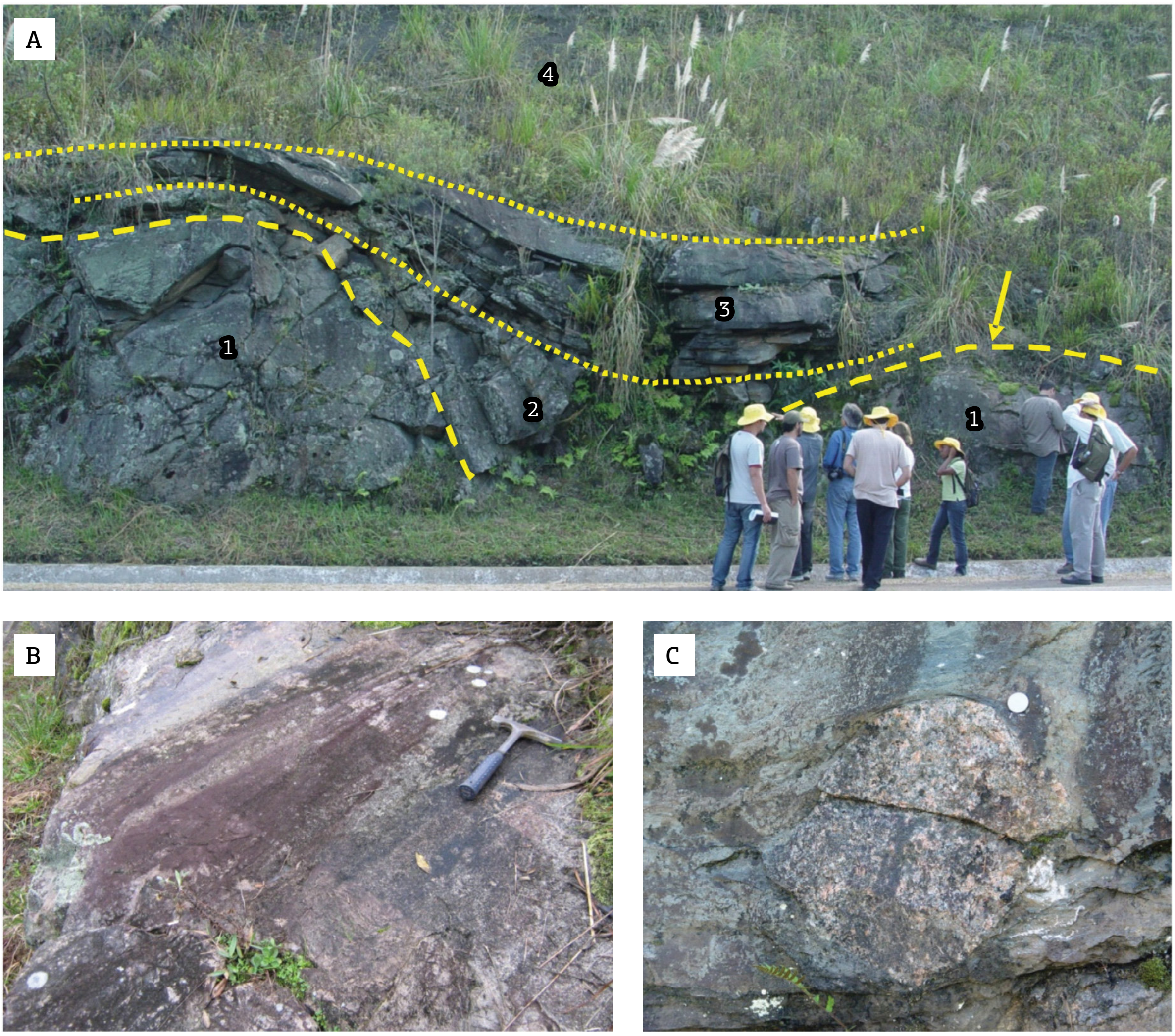

Figure 4. Striated pavement at Alfredo Wagner (Santa Catarina state). (A) Overview of the outcrop: 1 – Precambrian granite; 2 – massive diamictite; 3 – stratified diamictite; 4 – black shale; Arrow – striated surface shown in (B); (C) Detail of a granite boulder in the massive diamictite (coin as scale).

or sediment. In this section, we only refer to streamlined landforms that form due to subglacial erosion on pre-existing bedrock protrusions (Bennet & Glasser 2009). Two main types are documented in the Paraná Basin: whalebacks, which are near symmetrical landforms produced by subglacial abrasion, and *roches moutonnées*, which are stoss-and-lee (asymmetrical) landforms generated by abrasion in the upflow termination and plucking on the downflow end.

Almeida (1948) and Amaral (1965) reported *roches moutonnées* on Precambrian granites in Salto (São Paulo state), which are covered by a thin and highly compacted diamictite of likely subglacial origin (Fig. 6A). The landforms show the typical asymmetry of the *moutonnées* and display superimposed striations indicating paleo ice-flow to the northwest. Later at the same locality, Viviani & Rocha-Campos (2002) briefly noticed additional occurrences of streamlined landforms (*moutonnées* and whalebacks), which also indicated a NW paleo ice-flow direction.

At the locality of Estancia de Las Moras (Uruguay), located in the southernmost segment of the Paraná Basin (or Chaco-Paraná Basin), Assine *et al.* (2010) noticed several whalebacks on the Precambrian basement below deposits of the San Gregorio Formation (equivalent of the Itararé Group in Uruguay). Different from the *moutonnées* of Salto, the landforms have no plucked downflow terminations and are striated on all sides indicating abrasion as the only erosive mechanism. These whalebacks are oriented NNW-SSE and their asymmetry suggest a NNW ice-flow direction.

In several places where the contact between the Precambrian basement and the Itararé Group is exposed, smoothed protrusions are observed in road cut sections. One example is the structures described by Rocha-Campos *et al.* (1968) in Mococa (São Paulo state) and referred to as "streamlined elongated bodies". The bodies are made up of granitic rocks that exhibit delicately striated surfaces oriented in a SE-NW. Similar protrusions crop out in road cuts that expose the contact between the metamorphic basement and the Itararé Group along the SC-416 highway just north of Vidal Ramos, Santa Catarina state. In one of the outcrops (Fig. 6B) a positive landform about 2.5 m high are covered by a thin layer of clast-rich diamictite and, above it, a thick succession of black shale with sparse dropstones that onlaps the flanks of the structure. Although this exposure does not allow for a 3D visualization, the size and the transversal profile of the protrusion are the same as expected for streamlined landforms.

Subglacial landforms on soft beds

Landforms generically denominated as soft-sediment striated (or grooved) surfaces are more common in the Paraná Basin than those formed on rigid substrates. This fact has been overlooked in the literature in such a way that very different ice-related landforms are commonly treated indiscriminately in paleoenvironmental and paleogeographic interpretations (see Vesely & Assine (2014) for a discussion). According to Woodworth-Lynas & Dowdeswell (1994), ice-related, soft-sediment striated surfaces may form:

1. subglacially;
2. at the grounding zone of tidewater glaciers; or
3. as ice-keel scours generated by free-floating ice (icebergs or sea/river/lake ice).

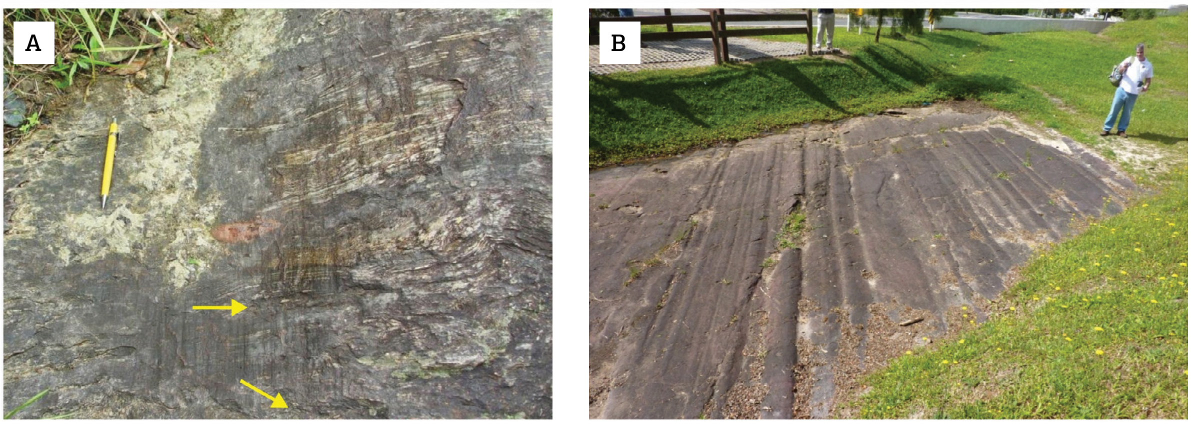

Figure 5. Striated/grooved pavement with non-striated steps (arrows) on Precambrian metamorphic rocks at Vidal Ramos, Santa Catarina state (A), and on Devonian sandstones of the Furnas Formation in Witmarsum, Paraná state (B). Paleo ice-flow was toward the lower part of the image in both cases.

In this section we will describe only those soft-sediment striated surfaces that hold evidence for having been formed beneath advancing glaciers, corresponding, therefore, to subglacial or grounding zone landforms. These landforms are generated when glaciers plough unconsolidated beds creating striations, grooves, ridges and flutes (sediment ridges formed by subglacial deformation and/or accumulation of sediment at the lee-sides of obstacles). Because the glacier/bed interface is laterally extensive, subglacial soft-sediment surfaces tend to be flat and several tens to hundreds of meters

Figure 6. Streamlined landforms underlying glacial deposits of the Itararé Group. (A) Partially mined *roche moutonnée* in Salto (São Paulo state). Arrow indicates the direction of striae; Dm is a subglacially deposited diamictite draping the flank of the landform; (B) Transverse exposure of a probable streamlined landform on metamorphic rocks in Vidal Ramos (Santa Catarina state). The convex-upward structure is covered by a thin layer of diamictite (not visible), above which a thick shale succession was deposited.

wide or more in lateral extent (e.g. Woodworth-Lynas & Dowdeswell 1994).

In the Rio Grande do Sul state, southern Paraná Basin, Tomazelli & Soliani (1982, 1997) described three widespread, striated/grooved surfaces on diamictites of the Itararé Group. Remarkable in one of the localities (Cachoeira do Sul) is a granitic boulder embedded at the end of a large groove (Fig. 7A). Deformation of the sediment associated to boulder emplacement is a clear evidence of the soft character of the bed and it allows to determine a paleo ice-flow direction towards the north. The other surfaces, located in the Pinheiro Machado and

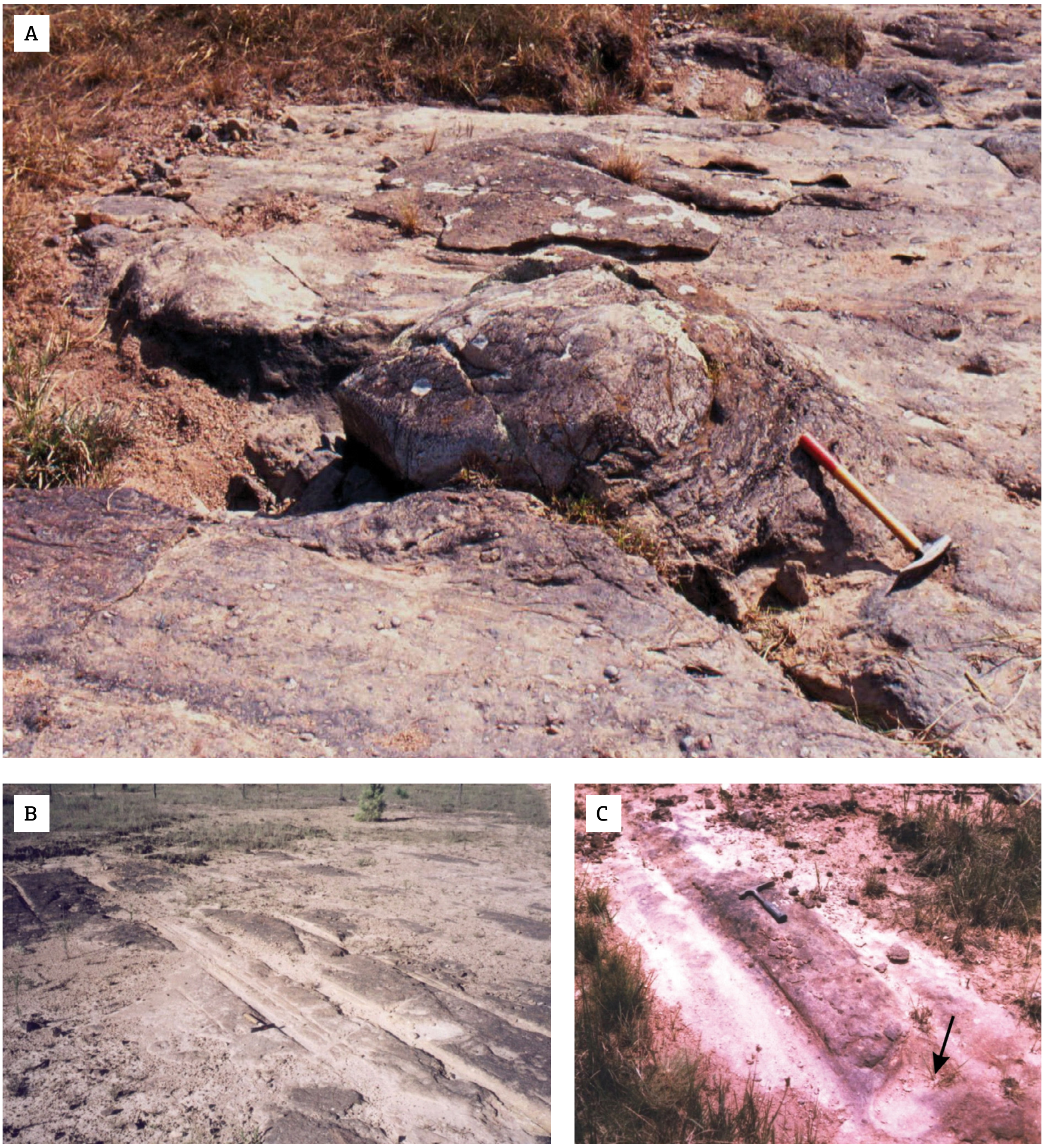

Figure 7. Subglacial landforms developed on soft beds. (A) Boulder embedded at the downflow end of a large groove (Cachoeira do Sul, Rio Grande do Sul state) indicating paleoflow towards the right; (B) Grooved surface on diamictites of the lower Itararé Group in São Luiz do Purunã (Paraná state); (C) Closer view of the same surface shown in the previous image, highlighting a flute developed on the lee-side of a boulder (the impression left by the boulder is indicated by arrow).

Suspiro localities, exhibit striations and grooves trending N15E and N-S respectively.

A soft-sediment striated/grooved surface very similar to those from Rio Grande do Sul was documented by Trosdtorf *et al.* (2005) in São Luiz do Purunã, about 40 km west of Curitiba (Paraná state). This surface is exposed for about 1,200 m² and displays tens-of-meters-long striations, grooves and ridges carved on a sand-rich diamictite of the lowermost Itararé Group (Fig. 7B). The linear features trend N2E and the presence of clasts at the end of some grooves indicate a paleo ice-flow direction towards the northeast. The same outcrop was later reexamined by Vesely *et al.* (2015), who recognized a small-scale flute (Fig. 7C) that corroborates the subglacial origin and the previously indicated paleo ice-flow.

Other occurrences of soft-sediment striated/grooved-surfacesof subglacial origin were described by Caetano-Chang *et al.* (1990) in Engenheiro Maia (São Paulo state) and by Riccomini & Velázquez (1999) in Escobar (Paraguay). The Engenheiro Maia surface lies on a diamictite interpreted by Caetano-Chang *et al.* (1990) as a subglacial till deposit. On the surface, striations terminating in lodged pebbles allow an inference of a paleo ice-flow to the NW. The Escobar surface, located along the western border of the basin was described by Riccomini & Velázquez (1999) on diamictites and sandstones of the Aquidabán Formation (equivalent to the Itararé Group in Paraguay). The authors considered that the presence of crescentic fractures indicated that the bed was rigid at the time of formation, and credited this rigidity to freezing or early lithification of the subglacial sediment. However, frozen substrates are incompatible with glacial striation because they imply cold-based glaciers that are not able to flow by sliding because of the absence of subglacial meltwater (Bennet & Glasser 2009). An early diagenetic cementation, on the other hand, would indicate some time had elapsed between deposition and glacial erosion, thus generating uncertainties about the nature of this surface.

The surfaces reviewed above share some characteristics that fit into the model of soft-sediment surfaces generated by subglacial erosion (e.g. Woodworth-Lynas & Dowdeswell 1994). These include the flat and laterally extensive character of the surface, the presence of flutes, the absence of marginal berms and a substrate composed of poorly-sorted sediment (mostly diamictite) that corroborates a glacial origin.

Ice-keel scour marks

Keels of free floating ice carried by winds, waves or currents can erode the bottom sediment in aquatic environments if the base of the ice becomes grounded on the substrate. Movement of the grounded ice produces straight to sinuous furrows of variable widths (few meters to hundreds of meters), lengths up to tens of kilometers and depths of centimeters to tens of meters, referred to as ice-keel scour marks (IKSM). Internally, the scours may exhibit parallel sets of striations, grooves and ridges that can be placed in the category of soft-sediment striated surfaces as considered in the present paper (Fig. 8). IKSM are very common in Quaternary to modern high-latitude settings, but surprisingly, are poorly documented in the pre-Pleistocene glacial record (Woodworth-Lynas & Dowdeswell 1994, Vesely & Assine 2014 and references therein).

The first comprehensive report on IKSM in the Paraná Basin was provided by Santos *et al.* (1992), whose found shallow, non-striated scours within rhythmite beds in Trombudo Central (Santa Catarina state). The general characteristics of the structures like the presence of marginal berms, sub-scour deformation, and the genetic relationship with subaqueous deposits, support an origin related to icebergs grounding (e.g. Woodworth-Lynas & Dowdeswell 1994). In addition, the existence of dropstones and dump structures within the rhythmites corroborates the action of floating ice in the depositional environment.

In southeastern Paraná state, soft-sediment striated surfaces occur at different stratigraphic levels within sandstones of the Itararé Group (Vesely & Assine 2002, Vesely 2006, Vesely & Assine 2014, Rosa 2015). The surfaces are laterally discontinuous, exhibit trough-like cross-sectional profiles, and are commonly bordered by low-amplitude, non-striated marginal berms (Figs. 9A and B). Directional trends measured by Vesely & Assine (2014) from 19 striated surfaces in this area show a deviation of up to 40° from the regional paleo-ice flow indicated by subglacial landforms on the underlying Furnas Formation. These characteristics and the fact that the surfaces are not associated with poorly sorted glaciogenic deposits support an origin related to iceberg scouring instead of subglacial erosion (cf. Woodworth-Lynas & Dowdeswell 1994).

Vesely & Assine (2014) argued that the features observed in the striated surfaces of southeastern Paraná are comparable to IKSM reported by Eyles *et al.* (2005) in the Pleistocene of North America and by Dionne (1969) from modern tidal flats in Canada. Also, they speculated that similar late Paleozoic soft-sediment striated surfaces found in other localities of Gondwana and originally treated as subglacial landforms should have the same origin. One possible example is the striated surface described by Gesicki *et al.* (2002) in the locality of Serra Negra, Mato Grosso do Sul state (outcrop Serra Negra II of author's terminology). As shown in Figures 9C and D, and according to the original description, this surface has a concave-up transverse profile flanked by berms and the striations are restricted to the area in between the berms. Furthermore, instead of being associated with glacial deposits, the surface lies within thin-bedded rhythmites of the Aquidauana Formation, indicating its formation in an aquatic environment.

Because of the characteristics listed above, the Serra Negra II striated surface, which was originally considered as subglacial in origin (cf. Gesicki *et al.* 2002), is here reinterpreted as an IKSM. Considering that the other localities described by the same authors (Rio Aquidauana, Serra Negra I and Rio Estrela) are equivalent in terms of characteristics and facies associations, an origin related to ice-keel scouring have to be at least considered. With a subglacial origin being placed in question, most of the striated surfaces that exist in the western portion of the Paraná Basin should be critically evaluated before they are interpreted as paleo ice-flow indicators.

Striated clast pavements

Striated clast pavements are linear concentrations of clasts of different sizes all contained within the same stratigraphic horizon. They are commonly found within diamictites and the upper faces of the clasts are often flat and contain parallel striations with a uniform orientation (Benn & Evans 2010). Regarding its origin, Clark (1991) assumed that these pavements are subglacial features generated by the rearrangement of clasts in unconsolidated sediment when overridden by an advancing glacier. The top striated surfaces of the clasts are formed by abrasion impinged by the overlying sliding glacier. On the other hand, Eyles (1988) postulated that striated boulder pavements found within glaciomarine diamictites were formed as residual deposits by the removal of finer sediment due to wave activity in a shallow marine environment. Subsequently, the clasts were striated by subglacial abrasion when a glacier advanced onto and over the marine sediment.

In the Paraná Basin, two striated clast pavements were documented by Rocha-Campos *et al.* (1968) and

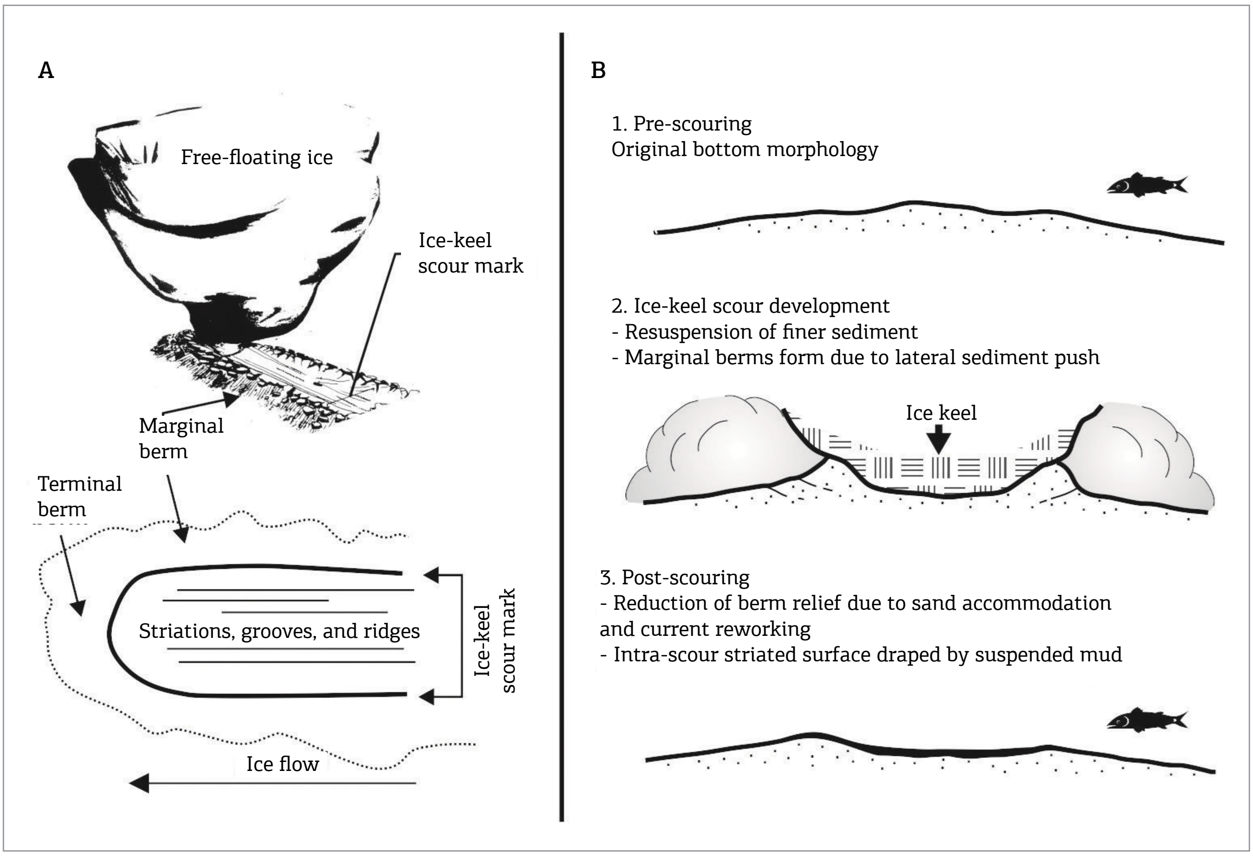

Figure 8. (A) Mechanism for development of soft-sediment striated surfaces due to ice-keel grounding and plan view of an ice-keel scour mark showing striations, grooves and minor ridges between the marginal berms (after Woodworth-Lynas & Dowdeswell 1994 and Eyles *et al.* 2005); (B) Model for generation and preservation of soft-sediment striated surfaces associated with ice-keel scouring (adapted from Woodworth-Lynas & Guigné 1990).

Rocha-Campos *et al.* (1976) in the localities of Jurumirim and Capivari (São Paulo state) respectively. The Jurumirim pavement is within diamictites interpreted as subglacial tillites that display faceted clasts with striated upper surfaces. A paleo ice-flow to the northwest was interpreted based on clast imbrication and the presence of crescentic fractures in a granitic boulder contained within the pavement (Rocha-Campos *et al.* 1969). In the Capivari locality (Fig. 10A) two separated clast pavements contained in a diamictite (originally interpreted as tillite) crop out in a road-cut exposure (Rocha-Campos *et al.* 1976). Both pavements have faceted clasts with top surfaces exhibiting striations oriented 285° to 360°, and a paleo ice-flow direction oriented to the N-NW was interpreted based on clast imbrication. The origin assumed for these two localities is similar to that proposed by Clark (1991) that is of intratill surfaces formed by subglacial abrasion.

Striated clast pavements have been reported in other late Paleozoic glacial units, such as in the Dwyka Formation of southern Africa (Visser & Hall 1985) and the Hoyada Verde Formation in Argentina (e.g. López-Gamundí & Martínez 2000), both associated with diamictite units. The Hoyada Verde section was reexamined recently by López-Gamundí *et al.* (2016) who reported two stratigraphically distinct striated boulder pavements. In both pavements, striations are aligned parallel to the a-axis of the clasts (Fig. 10B). The lower pavement is defined as an intratill horizon placed within massive diamictites (tillites) whereas the upper one in an intertill pavement on top of the tillite succession and covered by bedded mudstones with ice-rafted debris.

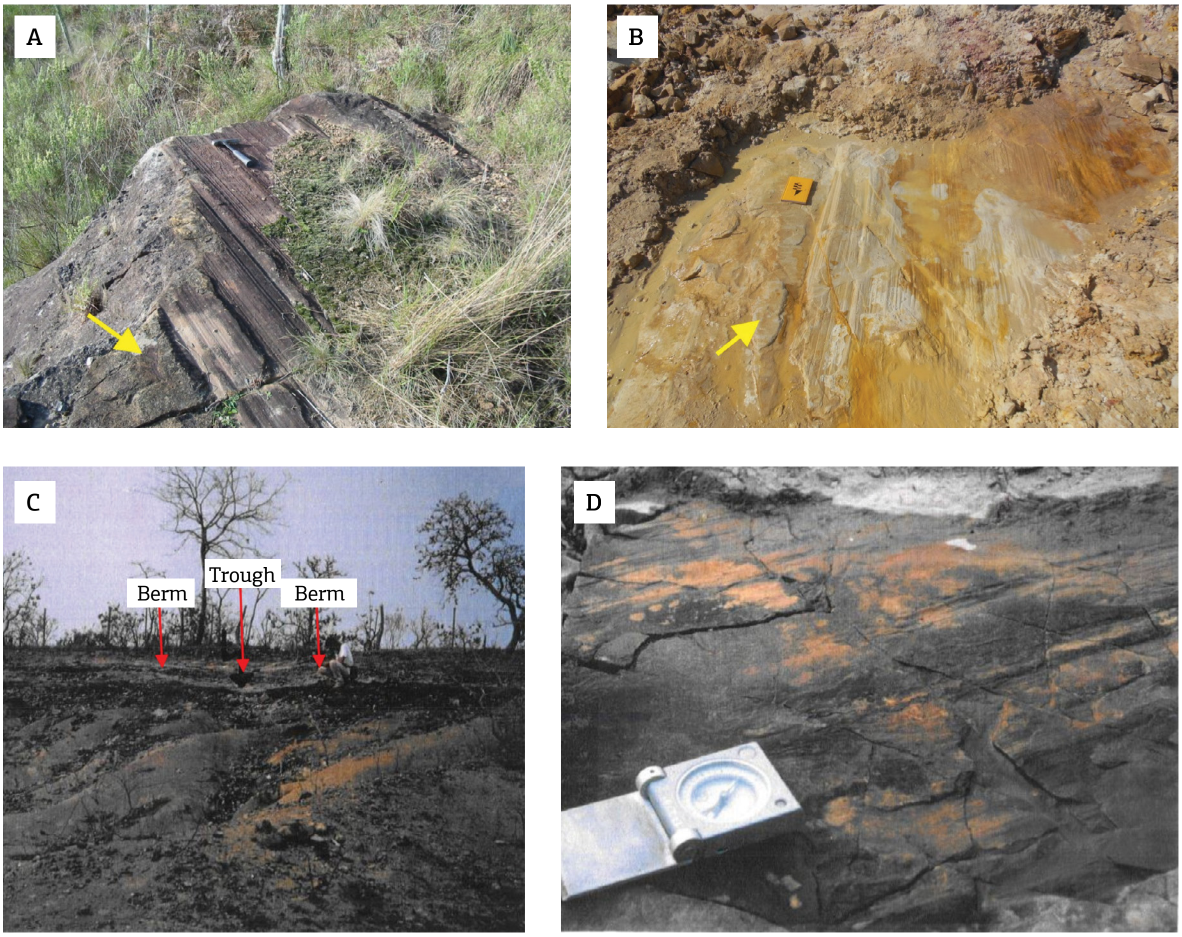

Figure 9. Soft-sediment striated surfaces interpreted as ice-keel scour marks from different localities in the Paraná Basin. (A) At Lapa (Paraná state); (B) at São Luiz do Purunã (Paraná state); (C, D) at Serra Negra (Mato Grosso do Sul state) (modified from Gesicki 1996). Absence of striation on outer side of the marginal berms shown by yellow arrows in A and B. Pictures C and D are from the same surface originally interpreted as a subglacial landform by Gesicki (1996).

Striated clast pavements as described above are reliable records of the advance of glaciers onto unconsolidated sediments, and thus can be seen as excellent paleo ice-flow indicators. Moreover, their presence within sediment interpreted as glaciomarine testify that, at least in some instances, the ice margins advanced into the basin and were not restricted to the basin margins.

IMPLICATIONS FOR PALEOGEOGRAPHY

This review provides an integrated perspective of the different erosional ice-related landforms described from the Paraná Basin and, more importantly, allows for a comprehensive distinction of landforms generated by the advance of glaciers (subglacial) from those formed by non-subglacial processes (Tab. 1). Among all types of landforms presented, those generated subglacially are the only that can be used in paleogeographic reconstructions of paleo ice-flow. This excludes soft-sediment striated surfaces interpreted as ice-keel scour marks, as floating ice is driven by processes other than glacier advance (e.g. Hill *et al.* 2008).

The most confident paleo ice-flow indicators in the Paraná Basin are streamlined landforms, such as whalebacks and *moutonnées*, striated pavements on rigid beds, and subglacial soft-sediment surfaces, which are produced beneath active glaciers. Such features are concentrated in the eastern and southern borders of the basin and, locally along the western margin (Fig. 1, Tab. 1). However, not all of the sites have well documented kinematic indicators such as crescentic gouges/fractures, nailhead furrows and stoss-and-lee profiles.

Most of these subglacial, erosional landforms are on the preglacial substrate or on glacial deposits of the Itararé Group few meters above its basal boundary. This suggests that advancing glaciers were effective in sculpturing the pre-Itararé substrate and in influencing deposition during early stages of deglaciation due to fluctuations of the ice margins (e.g. Vesely *et al.* 2015). The only exception is the clast pavements reported by Rocha-Campos *et al.* (1976) and Rocha-Campos *et al.* (1968) that are within diamictites of the middle to upper Itararé Group and that testify a possible younger advance of glaciers over the basin.

An ice source located east of the Paraná Basin is well supported by the *moutonnée* of Salto (Almeida 1948), subglacial landforms in the Paraná state (Bigarella *et al.* 1967, Trosdtorf *et al.* 2005), the occurrence at Engenheiro Maia (Caetano-Chang *et al.* 1990) and the striated surfaces found on the Precambrian basement in Santa Catarina state (Barbosa 1940, Carvalho 1940, Rocha-Campos *et al.* 1988, Puigdomenech *et al.* 2014). Nevertheless, localities in the southern Paraná state (southern flank of the Ponta Grossa arch) have a different orientation (N-S) when compared to the other localities, which show a consistent NW trend (Fig. 1). This suggests that multiple ice lobes entered the Paraná Basin instead of a just single continental ice sheet.

The most suitable source of ice to eastern Paraná Basin would be highlands located in Namibia (Windhoek highlands; Visser 1987, Santos *et al.* 1996). Evidence of west-flowing glaciers in western Namibia was reported in several localities near Huab and Kunene, including *roches mountonnées* and crescentic gouges carved on the Precambrian basement (Frakes & Crowell 1970, Martin 1981a). Furthermore, this

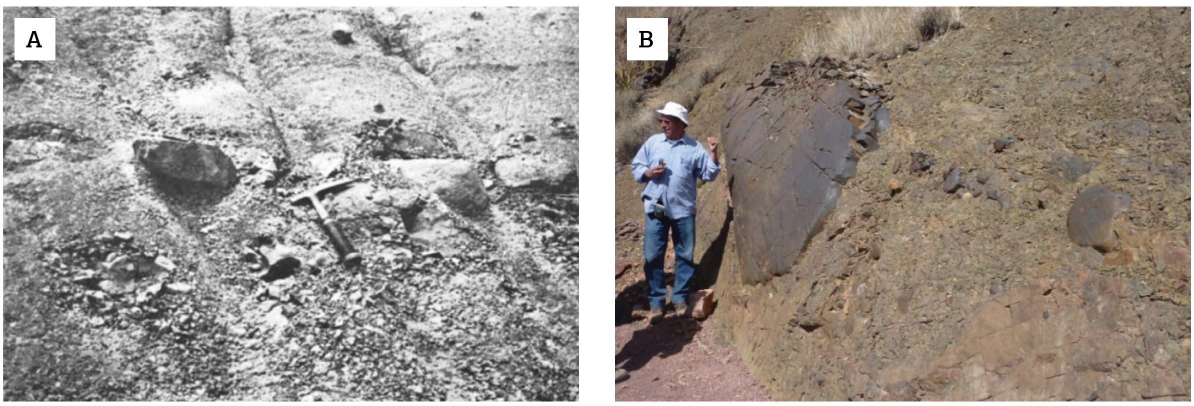

Figure 10. Striated clast pavements in late Paleozoic diamictites. (A) Outcrop in Capivari (Paraná Basin) showing a horizon with clast concentration. Note the alignment of the upper faces of the clasts (photo taken from Rocha-Campos *et al.* 1976); (B) For comparison, striated clast pavement in the Carboniferous Hoyada Verde Formation in the Calingasta-Uspallata Basin, Argentina (beds dipping about 60º toward the left bottom of the photo).

area also has deposits confined in paleovalleys (Visser 1987), which reinforce the existence of elevated land and indicate topographically constrained ice flow towards the Paraná Basin. The angular unconformity separating Devonian from Carboniferous strata in eastern Paraná Basin (Ponta Grossa Arch area) and the absence of pre-Carboniferous Paleozoic units in western Namibia are indicative of latest Devonian to Mississippian uplifting east of the present border of the Paraná Basin (Vesely *et al.* 2015). This tectonic event was probably the cause for uplifting the land above the equilibrium-line altitude, leading to net snow accumulation and glacier growth (e.g. Isbell *et al.* 2012).

In the southern portion of the basin (Rio Grande do Sul and Uruguay), subglacial streamlined landforms on the basement (Assine *et al.* 2010), as well as grooved surfaces on diamictites located about 40 m above the basement boundary (Tomazelli & Soliani 1982, 1997), indicate a consistent paleo ice-flow towards the north. These northward ice-flow indicators occur in both the southern and the northern flanks of the Rio Grande "high", which indicate that this area probably did not acted as a glacial spreading center in the Carboniferous and that an ice source farther to the south is more likely.

Ice-spreading centers located to the west of the Paraná Basin were inferred by Frakes & Crowell (1969), França & Potter (1988) and Limarino *et al.* (2014), assuming that the Asunción Arch was glaciated during the LPIA. The argument used by França & Potter (1988) was based on a high proportion of diamictites in the subsurface. Later, Gesicki (1996) and Gesicki *et al.* (2002) disagreed with such an interpretation and inferred a paleo ice-flow to the northwest based on the orientation of striated surfaces in Mato Grosso do Sul state. However, reliable kinematic indicators in these surfaces are sparse and/or poorly documented (Gesicki *et al.* 2002, their Figure 3B) and it should also be noted that at least some of the surfaces in that area may be ice-keel scour marks instead of subglacial landforms. In addition, fluvial paleocurrents of the Aquidauana Formation presented by Gesicki (1996) show a high degree of dispersion and some vectors point to the southeast and southwest, in the contrary direction or orthogonal to the inferred ice flow direction. Moreover, the striated surface described by Riccomini & Velázquez (1999) in Paraguay (Escobar locality) shows a paleo ice-flow to the northeast, suggesting glaciers coming from the Asunción Arch. Taking it into account, the interpretation of a northwestward paleo ice-flow in this area of the basin is problematic and an ice source located to the west should not be discharged.

The ice lobes that entered the Paraná Basin were probably associated with different ice-marginal depositional environments. Ice-marginal deposits in southern Paraná state (Vesely *et al.* 2015) and in some localities of Rio Grande do Sul state (Tomazelli & Soliani 1997) present characteristics that suggest deposition in continental settings (subglacial tillites overlain by glaciofluvial or glaciolacustrine facies), similar to the present day outlet glaciers from Iceland that terminate on land (e.g. Kjaer *et al.* 2008). Ice lobes of Santa Catarina state (Alfredo Wagner and Vidal Ramos), on the other hand, probably advanced in a marine environment once the abraded basement in that area is covered by marine shale and turbidites accumulated in relatively deep water settings (Puigdomenech *et al.* 2014).

Considering the data described in this paper, it can be concluded that the paleogeography of the LPIA in the Paraná Basin fits better into a model of multiple diachronic ice lobes instead of a massive continental ice sheet out of Antarctica (Fig. 11). This scenario corroborates interpretations from previous authors (e.g. França & Potter 1988, Santos *et al.* 1996).

CONCLUSIONS

Through a critical review of late Paleozoic ice-related landforms reported in the Paraná Basin, some conclusions can be drawn regarding the evolution of the LPIA in this sector of Gondwana:

- The study of the literature combined with field observations revealed that ice-related landforms are exposed in the western, southern and eastern borders of the Paraná Basin. They can be placed into four categories according to their origin:
  1. subglacial landforms developed on rigid substrates;
  2. subglacial landforms on soft beds;
  3. ice-keel scour marks; and
  4. subglacially abraded, striated clast pavements.

- Subglacial landforms on soft beds are evidence that glaciers not only sculptured the preglacial substrate but also advanced within the basin overriding previously accumulated sediments.
- The most reliable paleo ice-flow indicators are subglacial landforms once they indubitably indicate the advance of glaciers. However, several striated surfaces found in the Paraná Basin were generated by free-floating ice and should not be used to determine the paths of former glacial lobes.
- Based on reliable paleo ice-flow indicators, several glacial lobes derived from ice-spreading centers located to the east and to the south can be recognized. The interpretation

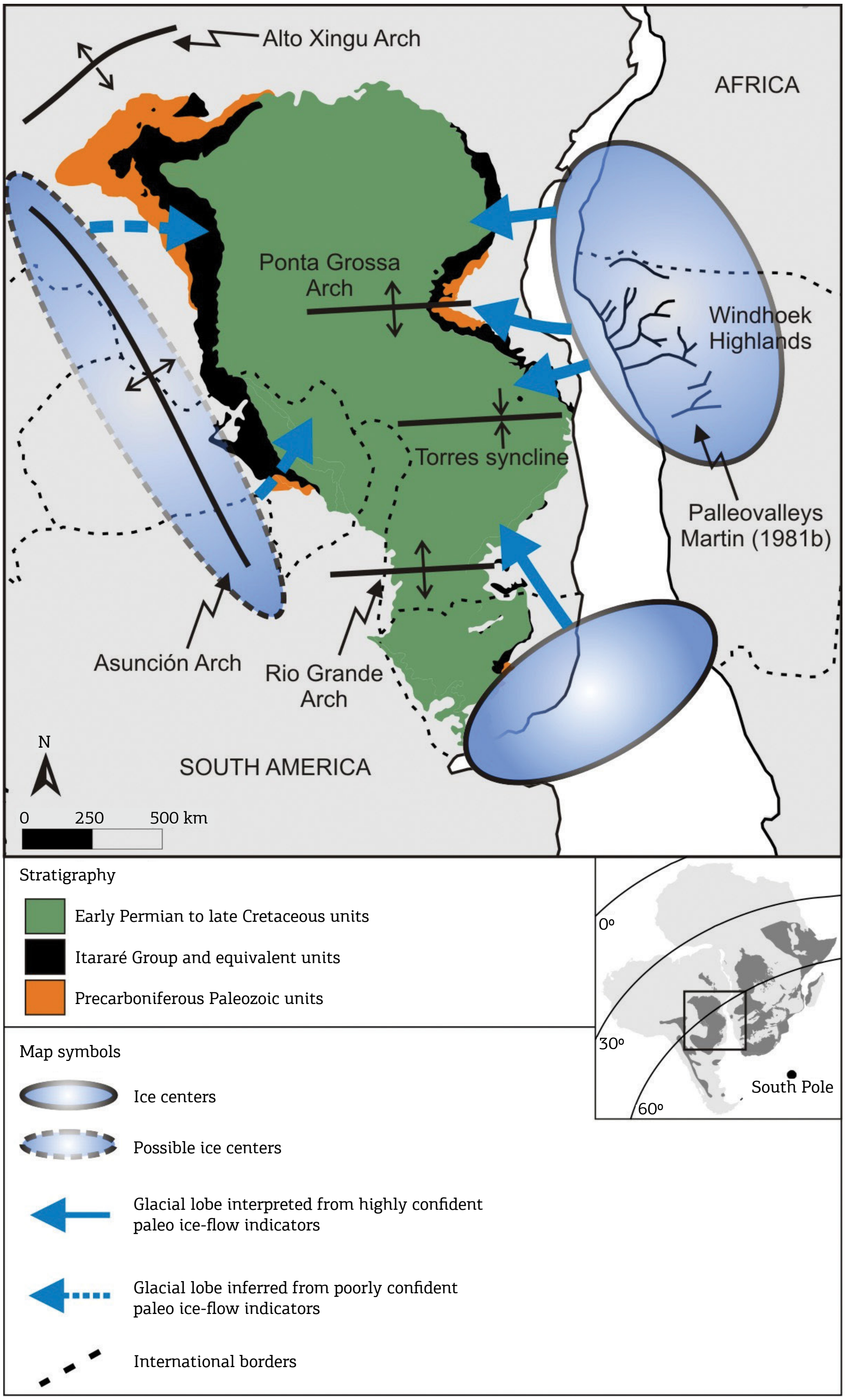

Figure 11. Paleogeographic reconstruction of the Paraná Basin during the Late Paleozoic Ice Age with the interpretation of ice-spreading centers and glacial lobes based on paleo ice-flow indicators discussed in the text.

of an ice source to the west and northwest cannot be rejected based on available data.

- The LPIA in the Paraná Basin is better depicted as several ice centers developed on adjacent highlands instead of huge continental ice sheets sourced from a polar ice mass.

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