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Ice flow direction during late Paleozoic glaciation in western Paraná Basin, Brazil

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Abstract

The recent discovery of ice-striated surfaces associated with the late Paleozoic Aquidauana Formation suggests that glaciers coming from southwest Africa reached westernmost parts of the Paraná Basin in central Brazil. Abrasion features were developed by glaciers moving from SSE towards NNW, mainly on an unconsolidated bed. These records expand to about 1,050,000 km^2, the coverage of the late Paleozoic glaciation in the region of the Paraná Basin in Western Gondwana. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Paraná Basin; Paleozoic glaciation; Aquidauana Formation

Resumo

A recente descoberta de superfícies estriadas associadas à Formação Aquidauana, de idade permocarbonífera, sugere que as geleiras provenientes do sudoeste da África alcançaram as porções ocidentais da Bacia do Paraná, na região central do Brasil. As feições de abrasão foram geradas pelo deslocamento de geleiras de SSE para NNW, principalmente sobre substrato inconsolidado. Estes novos registros evidenciam que a glaciação neopaleozóica cobriu uma área de pelo menos de 1.050.000 km^2 na região ocupada pela Bacia do Paraná no Gondwana Ocidental. © 2002 Elsevier Science Ltd. All rights reserved.

Palabras chave: Bacia do Paraná; glaciação paleozóica; Formação Aquidauana

1. Introduction

Late Paleozoic units of the Paraná Basin have been investigated since the end of the last century, together with the first speculations on glacial activity in the sedimentation of the Itararé Group (Late Carboniferous–Early Permian). The glacial influence on the deposition of this unit has been largely confirmed by further investigations, mainly in the southeast part of the outcropping belt of this basin (Rocha-Campos, 1967; Rocha-Campos and Santos, 1981; Gravenor and Rocha-Campos, 1983; França and Potter, 1988; Santos et al., 1992a, 1996). The identification of striated surfaces on the basement rocks and glacial deposits (*s.s.*) (tillites, eskers, drumlins) was essential for the definition of the late Paleozoic paleogeography and the direction of movement of the ice sheet in Western Gondwana (Rocha-Campos et al., 1968; Crowell and Frakes, 1975).

The essentially sandy and red-colored sedimentary deposits of the Aquidauana Formation were partially correlated by Gesicki et al. (1998) to the Lagoa Azul, Campo Mourão, and Taciba Formations (Fig. 1) of the Itararé Group (*sensu* França and Potter, 1988), which crop out along the northern and western border of the Paraná Basin. The recent discovery of striated surfaces associated with the Aquidauana deposits in the western border of the Paraná Basin, Mato Grosso do Sul, reinforces the hypothesis that the late Paleozoic Gondwanic glaciers, coming from southwest Africa, also reached the western parts of the basin, as previously pointed out by Gesicki et

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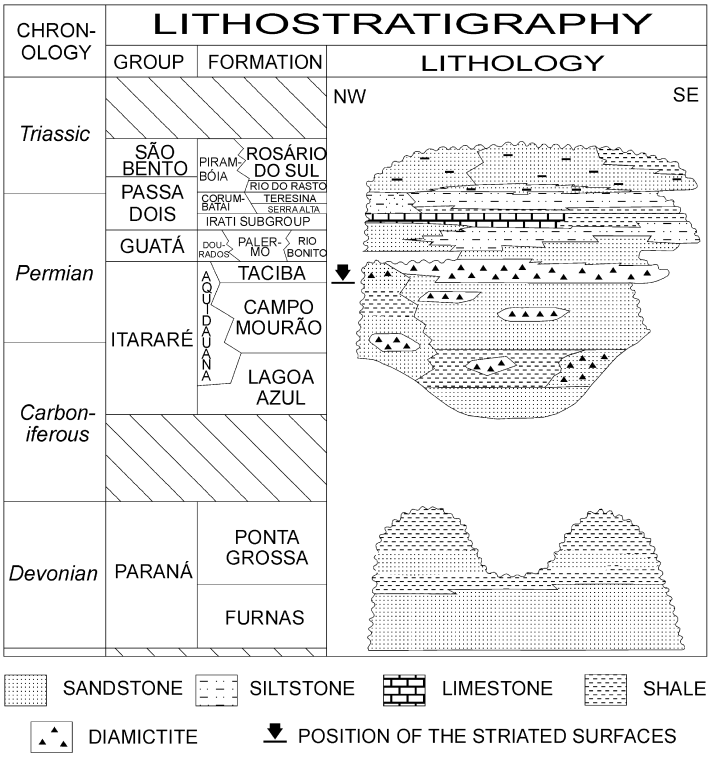

Fig. 1. Lithostratigraphic chart of the Paleozoic section of the Paraná Basin in Brazil, based on França and Potter (1988) and Matos (1995).

al. (1998) and Crowell (1999). These new data refute the idea that a dispersion center over the Asunción Arch was the main source area of glaciers during the Aquidauana sedimentation (Crowell and Frakes, 1975; Santos et al., 1996).

2. The directions of ice movement in the Itararé Group

Occurrences of late Paleozoic ice-striated pavements on basement rocks of Itararé Group (Precambrian granitic rocks and Silurian–Devonian sandstones of Furnas Formation), shown in Fig. 2, were first described by Barbosa (1940) and Carvalho (1940) near the town of Mafra, in the State of Santa Catarina. Almeida (1948) and Amaral (1965) registered the remarkable occurrence of *roche moutonée* in the neighborhood of Salto and Itu cities, São Paulo. In subsequent studies, new occurrences of striated surfaces were reported by Salamuni et al. (1966) and Bigarella et al. (1967) in the Wittmarsum locality, Paraná, and by Rocha-Campos et al. (1988) in Alfredo Wagner, Santa Catarina.

Within the Itararé Group, striated surfaces on sandstones and diamictites were found (Fig. 2) at the Cachoeira do Sul, Pinheiro Machado (Tomazelli and Soliani, 1982) and Suspiro (Tomazelli and Soliani, 1997) localities, Rio Grande do Sul and Rio Piritubinha, São Paulo (Caetano-Chang et al., 1990). More recently, a striated surface developed upon glacial deposits of the Aquidabán Formation, correlatable to the Itararé Group, was found in the village of Escobar, eastern Paraguay (Riccomini and Velázquez, 1999).

In Trombudo Central, Santa Catarina, Santos et al. (1992b) described iceberg scours, dump structures as well as debris left by grounded icebergs over rhythmites, probably generated by the last deglaciation episode during the Early Permian of the Paraná Basin.

The late Paleozoic glaciation was also recognized in rocks of the Santa Fé Group, Minas Gerais, by Dardenne et al. (1991) and Campos (1992), who reported the occurrence of striated surfaces on red rhythmites of this unit (Fig. 2). According to Campos (1992), the Santa Fé Group shows the broad extent of the sedimentary basin during the Itararé epoch, which covered the southern part of the São Francisco Craton and was later removed by erosion.

The strikes of subglacial abrasion features are consistent around NNW, with small variations to N–S, NNE, and NW, revealing that the southeastern terrains of the Paraná Basin were the main glacier source area during the greater part of Itararé sedimentation (Santos et al., 1992a). Studies of late Paleozoic paleogeography of glaciers have attempted to show that ice masses advanced into the Paraná Basin through five main glacial lobes: Uruguay, Paraná, and Kaokoveld lobes (Crowell and Frakes, 1975), coming from southwest Africa; and the Mato Grosso and Santa Catarina lobes (França and Potter, 1988), from the Asunción Arch, which reached the western part of the basin.

3. Evidence of glacial advance in the Aquidauana Formation

Striated surfaces occur in many localities in the southern and central parts of Mato Grosso do Sul (Fig. 2), mainly within a single stratigraphic interval of the Aquidauana Formation. Striae directions vary from N22E to N28W, and NNW is the predominant direction observed in outcrops.

Glacial abrasion structures within the Aquidauana Formation were produced on diamictites and sandstones that occur at the base of the upper stratigraphic interval of this formation (Fig. 1), along the outcropping belt of the western border of the basin. In this sedimentary interval, the early depositional processes were progradational in succession to the remarkable transgressive episode responsible for the deposition of a thick package of rhythmites. These coastal progradational processes, dominated by continental and transitional depositional systems, reflect global climatic changes with variations of relative sea level, associated with new episodes of glacial advance into the basin. Glaciers coming from southeast were the main source for sedimentation in the basin. These sediments were strongly reworked in a proglacial context during the time interval between the glaciation peaks, with the development of alluvial fans, braided fluvial streams, and a later reworking by storms and resedimentation in a marine or lacustrine environment.

The lower contact of the Aquidauana Formation with the Silurian and Devonian units of the Paraná Basin is a remarkable unconformity. In the central–western part of Mato Grosso do Sul, the Aquidauana Formation locally lies directly over the Furnas Formation, along an irregular contact surface. This suggests that glacial erosion removed the Ponta Grossa Formation (Devonian).

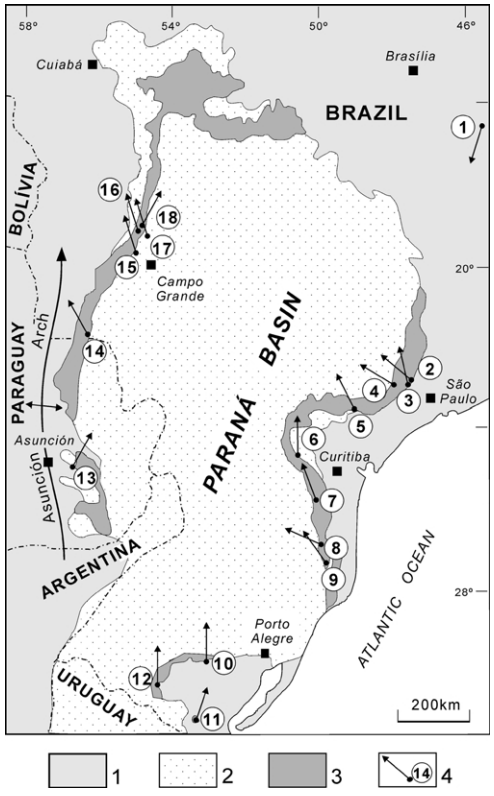

Fig. 2. Main localities with Late Paleozoic subglacial abrasion features of the Paraná Basin in Brazil, with arrows indicating the probable sense of ice movement (modified after Riccomini and Velázquez, 1999): 1 = Cambrian and older rocks; 2 = Paraná Basin; 3 = outcropping belt of the Itararé Group and Aquidauana Formation (Brazil) and Aquidabán Formation (Eastern Paraguay); 4 = striated surfaces with the sense of ice movement. Striated surfaces already known in the outcropping belt of the Paraná Basin (numbers in circles): 1 = striated surfaces on rhythmites of the late Paleozoic Santa Fé Group, Santa Fé de Minas locality (Dardenne et al., 1991; Campos, 1992); 2 = Roche Moutonée on Precambrian granitic basement of the Salto locality, São Paulo (Almeida, 1948); 3 = striated pavement on Precambrian granitic basement of the Itu locality, São Paulo (Amaral, 1965); 4 = boulder pavement in the Itararé Group diamictites of the Jumirim locality, São Paulo (Rocha-Campos et al., 1968); 5 = striated surface on sandstones of the Itararé Group, Piritubinha River locality, São Paulo (Caetano-Chang et al., 1990); 6 = striated pavements on sandstones of the Devonian Furnas Formation, Wittmarsum locality, Paraná (Salamuni et al., 1966; Bigarella et al., 1967); 7 = striated pavement on Precambrian granodioritic gneiss basement, Mafra locality, Santa Catarina (Barbosa, 1940); 8 = striated pavement on Precambrian granitic basement, Alfredo Wagner locality, Santa Catarina (Rocha-Campos et al., 1988); 9 = iceberg scour features in rhythmites of the Itararé Group, Trombudo Central locality, Santa Catarina (Santos et al., 1992b); 10 = striated surface on diamictite of the Itararé Group, Cachoeira do Sul locality, Rio Grande do Sul (Tomazelli and Soliani Jr., 1982); 11 = striated surface on diamictite of the Itararé Group, Pinheiro Machado locality, Rio Grande do Sul (Tomazelli and Soliani Jr., 1982); 12 = striated surface on diamictite of the Itararé Group, Suspiro locality, Rio Grande do Sul (Tomazelli and Soliani Jr., 1997); 13 = striated surface on diamictite of the Aquidabán Formation, Escobar locality, Eastern Paraguay (Riccomini and Velázquez, 1999). Striated surfaces in the Aquidauana Formation described in this paper (Mato Grosso do Sul, western border of the Paraná Basin): 14 = Rio Estrela locality, Ponta Porã–Bela Vista road, 23.6 km east from Bela Vista, near the Brazil–Paraguay international boundary; 15 = Aquidauana River (Ponte do Grego) locality, Cipolândia–Terenos road, 3.5 km west from Ponte do Grego; 16 = Rio Negro locality, Rio Negro–Taboco road, pavement at the bed of the Negro River, 19 km south from Rio Negro; 17 = Serra Negra I locality, Fala Verdade–Rio Negro road, 98 km north from Corguinho; 18 = Serra Negra II locality, Fala Verdade–Rio Negro road, 82 km north from Corguinho.

4. Glacial abrasion features

Striated pavements were recognized in five localities (Fig. 2): Aquidauana River (Ponte do Grego), Serra Negra I, Serra Negra II, Rio Negro, and Rio Estrela. Using kinematic indicators (v.g. Boulton, 1974; Petit, 1987; Eyles and Boyce, 1998), the sense of ice movement was established for three occurrences. Taking into account that the directions of the grooves vary little from place to place and the fact that all the occurrences are in the same stratigraphic position (except at Rio Negro locality), it is likely that the same sense of ice movement, from SSE to NNW, took place at all localities.

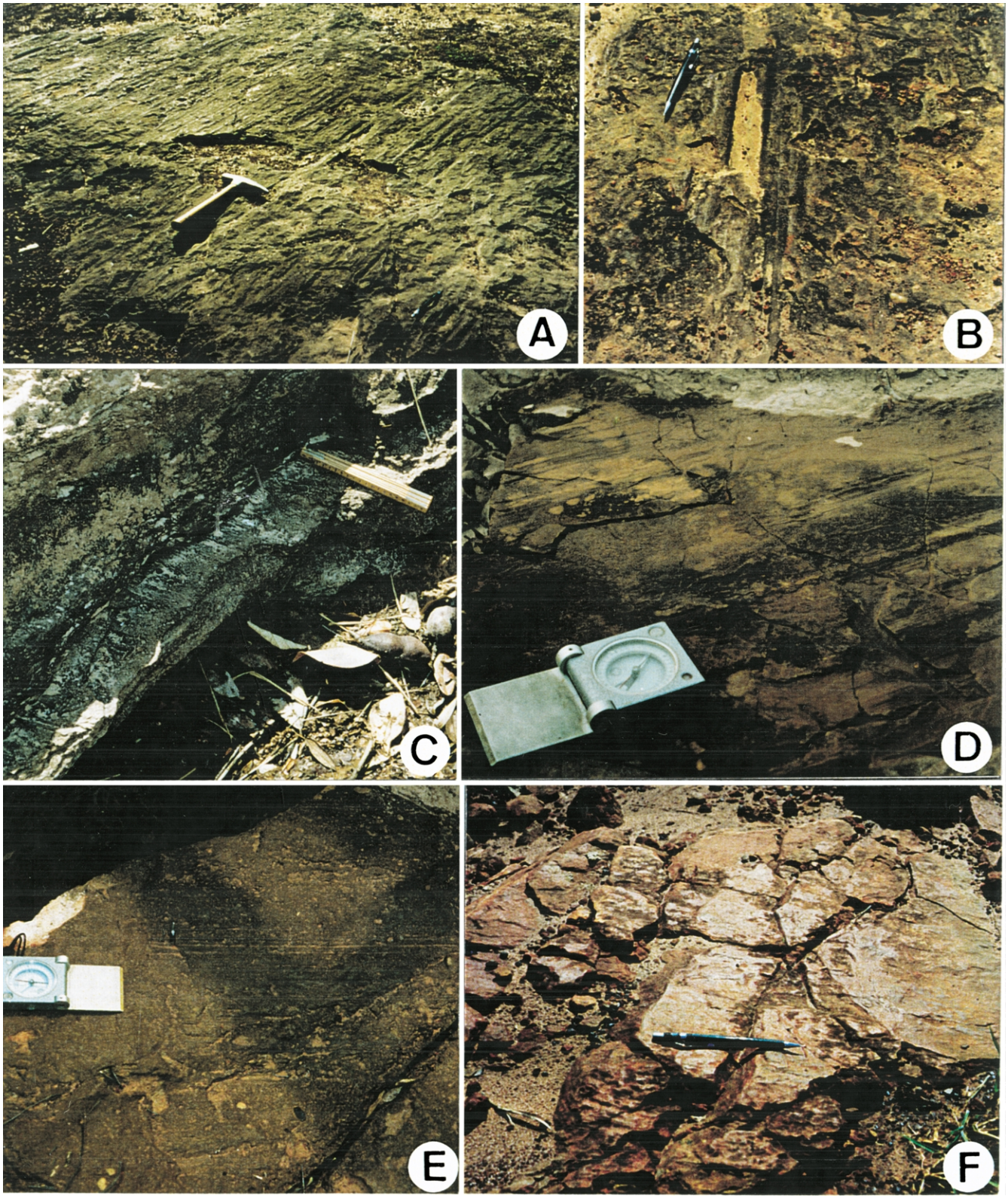

Fig. 3. Striated surfaces found in the Aquidauana Formation in Mato Grosso do Sul: (a) wide striated surface made by overriding ice mass on diamictites with ice abrasion features indicating paleoflow toward N20W, Rio Aquidauana locality (Ponte do Grego). The sense of movement is from the left lower to right upper corner of the photograph. (b) Detail of previous surface showing a pebble buried in the unconsolidated bed after sliding over it, leaving a roughness of sediment in front of it (downstream side). (c) Striated surface included in the same stratigraphic context of the previous locality, found at the margin of the Aquidauana River. (d) Striated surface on decimetric bed of fine sandstones interlayered in a package of red diamictites, Serra Negra I locality. (e) Striated pavement on coarse pebbly sandstones of the Silurian–Devonian Furnas Formation at the bed of the Negro River, displaying straight and thin striae along the N18W direction, Rio Negro locality. (f) Striated surface on diamictites at Ponta Porã–Bela Vista road, near the Brazil–Paraguay international boundary (Rio Estrela locality).

4.1. Rio Aquidauana

The occurrence of Rio Aquidauana (Fig. 2, locality 15) includes two outcrops located near the small village of Ponte do Grego. In the main exposure the striated surfaces crop out discontinuously over an area of 50 m wide by almost 300 m long, along the road between Terenos and Cipolândia (Fig. 3(a) and (b)). The second is a small (2–3 m^2) outcrop, on the margin of the Aquidauana River (Fig. 3(c)). The main surface has straight and shallow grooves, with a maximum width of 3 cm and average depth of 1 cm and is developed on a diamictites matrix, with striated and faceted clasts whose major axes reach 40 cm. Here, the average vector of the glacier paleoflow is N21W, and the northwestward direction of ice movement was defined by the pebbles at the termination of some furrows (Fig. 3(b)), showing that these pebbles stayed buried after the sliding, grooving, and furrowing of the sedimentary bed, deforming the sediment in front of it.

4.2. Serra Negra I and II

The striated surfaces of Serra Negra I and II localities are morphologically different although in the same stratigraphic position. They are located in the road between Corguinho and Rio Negro cities, on the flank of the Serra Negra. In the Serra Negra I locality (Fig. 2, locality 17), the large exposed surface shows straight grooves with an 'U' shaped profile and average width and depth of 7×4 cm, respectively, spaced up to 10 cm from another groove by rounded and straight crests in the N–S direction. In the Serra Negra II locality (Fig. 2, locality 18), the surface crops out in a 100 m long exposure and includes thin, straight, and shallow grooves and furrows (0.5 cm in depth) with a N22E direction (Fig. 3(d)). Transverse fractures (Boulton, 1974) associated with the surface indicate ice movement from southwest to northeast.

The surfaces at this locality reveal different hydroplastic conditions of the sedimentary substrate. In Serra Negra II the striated surface occurs on a decimetric layer of very fine grained and well-lithified sandstones intercalated within a package of muddy diamictites. The cohesive behavior of this surface during the glacier movement shows that the substrate was consolidated by early diagenesis, or it may have been frozen. In the Serra Negra I locality, the local fluvial reworking of the diamictites has led to the deposition of medium to coarse cross-bedded sandstones. Over this less cohesive and more permeable coarse-grained sedimentary bed, probably under subaerial conditions, the glacier movement left deeper furrows in a surface developed upon more deformable sediments.

4.3. Rio Negro

The striated surface of Rio Negro is located in the bed of the Negro River, below the bridge on the Rio Negro–Vila Taboco road (Fig. 2, locality 16). It is developed on Silurian–Devonian pebbly fluvial sandstones of the Furnas Formation (Fig. 3(e)) and is covered by a metric package of polymictic orthoconglomerate of the Aquidauana Formation, with well-rounded clasts and a faint stratification as shown by the preferential orientation of elongate clasts.

The grooves on the Rio Negro surface are thin, shallow, and straight, with orientation N28W. The conglomerates of the Aquidauana Formation are interpreted as proglacial alluvial fans filling irregular surfaces carved and striated by ice abrasion on the older Silurian–Devonian deposits. The ice movement in this locality was from southeast to northwest and has contributed to the erosion of the Devonian Ponta Grossa Formation and perhaps of older deposits of the Aquidauana Formation. Chronological data, which date this glacial advance, are still unavailable, but it could represent an older episode than that which affected other described localities of Mato Grosso do Sul.

4.4. Rio Estrela

The occurrence of Rio Estrela (Fig. 2, locality 14) is a surface of small dimension showing thin and straight striae along N28W, developed over red-colored diamictite (Fig. 3(f)) that crops out on the Ponta Porã–Bela Vista road, close to the headwaters of Rio Estrela, on the Brazil–Paraguay international boundary.

5. Discussion

The above described features were undoubtedly produced by subglacial abrasion. Flattened surfaces with furrows and straight shallow grooves reveal a cohesive behavior of the unlithified sedimentary bed (diamictites and sandstones) as a result of the relatively high shear strength and low permeability of the bed. The cohesiveness of the substrate suggests either an early diagenetic hardening or the underlying beds were frozen.

In the case of Serra Negra I locality, the bed composed of cross-stratified sandstones derived from fluvial reworking reveals higher interstitial water contents, resulting in a more plastic (deformable) behavior of the bed in response to subglacial abrasion.

Boulton (1979) and Boulton and Jones (1979) found that, in temperate glaciers, the unlithified sedimentary substrate shows a predominant tendency to deformation beneath moving glaciers because of the low hydraulic transmissibility of the bed and the thaw water contents in the ice/bed interface, which turns the adhesion very low. The authors demonstrated that net forward movement of glaciers may be greatly improved by deformation of the unconsolidated bed. On the other hand, the frozen sedimentary substrate may present a relatively high resistance to shearing applied by the moving ice masses (either of polar or temperate-type), showing a rigid behavior similar to bedrock.

Recent studies on the stratigraphy of the Itararé Group (França and Potter, 1988, 1991; Eyles et al., 1993), indicate

a succession of basal diamictites and upper sandstones for the Taciba Formation, representing the third (and last) Paleozoic glacial episode as well as the most extensive sedimentary event in the basin. According to França and Potter (1991) the glaciation model of the Itararé Group would combine continental and marine ice sheets developed in the Paraná Basin during three major cycles of sedimentation. The last two major ice advances would have occurred during important marine transgressions, with the development of ice masses in the southern and deeper part of the basin, while the northern part would have been shallower and more marginal.

The NNW direction of ice movement registered in the Aquidauana Formation shows the same general strike of ice paleoflow recognized for the Itararé Group in the eastern part of the Paraná Basin. This suggests that the glaciers coming from the southeast formed an extensive ice cover, probably over almost the entire basin, reaching at least as far as its present-day western border. Stratigraphically, this glacial advance is placed on the lower part of the upper interval of the Aquidauana Formation and would represent the last glacial episode of the Itararé Group, coeval to the Taciba Formation, as recognized by França and Potter (1988, 1991).

The paleogeographic reconstructions of late Paleozoic glaciers (Frakes and Crowell, 1969; Crowell and Frakes, 1975; França and Potter, 1988, 1991; Santos et al., 1992a; Eyles et al., 1993), are in agreement with respect to the delimitation of eastern and western domains, which would have acted as glacier source areas for the basin during sedimentation of Itararé Group.

In the eastern domain, subsurface diamictite isopachs and the vectors of glacial movement obtained in outcrops of the Itararé Group and its basement establish an ice source in southwest Africa. This would have been the main source of glaciers and sediments during the glacial and interglacial periods.

The scarcity of detailed studies of the western domain of the Aquidauana Formation has opened the opportunity for speculation. Paleocurrent data reveal mainly westward paleoflow of the fluvial systems and sediment gravity flow processes and indicate that the sediment source areas would probably be the same as was recognized for the eastern border of the basin. Even so, review papers on the late Paleozoic glaciation (v.g. Crowell and Frakes, 1975; Eyles et al., 1993), mainly based on subsurface data (isopach maps), always pointed to an important sedimentary source from the west, placed in the Asunción Arch, which would constitute the main source area of the Aquidauana Formation glaciers (i.e. the Mato Grosso and Santa Catarina lobes as defined by França and Potter (1988)).

The data presented here show that the glacial advance recognized in the upper stratigraphic interval of the Aquidauana Formation in the western border of the Paraná Basin represents the last and the most important continental glacial event, maybe the largest in the Paraná Basin, where the ice masses probably covered all Western Gondwana. In the Paraná Basin, the glaciers coming from southwest Africa were the main sources of sediments and reached the western portions of the basin probably during the stadial maxima of the glacial period, at least in the last great episode of the Itararé Group. Sedimentological evidence sustaining the hypothesis of a glacier dispersion center on the Asunción Arch (Crowell and Frakes, 1975; Eyles et al., 1993) are still absent.

6. Conclusions

Striated surfaces were recognized on sedimentary rocks of the upper stratigraphic interval of the Aquidauana Formation in four localities of its outcropping belt, in the western border of the Paraná Basin, in Brazil. The surfaces exhibit straight thin striae and shallow grooves (Rio Aquidauana, Serra Negra II, Rio Negro, and Rio Estrela localities) that indicate subglacial abrasion and glacier paleoflow from SSE towards NNW. In the Rio Negro I locality, the favorable hydroplastic and strength conditions of the unconsolidated bed allowed the development of deeper and larger straight grooves, characterizing plastic behavior of the deformable sedimentary substrate. The consistency of the abrasion features of the Aquidauana Formation and their parallelism with those already known in the eastern outcropping belt of the Itararé Group in the basin, permit the interpretation that the glaciers coming from southwest Africa reached the westernmost portions of the sedimentary basin, over an area of approximately 1,050,000 km^2, probably during the climaxes of the last late Paleozoic glacial event in the Paraná Basin. No surface sedimentological data were found that point to a western glacier source area in the Asunción Arch, as previously proposed by Crowell and Frakes (1975), França and Potter (1988, 1991) and Eyles et al. (1993).

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