Reprinted from:
IV International Gondwana Symposium, 1977
Calcutta, India

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HINDUSTAN PUBLISHING CORPORATION (INDIA)
DELHI-110007

sgmo = 3472532

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ABSTRACT

Two extensive intratill boulder pavements were identified included at two levels within a single diamictite horizon of the Late Palaeozoic Itararé Subgroup, in the northern part of the Parana Basin, Brazil. Structural features of pavements and a comparison of the composition of their clasts and those dispersed in the diamictite matrix suggest their formation as concentrates along shear or slippage planes inside a basal till under a flowing glacier.

A detailed study of surface characteristics of clasts dispersed in the diamictite shows that up to 48% of them bear some sort of striae, mostly of the subparallel type. These are more commonly oriented parallel with the longest axes of the clasts.

The measurement of striae on cobbles and boulders of the lower and upper pavements averaged N75°W and N-S, respectively. The interpretation of local sense of glacier movement is based on the probable up-glacier inclination of the upper plane surface of clasts in the pavements, which indicates towards N and NW. The general sense of movement was interpreted to have been towards N37°W.

INTRODUCTION

The determination of sense of Late Palaeozoic (Gondwana) ice flow in eastern Paranā Basin has been mostly based on the orientation of folds attributed to ice-pushing (Martin, 1961) and palaeoccurrent studies of beds associated with the diamictites (Bigarella, *et. al.*, 1967; Frakes, *et. al.*, 1969). Deductions based on structures or features directly related to the movement of glaciers, as striae on pavements (Almeida, 1948; Amaral, 1965; Bigarella, *et al.*, 1967), or on boulder pavements (Rocha-Campos, *et al.*, 1968, 1969; Frakes, *et al.*, 1969), elongation of streamline moulded forms (Rocha-Campos, *et al.*, 1968), etc., which are generally considered as more reliable indicators, are still insufficient, especially taking into account the large extension of the Itararé Subgroup outcrops. Although, as shown by Rocha-Campos (1967) and Frakes, *et. al.* (1969), both approaches have yielded grossly similar results, indicating general sense of ice-flow towards north and northwest, further studies of ice-flow derived features combined with facies analysis are still necessary to obtain a detailed palaeogeographic picture of the Late Palaeozoic glaciation, particularly its geographical and stratigraphical variations in pattern. These studies may be useful to elucidate the number and distribution of the different glacial lobes and source areas during the long Late Palaeozoic glacial interval in the Paranā Basin.

The purpose of this report is to describe structures identified as glacial boulder pavements included within a single diamictite horizon in central eastern São Paulo State and to discuss problems related to the origin of these structures and the interpretation of sense of Late Palaeozoic ice-flow in the areas. Identification of these structures bears also on the discrimination of local facies of the diamictites.

STRATIGRAPHY

Strata and structures described below belong to the middle part of the Late Palaeozoic Itararé Subgroup in central eastern São Paulo State, outcropping on two parallel faces of a road cut of highway SP 101, between 35 and 36 km (Plate 138). The following description is based on the southern face of the cut which is more easily accessible.

The local section (Plate 139) is made up (from base to top) of sandy or silty, yellowish-greenish matrix diamictite, up to 5 metres thick and intercalated with several large or small, lenticular, elongated bodies of fine-to-medium or coarse grained, feldspathic sandstone, often pebbly. Clasts in the lower diamictite are relatively rare; their characteristics and composition are synthesized in Tables 1 and 2.

Several large, elongated sandstone interbeds at the upper part of the diamictite vary in thickness in a pinch-and-swell manner and are disrupted and deformed. Some of the smaller sandstone lenses have apparently resulted from the fragmentation of larger bodies. At least one large, cross-bedded sandstone body is channel-like in cross-section and shows a thin, wavy stratification. A large, lenticular, coarse badly sorted, massive, feldspathic sandstone body, locally pebbly, at the top of the lower diamictite, is unconformably overlain by an upper diamictite bed. Surface of unconformity shows only minor irregularities and at several places the upper surface of sandstone bears a faint lineation, probably due to soft sediment deformation, as drag lines oriented along N5°W.

The upper diamictite is yellowish-greenish, silty matrix, mostly megascopically massive and homogenous. Maximum thickness exposed is about 5 metres. Clasts are relatively commonly, widespread within the matrix and are also concentrated along two horizons forming two clast pavements. Lithology of clasts and some of their surface characteristics are shown in Tables 1 and 2.

TABLE 1

Lithology of Clasts of the two Diamictites at Capivari

(1457 clasts)

Lithologies	*Lower Diamictite*	*Upper Diamictite* Below Lower Pav.	*Lower Pav.*	*Between Pavems.*	*Upper Pav.*	*Above Upper Pav.*
Red or violet arkose	4.3	26.0	2.0	12.0	18.6	44.0
Quartzite	39.1	18.6	10.2	7.0	7.2	29.4
Red or violet quartzite	2.2	7.3	24.5	19.0	9.3	—
Metarenite	15.2	12.5	6.1	25.0	9.3	1.5
Gneiss	—	6.3	8.2	4.0	1.0	7.4
Schist	10.9	4.2	6.1	15.0	3.1	2.9
Very fine qtzite (or chert)	4.3	1.0	2.0	1.0	3.1	11.8
Sandstone	8.7	—	—	—	—	1.5
Red siltstone	—	—	—	1.0	—	—
Meta siltstone	2.2	—	—	3.0	—	—
Granite	10.9	15.6	36.7	6.0	41.2	—
Metadiabase	—	4.2	4.1	3.0	1.0	—
Metavolcanics	—	3.1	—	2.0	—	—
Metaconglomerate	—	—	—	—	3.1	—
Phyllite	2.2	—	—	—	2.1	—
Pegmatite	—	—	—	—	1.0	—
Vein quartz	—	—	—	1.0	—	—
Quartz porphyry	—	—	—	1.0	—	—

Description of Clast Pavements

The reconstruction of structures described below as planar and horizontal or pavement is based on their characteristics examined on the parallel faces of the road cut about 20 metres apart. They are better exposed along the southern face of the cut, which will mainly serve as a basis for the description.

The upper alignment can be followed for at least 80 metres, from the northeastern extremity of the outcrop to about $\frac{1}{4}$ of its entire length, being truncated by the present surface of the terrain. The alignment is astonishingly rectilinear in vertical view and formed by more or less densely disposed pebbles, cobbles and boulders. Vertical dispersion is minimum (less than $\frac{1}{2}$ metre) and irregular horizontal concentrations of clasts include imbrications.

The lower alignment, essentially parallel to the first, occurs two metres below and is exposed along at least 60 metres on the southwestern road cut, starting a few metres before the southwestern extre-

TABLE 2

Type and Disposition of Striae on 310 Clasts of the two Diamictites at Capivari

Levels	*Total % striate*	*Type of striae* Parallel	*Subpar.*	*Grid*	*Scatter*	*Orientation of striae* Parallel	*Oblique*	*Perpend.*	*Indet.*
Above Upper Pavement	48.0	6.1	87.9	6.1	—	72.7	9.1	9.1	9.1
Between Pavements	17.0	29.4	82.4	—	5.8	82.4	17.6	17.6	—
Below Lower Pavement	39.0	5.3	86.8	7.9	—	84.2	2.6	—	13.2
Lower Diam.	26,0	8.3	83.3	8.3	—	66.7	16.7	8.3	8.3

Explanation: parallel=parallel of longer axis; oblique=45° of longer axis; perpendicular=90° of longer axis; indeterminate: chaotic; type of striae according to Wentworth (1936). Percentages may be above 100 because more than one type of striae with different disposition occur on the same clast.

mity of the upper alignment, to about the middle part of the cut. Except for wider horizontal discontinuities and higher vertical dispersion, the characteristics of the lower alignment are coincident with those of the upper one.

A closer examination of clasts along the two alignments on both road cuts revealed that many present an upper plane or faceted surface, mostly inclined towards south (Plate 139). They generally bear subparallel or some times grid type striae (Wentworth, 1936), the first generally parallel to the long axes of clasts of the pavement, which also tend to be parallel. The measurement of striae on 48 cobbles and boulders of the upper alignment and 13 in the lower, averaged N-S and N75°W, respectively (Plates 140 and 141).

Origin of Clast Pavements

Boulder pavements are flat-lying layers of clasts ranging from pebbles to boulders which occur between tills (intertill pavements), or inside a single till unit (intratill pavements; Dreimanis, in press). The upper surfaces of clasts are beveled and contain striae oriented in a parallel fashion (Flint, 1957, 1961; Dreimanis, *et al.*, 1953, Dreimanis, in press). Intertill pavements may be a part of the lower till, as demonstrated by examples where the clast lithology of both is similar, but may also belong to the overlying till, in cases where the older sediments do not contain clasts (Dreimanis, in press).

The first variety of intertill boulder pavements is thought to represent lag concentrated due to various processes of surface erosion of an older till, followed by rejuvenation of the glacier, which is responsible for the reorientation of clasts, beveling of the lower till and regular striation on the clasts (Flint, 1957, 1961; Dreimanis, in press). According to Flint (1957) the rejuvenation may or may not be associated to an intervening deglaciation period.

An interpretation of the genesis of the other two types involves some difficulties. They are generally supposed to be formed by processes related to "changes in the dynamics of a moving glacier" (Dreimanis, in press) which may include plastering of a till by planation or shearing of higher and faster moving debris below a flowing glacier (Holmes, 1941; Dreimanis, *et al.*, 1953), and selective englacial or subglacial erosion of finer particles around larger clasts, which remain fixed as a pavement (Dreimanis, *et al.*, 1953). There is at least empirical geological evidence for the occurrence of single or multiple slippage or shearing planes inside a basal till under a moving glacier, as demonstrated by the beveled upper surfaces of clasts of pavements bearing polishing, parallel striae, grooves and sometimes even crescentic marks (Dreimanis, *et al.*, 1953; Frakes *et al.*, 1966; Rocha-Campos, *et al.*, 1968, 1969). This mechanism is, however, difficult to conciliate entirely with proposed models of sedimentation below moving continental glaciers (see Carey, *et al.*, 1961, p. 877-880).

In spite of the present difficulties in elucidating the origin of some pavements, they are very significant palaeoclimatological indicators, since no process other than glaciation is known to be able to produce concentration of clasts with the peculiar features described above. Boulder pavements are also useful in deciphering the direction of local flow of ice during deposition of the overlying till (Elson, 1957; Dreimanis, *et al.*, 1953).

Clast pavements associated to Late Palaeozoic (Gondwana) glacial sediments, coincident with the first and third variety of boulder pavements have been reported previously in the litterature from Antarctica (Frakes, *et al.*, 1966, 1971), Brazil (Rocha-Campos, *et al.*, 1968, 1969; Frakes, *et al.*, 1969), Africa (Frakes, *et al.*, 1970; Crowell, *et al.*, 1972; Rocha-Campos, in press) and Australia (Crowell, *et al.*, 1971).

In the case of structures and strata discussed here, a general glacial environment of deposition of the Itararé Subgroup is now firmly established, as well as its regional facies and paleogeography (Leinz, 1937; Rocha-Campos, 1967; Frakes, *et al.*, 1969, etc.). The two clast pavements at Capivari have all essential features of intratill boulder pavements; judging from their dimensions in outcrop they may represent two of the most extensive structures of this type so far reported in pre-Pleistocene deposits. Their identification indicates that the enveloping diamictite at Capivari represents a former glacial drift deposited as till by the Late Palaeozoic glaciers, most probably in the terrestrial environment. According to Dreimanis (in press) the intratill variety of pavements is associated with the basal till.

Characteristics of Clasts

A detailed study of the lithology and surface features of clasts of the local diamictites was attempted for the following purposes : (*a*) to identify the lithology of clasts from the lower and upper diamictites and at different levels of the upper one; (*b*) to determine the presence of striae and other features usually considered as evidence of glacial action, their types (Wentworth, 1936), and distribution in relation to characteristics of clasts in the two diamictites, and at different horizons within the upper diamictite (boulder pavements and intermediate zones). The two lines of investigation could furnish evidence towards the understanding of the origin of the diamictites, mechanisms of deposition and the genesis of the boulder pavements. Additionally, they could be useful to understand the provenance of the sediments. In spite of special care taken during field work, the variable state of weathering of different lithologies sampled, plus the erosion at the top of the outcrop caused some deficiency in the sampling.

In order to compare more quantitatively the composition of clasts at different levels, a cluster analysis was run on the basis of the data of Table 1. Results obtained indicate closer correlation (above 50%) between samples derived from the two pavements and of levels below the upper and lower pavements, these being thus consistent with the interpretation of the clasts as concentrates from the enveloping matrix. Two samples, one from the uppermost level of the upper diamictite, and the other from the lower diamictite, showed poorer correlation (less than 50%) with the first group. Inadequate sampling at the uppermost level of the upper diamictite, due to selective weathering and/or erosion at the top of the outcrop, may explain the results obtained for the first sample. With regard to the clasts from the lower diamictite, their relative lesser correlation may be due to slight difference in the composition of its source area. Qualitatively, an inspection of Table 1 shows the predominance of metamorphic types among the clasts of the lower diamictite.

As discussed below, the directional data on ice movement during deposition of the local diamictites indicate that they came from areas towards the southeastern, probably from the Precambrian shield, and this is consistent with the general composition of clasts analysed (Table 1). Larger exposures of red or violet quartzites are, however, presently unknown in the crystalline basement.

The results listed in Table 2, based on an examination of 310 clasts, are closely comparable with those obtained by Wentworth (1936) in a study of shapes and surface features of Pleistocene till clasts. The predominant striae is sub-parallel, usually parallel to longer axes of elongated clasts. Other types found are grid (and/or possibly scatter), followed closely by the parallel pattern. The subparallel, grid and scatter varieties are usually considered as glacial criteria, while the parallel type is not considered as unequivocal, since they occur frequently associated with tectonic activity (Frakes. *et al.*, 1969). The parallel disposition of striae with regard to long axes of elongated clasts suggests that these were transported through sliding inside the original till, most probably parallel with the flow of the sediment (Wentworth, 1936; Holmes, 1941).

SENSE OF MOVEMENT OF LATE PALAEOZOIC GLACIERS IN THE AREA

Plates 140 and 141 summarize the results of measurements of orientation of striae on top of clasts of the two parallel boulder pavements. The lower one, based on 13 clasts, shows a maxima in the northwest-southeast direction, while the upper yielded a maxima in the north-south direction. The determination of sense of ice movement in each case was based on the probable upglacier inclination of the upper faceted ends of clasts. They are mostly inclined towards south and the senses of movements must have been towards north. Other possible indicators of sense of flow, as imbrication of clasts or train of fragments (Frakes, *et al.*, 1966) seemed less reliable, or could not be used locally.

This situation reveals that direction of shearing over two different planes, within a single till unit, only two metre apart from each other, may differ substantially, as in the present case of about 75°, possibly due to heterogeneties inside the till mass.

The general sense of glacier movement during deposition of the upper diamictite is interpreted to have been in the direction of N37°W (average of the two sets of striae). In view, however, of the orientation of drag lines on top of the underlying sandstone (N5°W), the main movement may have occurred towards this direction, thus coinciding better with one set of striae. Deductions of direction of ice flow on the basis of only a few measurements may thus be conjectural, even when associated with indicators as reliable as the boulder pavements and the general geological framework should be examined.

The inferred glacial history of the area may be synthesized as follows : (*a*) deposition of the lower diamictite as till; deformation of sandstone interbeds may indicate some post-deposition mass movements which cause disruption of the included sand bodies. Reworking of the former diamicton by flowing melting water may have occurred possibly associated with a deglaciation period; (*b*) rejuvenation of the glaciation with deposition of the upper diamictite as a basal till; erosion of the underlying sediments occurred while they were still in the hydroplastic state, as demonstrated by the drag lines on top of the sandstones. Part or all deformation of the sandstone interbeds in the lower diamictite could be, alternatively, due to flow of overlying ice. Formation of the two boulder pavements occurred probably simultaneously, along shear planes developed on basal till by the flow of the younger glacier above it.

ACKNOWLEDGEMENTS

This report is a contribution of the IGCP Project, Upper Palaeozoic of South America (Proj .no. 73/I/42). Support for field work was provided by the Instituto de Geociencias, Universidade de São Paulo, Brazil. We thank Mrs. Elida B. Krauspenhar, Miss Maira Barberi and Messrs. Mitsuru Arai, A. M. Coimbra and F. Fittipaldi for collaboration during field and/or laboratory work.

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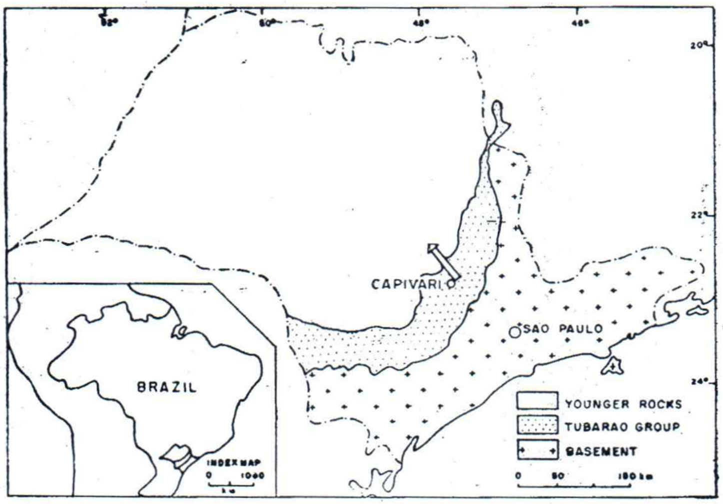

Plate 138. Location of the area studied and summarized data on sense of ice-flow.

Plate 139. Detail of upper boulder pavement showing four large clasts with plane upper surfaces.

A. C. ROCHA-CAMPOS AND ANTONIO R. SAAD

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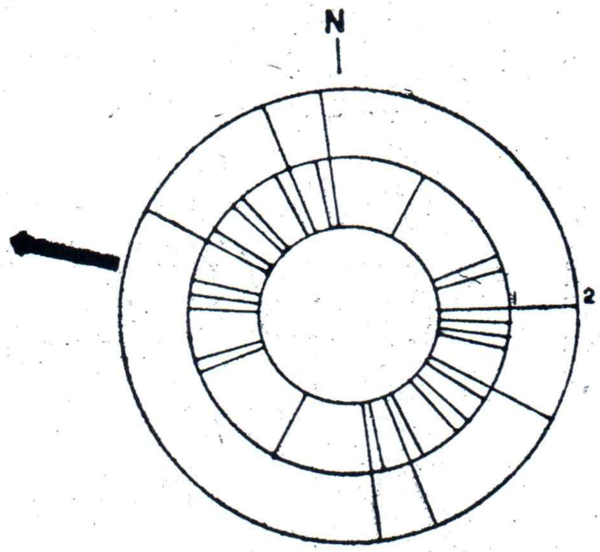

Plate 140.

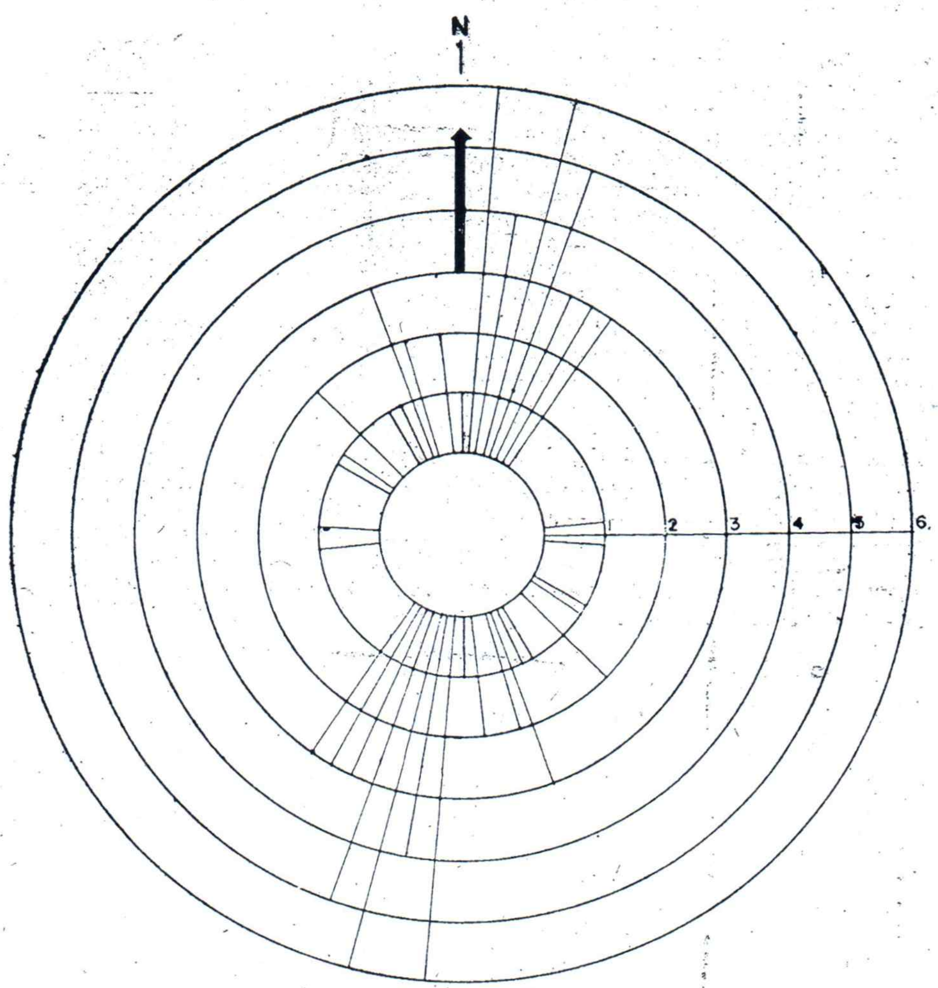

Plate 141.

Plates 140 and 141. Directional data : **Plate 140**—striae on clasts of lower pavement (13 determinations); **Plate 141**—striae on clasts of upper pavement (48 determinations). Arrows show interpreted senses of movements.

A. C. ROCHA-CAMPOS AND ANTONIO R. SAAD