# 3º Congresso Brasileiro de Geoquímica



SP 91

# 1º Congresso de Geoquímica dos Países de Língua Portuguesa

# INTERNATIONAL SYMPOSIUM ON MAFIC DYKES

## EXCURSION GUIDE

I

São Paulo, Brazil, 1991

# INTERNATIONAL SYMPOSIUM ON MAFIC DYKES AND RELATED MAGMATISM

## POST-MEETING EXCURSION

## PART I - LOWER CRETACEOUS MAFIC DYKE SWARMS ASSOCIATED WITH THE PARANÁ FLOOD VOLCANICS

October 03 to 11, 1991

Excursion Leaders:

Marcia Ernesto
Lelia S.Marques
Wilson Teixeira

São Paulo, 1991

# PART I - LOWER CRETACEOUS MAFIC DYKE SWARMS ASSOCIATED WITH THE PARANÁ FLOOD VOLCANICS

M. Ernesto[1]
E.M. Piccirillo[2]
M.I.B. Raposo[1]
J.P.P. Pinese[3]
L.S. Marques[1]
N. Ussami[1]

## INTRODUCTION

Expressive Lower Cretaceous mafic dyke swarms related to the Paraná basin magmatism occur at or near the eastern Brazilian coast. In the northern region of the Paraná basin, the Santos-Rio de Janeiro dyke swarm occurs along the coastline where the dykes trend N40-60E, subparalell to the regional structural lineaments of the Pre-Cambrian country rocks. The most significant dyke warm in northern Paraná is located in the Ponta Grossa arch where the dykes trend NW-SE and sometimes NE-SW. In the Florianópolis region (central Paraná) the dykes trend preferably NE and are frequently cut by NW dykes. Florianopolis dykes appear to be confined to a more restricted area than the Ponta Grossa dykes; they are very well exposed and show evident tectonic relationships with the country rocks or between the two sets of dykes.

The excursion is planned to visit Ponta Grossa and Florianópolis dyke swarms. Due to severe weathering conditions in southern Brazil, good outcrops (especially in the Ponta Grossa arch) are not frequent and long distances will be driven in order to visit representative exposures. A thick (about 1000 m) basalt-rhyolite sequence of the Serra Geral Formation will also be visited so as to offer a general view of the Paraná flood volcanics.

## GEOLOGICAL ASPECTS AND EVOLUTION OF THE PARANÁ BASIN

The Paraná Basin is located in central-eastern South America and covers an area of

[1]Instituto Astronômico e Geofísico, Universidade de São Paulo, Brasil.
[2]Istituto di Mineralogia e Petrografia, Università di Trieste, Italy.
[3]Departamento de Geociências, Universidade de Londrina, Brasil.

This post-symposim excursion is scheduled to depart on October 3 (Thursday) from São Paulo and arrives on October 11 (Friday) in Montevideo where it ends. It is planned to visit two Lower Cretaceous dyke swarms and associated Paraná flood volcanics in Brazil, and one Pre-Cambrian dyke swarm in Uruguay.

about 1.6x10$^6$ km$^2$ (Brazil:1.0x10$^6$; Argentina + Uruguay + Paraguay:0.6x10$^6$; Fig. 1). This intracratonic basin is set on those areas of the South America platform which were affected by the metamorphic and magmatic events of the "Brasiliano" Cycle (c. 700-450 Ma). The crystalline basement of the Paraná basin is probably formed by a cratonic nucleous surrounded by mobile belts (Cordani et al., 1984). The cratonization of the basement mainly occurred during early Paleozoic (Almeida, 1976), at the beginning of the sedimentary processes which piled up to 5000 m of sediments. The isopach map of pre-volcanic sediments shows that the axis of greater deposition trends about NE and this was probably controlled by a greater subsidence of the crystalline basement.

The most important tectonic features are positive elongated structures ("arches") which surround the basin, except towards the contimental margin (Fig. 1). The NNE and NE structures parallel the lineaments of the crystalline basement; notable is the Asunción arch which extends about 800 km over the southern border of the Amazônia craton and separates the Paraná from the Paraná-Chaco basin. The NW structures, transversal to the major axis of the Paraná basin, are represented by arches (Ponta Grossa, Campo Grande, Rio Grande), tectonic and/or magnetic lineaments (e.g. Guapiara, Rio Piquiri, Rio Uruguay) and the syncline of Torres. The formation of the NW-SE arches probably started in the Devonian and developed particularly in Triassic-Jurassic time (Fulfaro et al., 1982). The Ponta Grossa arch is of special interest since it is characterized by (1) numerous NW trending basic dykes, and (2) important NW trending magnetic anomalies (e.g. Guapiara, São Gerônimo-Rio Alonzo; Ferreira, 1982). Also, most of the South Atlantic oceanic fracture zones are subparallel to similar lineaments inland (e.g. Florianópolis vs. Rio Uruguay; Fig. 1).

The evolution of the Paraná basin can be distinguished in four stages. The <u>first stage</u> (Devonian-Lower Carboniferous) corresponds to the deposition of marine sediments; the end of this stage is characterized by epirogenetic movements and faulting, responsible for erosional surfaces. The <u>second stage</u> (Lower Carboniferous to Middle-Upper Permian) began with important tectonic movements. Most of the major tectonic structures were active during sedimentation, and marine to continental sediments rapidly accumulated preferentially along NNE direction. Due to persistent subsidence, the most important peripheral structures became progressively more elevated relative to the axial portion of the basin. Thus an important fluviatile to deltaic sedimentation dominated the end of the Paleozoic. The <u>third stage</u> (end of the Paleozoic to Jurassic) corresponds to a general uplift which promoted erosional processes and the final development of NW trending arch strutures (e.g. Ponta Grossa). The Mesozoic sedimentation is of contimental type and at the beginning of Jurassic time desertic conditions were dominant and the deposition of aeolian sandstones (Botucatu Formation) occurred in the entire Paraná basin. The <u>fourth stage</u> (end of Jurassic to Lower Cretaceous) began with important tectonic events which caused the Paraná basin to assume an antiform structure. Extensional tectonics allowed the outpouring of huge quantity of tholeitic basalts and comparatively scarce acid volcanics (Serra Geral Formation).

## PARANÁ FLOOD VOLCANISM

The total area affected by Serra Geral flood volcanism largely exceeded that of the present occurrence of volcanics (1.2x10$^6$ km$^2$), as indicated by numerous basalt dykes intruded in Paleozoic sediments or in pre-Cambrian crystalline basement. Dykes are concentrated in the NE sectors of the Paraná basin, mainly in the area of Ponta Grossa arch (Fig. 2) and along the Santos-Rio de Janeiro coastal regions but they are also found southwards in the Florianópolis region. The fissure-type volcanism of the Serra Geral Formation (140-130 Ma) was followed during the Upper Cretaceous-Tertiary (mainly 100-40 Ma; Ulbrich and Gomes, 1981) by an important central-type magmatism of alkaline nature which mainly occurred in the NE parts of the Paraná basin.

The maximum observed thickness of the volcanics is about 1000 m at the basin borders, and 1700 m in the central part of the basin. The estimated total volume of volcanics is 790,000 $km^3$.

Volcanics rest unconformably on the Botucatu aeolic sandstone and, locally, on Paleozoic sedimentary rocks. However, towards the basin margins, they have been also observed to rest directly on the crystalline basement. The volcanic sequences are essentially subhorizontal, gently dipping towards west. A single unit of cooling is frequently 50 m thick, while the average thickness for a single flow does not exceed 10-20 m.

Serra Geral volcanics are represented by tholeiitic basalts (c. 90% vol.), tholeiitic andesites (c. 7% vol.) and rhyodacites-rhyolites (c. 3% vol.). The latter cover an area of about 150,000 $km^2$, and are confined towards the continental margin (Fig. 1; Bellieni et al., 1986).

The basaltic and andesitic flows are represented by rock-types dominantly aphyric or subaphyric and their distinction in the field is quite difficult. On the contrary, the acid flows are quite easily distinguishable into two main types, namely Palmas and Chapecó. The acid volcanics of Palmas type (PAV) are usually aphyric to subaphyric. Aphanitic PAV, black in colour and with conchoidal fracture, are overlain by subphaneritic rock-types with light gray colour which, when altered, shows a "salt-pepper" texture (local name "basalto Carijó"). The outcrops of PAV volcanics typically show a subhorizontal, slab-like structure formed by irregularly broken plates 5-10 cm thick. Occasionally, at outcrop scale, PAV may show different dipping angles (up to vertical) which form geometrical variations of syncline-anticline type. PAV are concentrated in the state of Rio Grande do Sul and, subordinately, in the states of Santa Catarina and Paraná. The acid volcanics of Chapecó type (CAV) are frequently porphyritic (plagioclase crystals up to 20 mm) and therefore are easily distinguishable in the field from PAV. They are greenish-gray when fresh, and reddish-brown when altered. CAV show subhorizontal and extended millimetre to decimetre banding probably related to planar flow contacts. CAV are confined to the northern Paraná basin (border between São Paulo and Paraná states), while they are associated with PAV in the states of Paraná and northernmost part of Rio Grande do Sul.

Petrologically, the Paraná basin may be subdivided into three main portions (Fig. 1): (1) *southern Paraná* = south of the Rio Uruguay lineament; (2) *central Paraná* = between Rio Uruguay and Piquiri lineaments, and (3) *northern Paraná* = north of the Rio Piquiri lineament (Piccirillo et al., 1988a).

The *southern Paraná basin* (SPB) is mainly represented by basic volcanics (65% vol.) and, subordinately, by intermediate (22% vol.) and acid (13% vol.) rock-types. In general, the lower parts of the volcanic suites (Fig. 3) are composed by tholeiitic basalts and andesi-basalts (thickness: 30-550 m, mean 330 m), while the upper portions are essentially represented by rhyodacites and rhyolites (Palmas type; thickness: 60-440 m, mean 280 m). Usually, the uppermost parts of the acid suite are characterized by intercalations of basalts and/or tholeiitic andesites. The intermediate rock-types tend to be more abundant between the lower (basic) and upper (acid) portions of the suite. The acid volcanics appear to be concentrated towards the south-easternmost areas (thickness up to 400 m). A significant decrease in thickness (up to 60 m) of the acid volcanics is generally observed towards the western and northern regions of the SPB.

The *northern Paraná basin* (NPB) is essentially characterized by tholeiitic basalts which, in the south-easternmost regions, are overlain by rare (c. 0.3% vol.) acid volcanics (rhyodacites and rhyolites, Chapecó type) whose thickness ranges from 20 to 180 m. Locally, the volcanic suite ends upwards with thin basaltic flows overlying the acid volcanics. Intermediate rock-types are virtually absent.

The *central Paraná basin* (CPB) is characterized by volcanic suites similar to those in SPB and NPB. The basic volcanics (86% vol.) dominate over the acid analogues, namely Palmas type = 10% vol., and Chapecó type = 4% vol. The volcanic suites (Fig. 4) are represented by tholeiitic basalts and latibasalts (thickness: 50-550 m) covered by rhyodacitic and rhyolitic flows of Palmas (thickness: 30-250 m; mean = 90 m) and Chapecó (thickness: 40-250 m; mean = 88 m) types. Locally, Chapecó acid flows may be overlain by basalts (maximum thickness about 300 m), and rarely contain thin basaltic intercalations. The intermediate rock-types are rare and exclusive to the volcanic suites containing Palmas acid volcanics.

Recent studies (cf. Piccirillo et al.,1988b) have demonstrated that the Paraná basalts may be considered homogeneous in composition only in a very broad sense, since they are actually represented by two main rock-types. These two tholeiitic basalt-types show many important differences in chemical composition and may be distinguished by their contrasting low (<2% wt.) and high (>2% wt.) $TiO_2$ and incompatible elements (hereafter LTiB and HTiB, respectively).

It should be emphasized that low-$TiO_2$ basalts dominate (c. 93%) in SPB (Fig. 3), while high-$TiO_2$ basalts dominate (c. 94%) in NPB. Thick mixed sequences where either LTiB and HTiB are dominant can be found in the central Paraná basin (Fig. 4).

The acid volcanics of Palmas type are relatively poor in $TiO_2$ (and incompatible elements) and are usually associated with low $TiO_2$ basalts (i.e. southern Paraná basin). On the contrary, the Chapecó acid volcanics are comparatively rich in $TiO_2$ (and incompatible elements) and are systematically associated with high $TiO_2$ basalts (northern Paraná basin) (Bellieni et al., 1986).

## PARANÁ INTRUSIVE MAGMATISM

Sill-type intrusions of Lower Cretaceous age occur in the entire Paraná basin and are mainly emplaced within Paleozoic sediments. Rare sills occur in the Botucatu sandstones and Serra Geral basalt flows. In general, sills have variable thickness between 2 to 200 m.

The distribuition of sills in the Paraná basin is not uniform. They are concentrated in the central and northern regions (Paraná and São Paulo states), where the total thickness may be over 1000 m, and are scarce in southern Paraná (Rio Grande do Sul state), where the best exposures of volcanic sequences were observed (Fig. 5). It is notable that the maximum total thickness of volcanics (over 1500 m) is located where the sills are thicker (inset of Fig. 5). All the investigated sills (Bellieni et al., 1984; A to S in Fig. 5) are formed by tholeiitic basalts.

Dykes of Lower Cretaceous age occur in northern and central Paraná basin, and are virtually absent in southern Paraná. Most dykes are basic and rarely acid. They have geochemical and isotope compositions very similar to those of the tholeiitic basalt flows of the northern and central Paraná (Comin-Chiaramonti et al.,1983; Piccirillo et al., 1990; unpublished data).

**The Ponta Grossa Dyke Swarm**

The Ponta Grossa arch (PG) is a tectonic swell (Figs. 1 and 2) trending NW-SE and marked by strong magnetic anomalies paralell to its axis. PG-dykes intrude Precambrian basement and Paleozoic sediments preferably in the NW direction but they also trend NE-SW following the structural anisotropies of the Precambrian crystalline basement.

K/Ar ages for PG dykes range from 114 to 144 Ma (Piccirillo et al.,1990) with a mean of 132 ± 10 Ma. These ages are similar to those of the northern Paraná flood volcanics (131 ± 9 Ma; Rocha-Campos et al., 1988). Paleomagnetic data (Raposo & Ernesto, 1989; unpublished data) suggest that PG-dykes are contemporaneous to the Chapecó acid volcanics and intercalated basic flows occurring in the central Paraná basin, and which constitute a late stage of the Paraná volcanism. To this phase are also related the sill-type intrusions occurring in the NE portion of the Paraná basin (Ernesto & Pacca, 1988).

Locally, PG-dykes may be seen cutting the Paraná flows (northern basin). Ground magnetic profiles (Ussami et al., 1991) in the interior of the Paraná basin where dykes are not exposed indicate that they may extend northwesterly towards the center of the basin, cutting the thick pile of basalt flows. This supports that dyke eplacement represents a late tectonomagmatic event following the climax of the Serra Geral volcanism.

PG-dykes range in width from about 1 to 100 m, and may be tens of kilometers in length. In general, the dykes do not display layering, marked within-dyke discontinuities, and zoning, if present, is gradational.

The dykes are represented by basic and rarely by acid rock-types. They have aphyric to porphyritic textures, and are very fine (< 0.3 mm) to medium (> 1 mm) grained. A strong grain-size variation (0.1 - 5 mm) was found in the largest (> 30 m) dykes between the outer contacts and the central part of the dykes. Coarse grained dykes however are rare, and were observed mainly in the western portions of the arch.

Most PG-dykes correspond to tholeiitic basalts, andesi-basalts and, subordinately, to latiandesites, latites, dacites and rhyolites. Basaltic dykes may be distinguished into two main groups: a dominant, high-$TiO_2$ (>2% wt.) group and a subordinate, low-$TiO_2$ (<2% wt.) group, characterized, for similar MgO content, by high and low incompatible-element contents. In terms of Sr-Nd-isotopes most PG-dykes plot in the enriched quadrant of the mantle array. Details on chemical and isotope composition of PG-dykes can be found in Piccirillo et al. (1990). According to these authors PG-dykes are, on the whole, very similar to the flood basalts of northern Paraná basin and are distinct from the basalt-types occurring in CPB and SPB. The scarse dacitic to rhyolitic rock-types in PG-dykes are similar to the acid volcanics of Chapecó type (incompatible element rich), in particular those from northern rather than central Paraná.

Paleomagnetic data indicate that PG-dykes are younger than the Paraná flood volcanics. This and the isopach map of the volcanics suggest that PG-dykes were probably feeders of volcanics erupted in northern Paraná towards the continental margin and later eroded.

**The Florianópolis Dyke Swarm**

In the southeastern part of the Santa Catarina State Mesozoic mafic dykes intrude the crystalline basement rocks, mainly the "Pedras Grandes" granitic suite as defined by Silva (1987). In the Santa Catarina Island (near the city of Florianópolis) well exposed dykes crosscut post-tectonic granites of the "Brasiliano" Cycle and trend preferably N30-60E. However, N15-45W trending dykes are also found and are seen cutting the NE dykes. Based on recent preliminary observations, it may be said that thickness varies from 0.30 to 50 m and that generally chilled margins are present in the thicker dykes. Textures are aphyric to porphyritic; the largest dykes show grain-size variation from glassy margin to medium grained center.

References in the literature on Florianopolis dykes are rare; only very recently systematic and integrated geochemical and paleomagnetic studies were initiated. No radiometric data are available for the Florianópolis dykes. Silva (1987) relates these intrusives to the Serra Geral Formation, thus attributing to them a Lower Cretaceous age. Paleomagnetic data from about ten dykes (Raposo & Ernesto, unpublished data) suggest that they may be contemporaneous to PG-dykes. The different attitudes of the Florianopolis dykes appear associated to distinct paleomagnetic polarities: the younger NW dykes were magnetized by a normal polarity geomagnetic field whereas the older NE dykes recorded reversed polarities.

Preliminary geochemical data indicate the existence of high- and low-$TiO_2$ basalt-types, as found for the mafic dykes of the Ponta Grossa arch. Florianopolis and PG-dykes show chemical similarity with the Lower Cretaceous "regional dolerites" from Namibia (125-130 Ma; Duncan et al., 1991) and mafic dykes from southern Angola (Alberti & Piccirillo, unpublished data).

## GEOPHYSICAL STUDIES OF THE PARANÁ IGNEOUS PROVINCE

### Gravity Data

In the gravity map for southern Brazil, published by Ussami et al. (1990) (Fig. 6), the most prominent features are the steep anomaly gradients which surround the Paraná basin. The northeastern linear gravity feature, which trends N42W is characterized by a southwesterly positive gradient of 1.0 mGal $km^{-1}$ and is situated along the boundary between the southwestern São Francisco craton and the Paraná basin. Several interpretations are proposed to explain this linear gravity feature such as an ancient cryptic suture zone separating two cratonic blocks with different densities and thicknesses of the crust (Lesquer et al., 1981) or a variation in crustal thickness from a thicker São Francisco craton to a thinner crust under Paraná basin (Shiraiwa, 1985; Santero et al., 1988).

Within the Paraná basin (Fig. 7), Bouguer gravity values are generally higher (-100 to -50 mGal) relative to São Francisco craton gravity anomalies (-149 to -90 mGal). The most dominant gravity feature within Paraná basin is a sequence of NNE-SSW trending gravity highs localized over along the Paraná river.

The gravity high (about 30-40 mGal of amplitude) approximately coincides with the trend of maximum depth of the basement and thickness of basalts. On both sides of the central gravity high, a sequence of short wavelength negative anomalies might be caused by a thicker sequence of low density sediments overlain by a gradually thinner basaltic layer.

The northern Paraná basin data were interpreted by Molina et al. (1988). This study shows that the main source of the gravity high in the center of the northern Paraná basin cannot be entirely produced by near gravity sources (e.g. sediments and basalts). Therefore, the source of the gravity high might be deep seated.

An Airy model of isostatic compensation at a single depth (Moho) and single density variation would predict the free-air anomaly over the basin average zero. This does not occur in the Paraná basin, as shown in Figure 8. An alternative model of compensation for the observed topography (Fig. 8) could be a crust intruded with basalt material during the volcanism which affected the Paraná basin. The intrusion of high density material might have reached higher levels under and along the axis of the basin (Paraná river). An increase of 0.70 g $cm^{-3}$ in the lower-mid crust density would require approximately 15 km of the crust intruded with basalt material (e.g. sill-type intrusions) in order to explain both the observed Bouguer and free-air anomalies.

The main implication of this model is that no Moho uplift (or crustal thinning) is required to explain the gravity high. On the contrary, this result strongly suggests that the crust under the Paraná basin was underplated by mantle derived material. Further compelling evidence that underplating of the crust might have occurred is given by the history of subsidence of the Paraná basin during and after the volcanic event. In spite of a large thermal anomaly which was present under the basin, no significant thermal subsidence has been observed. One way of hampering further thermal sudsidence after extension is to increase the crustal volume by addition of material at the base and into the crust. This mechanism has already been suggested by McKenzie (1984) to explain epeirogenic uplift.

A preliminary analysis of the Bouguer anomaly map of the southern Paraná basin indicates that the latter overlies a distinct gravity province. Gravity modelling of profile B-B' (Fig. 6) suggests that the crust under the southeastern Paraná basin thinned by at least 5 km relative to the north-central part of the basin. This implies that the region where crust has been thinned, extension and consequently the thermal regime might have been more severe and reached higher levels in the crust. According to Piccirillo et al. (1988c), this could explain the occurrence of the majority of acid volcanics in this region. Another prominent gravity high trending NNW (Figs. 6 and 7) occurs over the Ponta Grossa ($50^0$W $25^0$S), an important site of mafic dyke swarms (Ussami et al., 1990).

**Paleomagnetism: Magnetostratigraphy and Paleopoles**

The magnetic stratigraphy of several volcanic sequences of the Serra Geral Formation (Fig. 9) was set up by Ernesto & Pacca (1988) and Ernesto et al. (1990). In the southern Paraná basin (Fig. 9) the roads cut the steep southeastern fringes of the volcanic plateau and espose up to 1000 m of lava, starting at the pre-volcanic Botucatu sandstones. Paleomagnetic results for ten of these sequences (Figs. 10 and 11) reveal that the accumulation of about thirty magma flows could be fast enough to occur within only two polarity intervals and give a smooth paleomagnetic record, as in the sequence GB(10). However, in other sequences eruptions were sporadic and less than twenty flows - e.g. sequence PH(5) - comprised up to six polarity intervals. In spite of the great number of recorded geomagnetic reversals within one sequence, the elapsed time is probably less than one million year, since most of the polarity intervals during Lower Cretaceous were of short duration and some of which are below the limit of detectability for the sea-floor anomalies (considering that the Mesozoic reversal scale is mainly based on sea-floor anomalies). Furthermore the polarity inversion itself is very fast and was rarely recorded by the Serra Geral flows.

In Figs. 9 and 10, the magnetic signature (changes in declination and inclination) in the southern Serra Geral flow sequences is used to tentatively correlate the sequences. Magnetic data are plotted against elevation, which allows account to be taken of possible missing flows in each sequence, which could not be sampled or did not give good results. By means of some characteristic features which are common in two or more sequences, a time relationship of the sequences is proposed. It is interesting to note that although parts of two or more sequences seem to be formed at the same time, flows are not likely to be the same even in sequences that are as close as 30 km - for instance, sequences CV(4) and PH(5), because rock-types are frequently different.

In CPB and NPB the exposed sequences are not so thick as in SPB and display three polarity horizons at most. The most striking feature in CPB is that the Chapecó acid flows which occur on the top of some sequences, are all of normal polarity. On the contrary, in NPB (Fartura region) the Chapecó flows are of reversed polarity and the same happens to the rare Chapecó acid dykes in the Ponta Grossa Arch (Raposo & Ernesto, unpublished data). Basic PG-dykes exhibit both normal and reversed polarities.

The available paleomagnetic poles (Ernesto & Pacca, 1988; Raposo & Ernesto, 1989) for the Paraná basin magmatic rocks are plotted in Fig. 12. It is clearly seen in this figure that most of the poles (excepting poles CH = Chapecó acid flows from CPB, PB = basic flow sequence from CPB, PG = Ponta Grossa dykes, SL = sills from NPB) form a tight group indicating that the majority of the volcanic activity inside the Paraná basin took place in a very short time interval. The mean age for this pole group is considered to be 135 Ma, based on the numerous radiometric ages existing in the literature (Rocha-Campos et al., 1988). The remaining poles (CH, PB, PG and SL) form a minor group displaced from the previous one towards younger ages when compared to an apparent polar path for South America is considered. Based on the radiometric data obtained for the PG dykes (Piccirillo et al., 1990) the age attiributed to this group of poles is 132 Ma and characterize a slightly younger phase or a "late stage" of the magmatic activity in the Paraná basin. It is interesting to note that the Chapecó flows from NPB are distinct from those from CPB respecting their reversed polarity magnetizations and the corresponding pole do not seem to match this younger pole group.

## FINAL REMARKS

### Petrogenetic Outlines

Following Piccirillo et al. (1988c, 1989), chemical variations, Sr- and Nd-isotope ratios and melting models suggest that the important chemical differences between the Paraná basalt types can be the result of variable melting degrees of different mantle source materials. Low-$TiO_2$ basalts would be related to relatively high melting degree (e.g. 20-30%) of a mantle source with low Sr- (0.704) and high Nd-isotope (0.5128) ratios, while high-$TiO_2$ basalts from northern Paraná would be the result of relatively low melting degree (e.g. 5-10%) of a mantle source with comparatively high Sr (0.705-0.706) and low Nd-isotope (0.5125-0.5123) ratios. Moreover, the mantle source in northern Paraná would be characterized by higher contents of incompatible elements relative to those of southern mantle source (Petrini et al.,1987; Cordani et al., 1988; Piccirillo et al.,1989).

The genesis of the *low- and high-$TiO_2$ Paraná basalts* implies that melting degree decreases from south to north. Such a model is consistent with the existence of a "transitional" region (central Paraná) where low- and high-$TiO_2$ basalts are closely associated, and a large quantity of the latter have $TiO_2$ between 2 and 3 wt%. Thus the boundary between northern and southern Paraná regions may be interpreted as a surface expression of basalt types related to variable melting degree of heterogeneous mantle.

*Paraná acid melts* are characterized by high (c. 1000 $^{o}C$) eruption temperatures, and can be related to "anhydrous" melting (10-20%) of basic material corresponding in composition to low- or high-$TiO_2$ (generating Palmas or Chapecó, respectively), or mafic/intermediate granulites with distinct and appropriate compositions. Chapecó acid melts have initial Sr-isotope ratios ($R_o$) similar to those of the associated high-$TiO_2$ basalts ($R_o$= 0.705-0.706), while Palmas acid melts have distinctly higher $R_o$ values (0.714-0.728, mean 0.720). If Palmas acid melts derived by melting of intermediate granulites (Ro c. 0.714) their high Sr-isotope ratios (up to 0.728) require crustal contamination.

**Significance of the Paraná Magmatism in the Contex of the Gondwanaland Break-up**

The Mesozoic magmatism in South American platform is concentrated towards the continental margin (Almeida, 1986) suggesting a close relation with the Jurassic-Cretaceous break-up of the Gondwanaland. The most important Mesozoic igneous activity attending the South Atlantic ocean opening developed in the Paraná basin. Low-$TiO_2$ Paraná basalts appear related to a melting degree distinctly higher than that estimated for high-$TiO_2$ basalts, indicating that the thermal anomaly was in general more intense in southern Paraná. This can explain why the great majority of the acid volcanics are found in southern Paraná, considering that the acid magmas are partial melts of continental crust (underplated basalts and/or basic-intermediate granulites). Moreover the confinement of the acid volcanics towards the continental margin indicates that their production was probably associated to early stages of major rifting processes responsible for initial crustal thinning.

The available data on the Paraná magmatism indicate:

(1) the onset of the flood volcanism predates the opening of the South Atlantic ocean;

(2) a north-eastern migration of the flood volcanism;

(3) a late stage emplacement of dykes and other intrusives of NE Paraná;

(4) the major rifting processes occurred after the eruptions of the voluminous acid volcanics;

(5) the existence of common geochemical characteristics and geographic location at pre-drift reconstruction between the Lower Cretaceous Paraná volcanics and intrusives and those coeval from Namibia and Angola;

(6) the South America-Africa continental separation started in southern Paraná and propagated northwards;

(7) the distribution of the low- and high-$TiO_2$ Mesozoic magmatic suites in Gondwanaland suggests a large scale mantle heterogeity and basalt production probably occurred in lithospheric mantle.

**REFERENCES**

ALMEIDA, F.F.M. (1976) An.Acad.brasil.Ci., **48**:15-26.

ALMEIDA, F.F.M. (1986) Rev.Bras.Geoc., **16**:325-349.

BELLIENI, B.; COMIN-CHIARAMONTI, P.; MARQUES, L.S.; MELFI, A.J.; PICCIRILLO, E.M.; STOLFA, D. (1984) TMPM, **33**:25-47.

BELLIENI, G.; COMIN-CHIARAMONTI, P.; MARQUES, L.S.; MELFI, A.J.; NARDY, A.J.R.; PAPATRECHAS, C.; PICCIRILLO, E.M.; ROISENBERG, A.; STOLFA, D. (1986) J.Petrology, **27**:915-944.

BREVILLE, G.L.; BEIERLE, C.W.; SANDERS, J.R.; VOSS, J.T.; WILCOX, L.E. (1973) DMAAC Technical paper n. 73-2, St. Louis, Missouri, 1:10000000 scale map.

COMIN-CHIARAMONTI, P.; GOMES, C.B.; PICCIRILLO, E.M.; RIVALENTI, G. (1983) Neues Jahr.Miner.Abh., **146**: 133-150.

CORDANI, U.G.; NEVES, B.B.B.; FUCK, R.A.; PORTO, R.; THOMAZ FILHO, A.; CUNHA, F.M.B. (1984) Petrobrás/Cenpes/S: :ep, Ciênc.Tec.Petróleo, Sec.Expl.Petróleo.

CORDANI, U.G.; CIVETTA,,L.; MANTOVANI, M.S.M.; PETRINI, R.; KAWASHITA, K.; HAWKESWORTH, C.J.; TAYLOR, P.; LONGINELLI, A.; CAVAZZINI, G.; PICCIRILLO, E.M. (1988) In: E.M.Piccirillo & A.J.Melfi (eds.) The Mesozoic flodd volcanism of the Paraná basin: petrogenetic and geophysical aspects. Instituto Astronómico e Geofísico, São Paulo University (Brazil), 157-178.

DUNCAN, A.R.; ARMSTRONG, R.A.; ERLANK, A.J.; MARSH, J.S.; WATKINS,R.T. (1991) In: A.J.Parker; P.C.Rickwood; D.H.Tucker (eds), Mafic Dykes and Emplacement Mechanism, Balkema, Rotterdam (Netherlands), 119-129.

ERNESTO, M. & PACCA, I.G. (1988) In: E.M. Piccirillo & A.J. Melfi (eds.), The Mesozoic fllod volcanism from the Paraná basin (Brazil): petrogenetic and geophysical aspects. Instituto Astronômico e Geofísico, São Paulo University (Brazil), 229-255.

ERNESTO, M.; PACCA, I.G.; HIODO, F.Y.; NARDY, A.J.R. (1990) PEPI, **64**:153-175.

FERREIRA, F.J.F. (1982) Master thesis, São Paulo University (Brazil).

FULFARO, V.J.; SAAD, A.R.; SANTOS, M.V.; VIANNA, R.B. (1982) Rev.Bras.Geoc., **12**:560-611.

LESQUER, A.; ALMEIDA, F.F.M.; DAVINO, A.; LACHAUD, J.C.; MAILLARD, P. (1981) Tectonophysics, **76**:273-293.

McKENZIE, D.P. (1984) Nature, **307**:616-618.

MOLINA, E.C.; USSAMI, N.; BLITZKOW, D.; MIRANDA FILHO, O.F. (1988) In: E.M.Piccirillo & A.J.Melfi (eds.), The Mesozoic flood volcanism from the Paraná basin: petrogenetic and geoph.sical aspects. Instituto Astronômico e Geofísico, São Paulo University (Brazil), 271-283.

PETRINI, R.; CIVETTA, L; PICCIRILLO, E.M.; BELLIENI, G.; COMIN-CHIARAMONTI, P.; MARQUES, L.S.; MELFI, A.J. (1987) J.Petrology, **28**:701-726.

PICCIRILLO, E.M.; MELFI, A.J.; COMIN-CHIARAMONTI, P.; BELLIENI, G.; ERNESTO, M.; MARQUES, L.S.; NARDY, A.J.R.; PACCA, I.G.; ROISENBERG, A.; STOFA, D. (1988a) In: J.D. Mcdougall (ed.), Continental Flood Basalts, Kluver Academic Publ., 195-238.

PICCIRILLO, E.M.; COMIN-CHIARAMONTI, P.; MELFI, A.J.; STOLFA, D.; BELLIENI, G.; GIARETTA, A.; MARQUES, L.S.; NARDY, A.J.R.; PINESE, J.P.P.; RAPOSO, M.I.B.; ROISENBERG, A. (1988b) In: E.M.Piccirillo & A.J.Melfi (eds.) The Mesozoic flood volcanism of the Paraná basin: petrogenetic and geophysical aspects. Instituto Astronômico e Geofísico, São Paulo University (Brazil), 107-156.

PICCIRILLO, E.M., Comin-Chiaramonti, P., Bellieni, G., Civetta, L, Marques, L.S., Melfi, A.J., Petrini, R., Raposo, M.I.B. and Stolfa, D., 1988c. In: E.M.Piccirillo & A.J.Melfi (eds.) The Mesozoic flood volcanism of the Paraná basin: petrogenetic and geophysical aspects. Instituto Astronômico e Geofísico, São Paulo University (Brazil), 179-205.

PICCIRILLO, E.M.; CIVETTA, L; PETRINI, R.; LONGINELLI, A.; BELLIENI, G.; COMIN-CHIARAMONTI, P.; MARQUES, L.S.; MELFI, A.J. (1989) Chem.Geol., **75**:103-122.

PICCIRILLO, E.M.; BELLIENI. G.; CAVAZZINI, G.; COMIN-CHIARAMONTI, P.; PETRINI, R.; MELFI, A.J.; PINESE, J.P.P.; ZANTEDESCHI, P.; De MIN, A. (1990) Chem.Geol., **89**:19-48.

RAPOSO, M.I.B. & ERNESTO, M. (1989) Rev.Brasil.Geoc., **19**:393-400.

ROCHA-CAMPOS, A.C.; CORDANI, U.G.; KAWASHITA, K.; SONOKI, H.M.; SONOKI, I.K. (1988) In: E.M.Piccirillo & A.J.Melfi (eds.) The Mesozoic flood volcanism of the Paraná basin: petrogenetic and geophysical aspects. Instituto Astronômico e Geofísico, São Paulo University (Brazil), 25-45.

SANTERO, O.; ZADRO, M.; BLITZKOW, D.; SÁ, N.C. (1988) In: E.M.Piccirillo & A.J.Melfi (eds.) The Mesozoic flood volcanism of the Paraná basin: petrogenetic and geophysical aspects. Instituto Astronômico e Geofísico, São Paulo University (Brazil), 257-269.

SHIRAIWA, SD. (1985) Master thesis, São Paulo University (Brazil).

SILVA, L.C. (1987) In: Mapa Geológico de Santa Catarina, escala 1:500000; Texto explicativo. DNPM/CPRM.

ULBRICH, H.H.G.J. & GOMES, C.B. (1981) Earth Sci.Rev., **17**:135-154.

USSAMI, N.; MOLINA, E.C.; SÁ, N.C. (1990) Proceedings of Southern American Gravity Project Meeting, Quito, December.

# STOP DESCRIPTIONS

## DAILY ROUTES

October 3: Departure at 7:30
São Paulo - Piraju - Ourinhos (420 km)
Night in Ourinhos (Pousada Ourinhos Hotel)

October 4: Departure at 7:30
Ourinhos - Londrina - Ortigueira - Ponta Grossa (525 km)
Night in Ponta Grossa (Vila Velha Palace Hotel)

October 5: Departure at 7:30
Ponta Grossa - Curitiba - Florianópolis (425 km)
Night in Florianópolis (Cris Hotel)

October 6 : Departure at 7:30
Florianópolis - Praia Grande - Itaimbezinho - Torres (375 km)
Night in Torres (Farol Hotel)

October 7: Departure at 7:30
Torres - Porto Alegre - Pelotas (476 km)
Night in Pelotas

October 8: Departure at 7:30
Pelotas - Jaguarão - Uruguay border (148 km)
Beginning of Excursion Part II: Pre-Cambrian Dykes

## OCTOBER 3

### STOP 1 - Piraju town, on the Piraju river side

Outcrops of Chapecó acid flows. On the road to Ourinhos, starting at the Hotel Beira-Rio, six flows with total thickness of about 75 m crop out. The rocks present a redish colour due to weathering. They are vesicular and show baked inclusions and "dykes" of Botucatu sandstones.

### STOP 2 - Road from Piraju to Fartura, 10 km south of Piraju

On the way to this point it can be seen a basic flow cropping out on the left (when we just take the road) followed by outcrops of Botucatu and Pirambóia sandstones sometimes cut by thin weathered dykes. At this stop we see a fine-grained columnar basalt forming a sill-type superficial intrusion. It is crosscut by a thin weathered acid dyke showing plagioclase phenocrysts (Chapecó type) and trending c. N-S.

### STOP 3 - Road from Piraju to Fartura, 17 km south of Piraju, at the border between Sarutaiá and Fartura towns

Chapecó-type acid flow crosscut by a thin N20E basic dyke which is seen close to the water source on the left. On the lower part of the outcrop, the Botucatu sandstones with their characteristic crossed stratifications are overlain by the Chapecó flow. The outcrop is strongly weathered but represents one of the few points where basic dykes cutting the Paraná acid flows can be observed.

### STOP 4 - Road from Piraju to Fartura, 20 km from Piraju

The road cuts some dykes mainly of acid type. At this stop a Chapecó dyke is cropping out. Its contacts are not visible but sandstones are seen on the hills on both sides of the outcrop and mark the limits of the dyke. Its apparent thickness is about 75 m but since grain-size does not vary significantly it is possible that the road cut is along the dyke length. Anisotropy of magnetic susceptibility (AMS) data indicate a magma flow in the N20E direction, which would also correspond to the dyke direction. Like the Chapecó flows in the Piraju area, this Chapecó dyke has a reversed polarity magnetization.

### STOP 5 - Road from Piraju to Fartura, 21 km from Piraju

The road is cutting a basic dyke intruding sediments. The dyke is cropping out at the road bend and its continuation is seen on the left through a sequence of aligned small hills trending nearly N-S. A baked contact can be observed in the upper part of the outcrop. This dyke produces an abnormally high magnetic peak ($3 \times 10^3$ nT) in ground-magnetometry measurements. Its normal remanence is also strong ($M = 139 \times 10^{-4}$ nT) but the calculated Koenigsberger ratio ($Q = 12\text{-}21$) does not account for the observed peak.

## OCTOBER 4

**STOP 6** - Federal highway BR 376 from Londrina to Ponta Grossa, 16 km north of Ortigueira; altitude= 1030 m.

Departing from Ourinhos we will drive about 250 km to get to this stop. During the way good exposures of basic Serra Geral lavas, as well as the underlying Botucatu sandstones can be observed. The whole pre-volcanic sedimentary sequence, from the top (Mesozoic Botucatu sandstone) to the bottom (Devonian Furnas sandstones), will be crossed from Londrina to Ponta Grossa. These sediments are crosscut by thick basic dykes.

The dyke we are observing at stop 6 does not show clearly its contacts: on the upper part of the outcrop (on the left), blocks of the country rocks suggest a near contact but the dyke is coarse-grained. On the right side of the road, the other contact is better indicated by the presence of sediments. The inferred direction is N70E and the AMS data indicate that the lava flux was in the N86E direction following an horizontal plane.

**STOP 7** - Federal highway BR 376 from Londrina to Ponta Grossa, 14 km from stop 6; altitude = 1000 m.

Basic dyke striking N20W. One of the contacts is marked by sandstone blocks on the ground. This dyke is normally magnetized in contrast with the dyke of stop 6 (reversed polarity); flux direction is horizontal.

**STOP 8** - Federal highway BR 376 from Londrina to Ponta Grossa, 2 km south of the access to Ortigueira; altitude = 880 m.

Basic dyke subparallel to the road; cooling fracture pattern is normal to the road. The rock is coarse-grained through all the outcrop. AMS indicate that the fracture was fed by an inclined ($I = 60^0$) flux of magma striking N74W.

## OCTOBER 5

**STOP 9** - Federal highway BR 376 from Ponta Grossa to Curitiba; Vila Velha carved sediments.

Carboniferous remnant sediments of the Itararé Subgroup are seen on the top of the hills forming sculptures carved by erosion processes.

**STOP 10** - Federal highway BR 376 from Curitiba to Joinville, 5 km south of the access to Tijucas do Sul.

Basic dykes cutting the gneissic rocks of the Pre-Cambrian basement. Three sub-paralell N30E trending dykes are exposed in this road cut. The dyke appearing on the right side (lower part of the outcrop) is the thickest one although its contacts are not well preserved. The second and thinner dyke is at about 100 m to the left and exhibits phenocrysts of plagioclase. The third dyke is fine-grained and outcrops at c. 30 m left from the second dyke.

## OCTOBER 6

**Stop 11** - Joaquina beach, Florianópolis.

Two sets of crosscutting basic dykes are seen at this stop. The dykes are beautifully exposed and intrude the pink post-tectonic granites of the "Brasiliano " cycle. The older set is formed by thicker (5-20 m) dykes trending N15-25E with chilled margins. The younger dykes strike N15-45W, are thinner (0.5 m - 2m) and show phenocrysts of plagioclase. Reversed and normal magnetizations characterize the older and younger dyke sets, respectively.

**STOP 12** - Pedrita quarry, km 6 of the Rio Tavares road, Florianópolis.

Three subparalell NE-trending dykes cut the granite basement rocks. They are thick (up to 50 m) and may correspond to the NE dykes seen in the Joaquina beach or are parallel to those dykes.

**STOP 13** - Road from Praia Grande to Cambará do Sul, 13 km from Praia Grande; altitude = 820 m.

This road crosses the eastern flank of the volcanic Serra Geral plateau which is deeply cut by tectonic-erosional processes exposing the basaltic sequence with the rhyolitic cover. The basaltic sequence (750 m) comprises about 90% of the total volcanic "package". Thin rhyolitic intercalations are present in the mid-upper part (540-570 m) of the basaltic sequence.

At 810 m of altitude the upper amygdaloidal part of the basic lava-flow is observed with cavities filled with zeolites and quartz. Rhyodacitic and rhyolitic rocks (Palmas type) of light gray colour rest on the basaltic flows. About 200 m of acid rocks compose the upper part of the volcanic sequence in this place.

**STOP 14** - Road RS-23, from São Francisco de Paula to Cambará do Sul, Itaimbezinho canyon; altitude = 930 m.

In the eastern border of the volcanic plateau a series of canyons are found, of which

Itaimbezinho and Fortaleza are the most important. These geomorphological features are formed by erosional processes, along tectonic lines easily recognizable.

In Itaimbezinho the canyon is about 600m deep and the vertical walls exhibit the volcanic pile observed in the section Praia Grande to Cambará do Sul. In the upper part levels of obsidian are observed. The rhyolitic cover of the plateau reaches a thickness of nearly 110 m.

## OCTOBER 7

**STOP 15** - Torres town, Guarita beach.

This is the farthest occurrence of basic lava-flows in the eastern part of the Paraná basin. It is formed by two main cliffs nearly 30 m high close to the Atlantic ocean. These flows rest on the Botucatu Formation. At this place the Botucatu sub-arkosic sandstones exhibit cross-bedding of large size, representing well preserved and consolidated paleo-dunes.PP12

Looking eastwards one can envisage the Torres-Walvis volcanic ridge connecting South America and Africa !!!

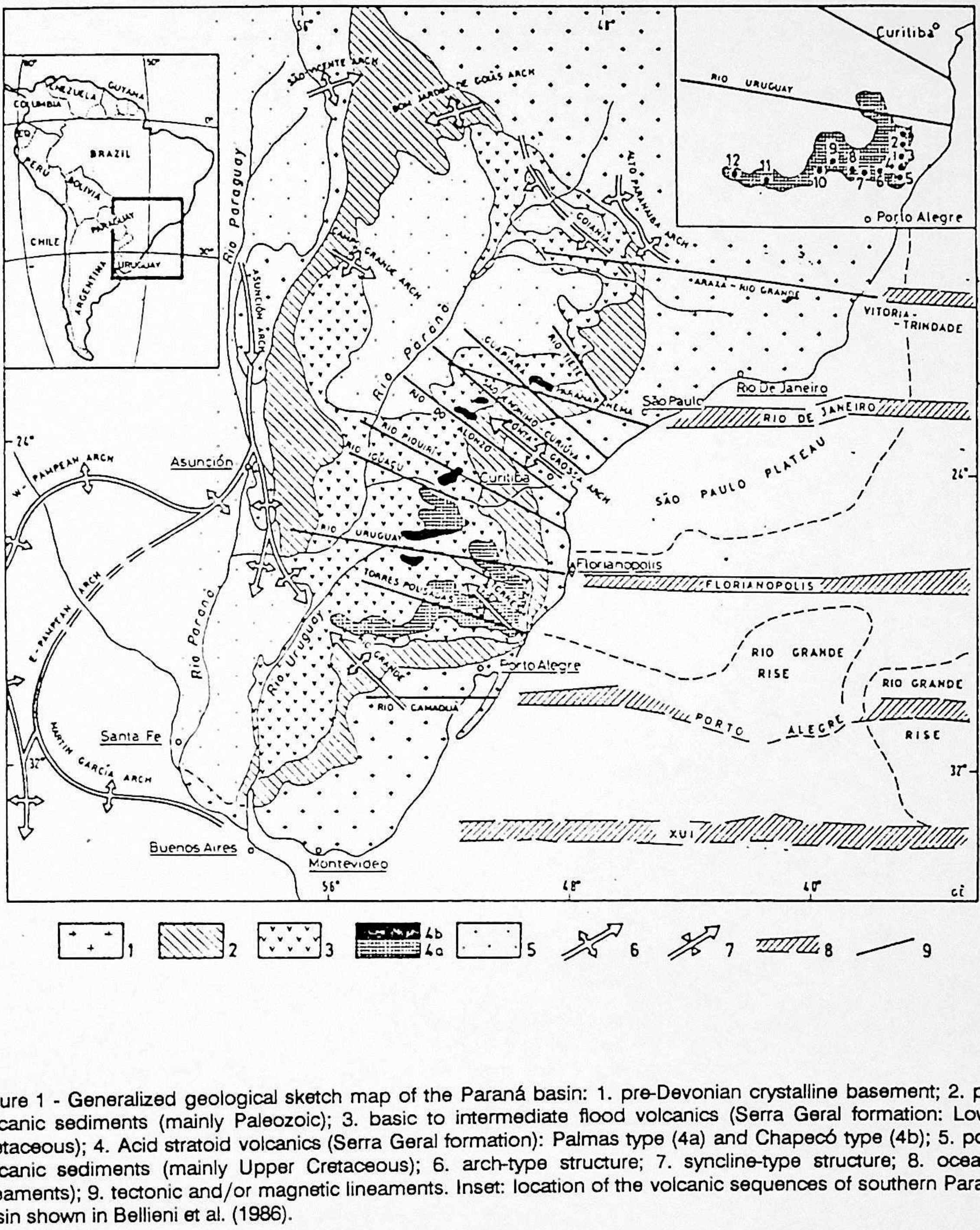

Figure 1 - Generalized geological sketch map of the Paraná basin: 1. pre-Devonian crystalline basement; 2. pre-volcanic sediments (mainly Paleozoic); 3. basic to intermediate flood volcanics (Serra Geral formation: Lower Cretaceous); 4. Acid stratoid volcanics (Serra Geral formation): Palmas type (4a) and Chapecó type (4b); 5. post-volcanic sediments (mainly Upper Cretaceous); 6. arch-type structure; 7. syncline-type structure; 8. oceanic lineaments); 9. tectonic and/or magnetic lineaments. Inset: location of the volcanic sequences of southern Paraná basin shown in Bellieni et al. (1986).

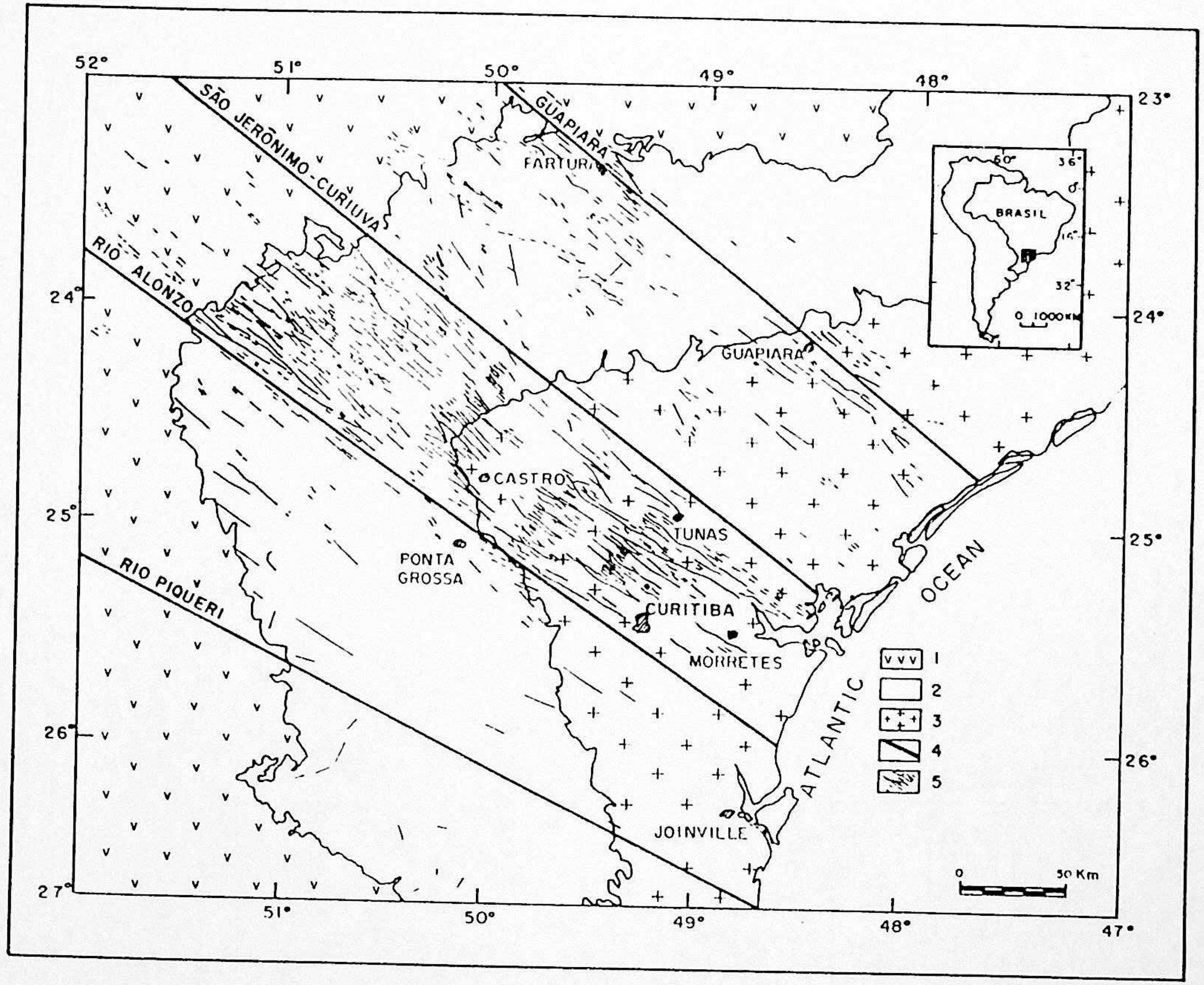


Figure 2 - Dyke swarm of the Ponta Grossa arch. 1. volcanics of the Serra Geral formation (Lower Cretaceous); 2. pre-volcanic sedimentary rocks (mainly Paleozoic); 3. crystalline basement (Pre-Cambrian); 4. tectonic and/or magnetic lineaments, and 5. dykes and/or remote-sensing lineaments.

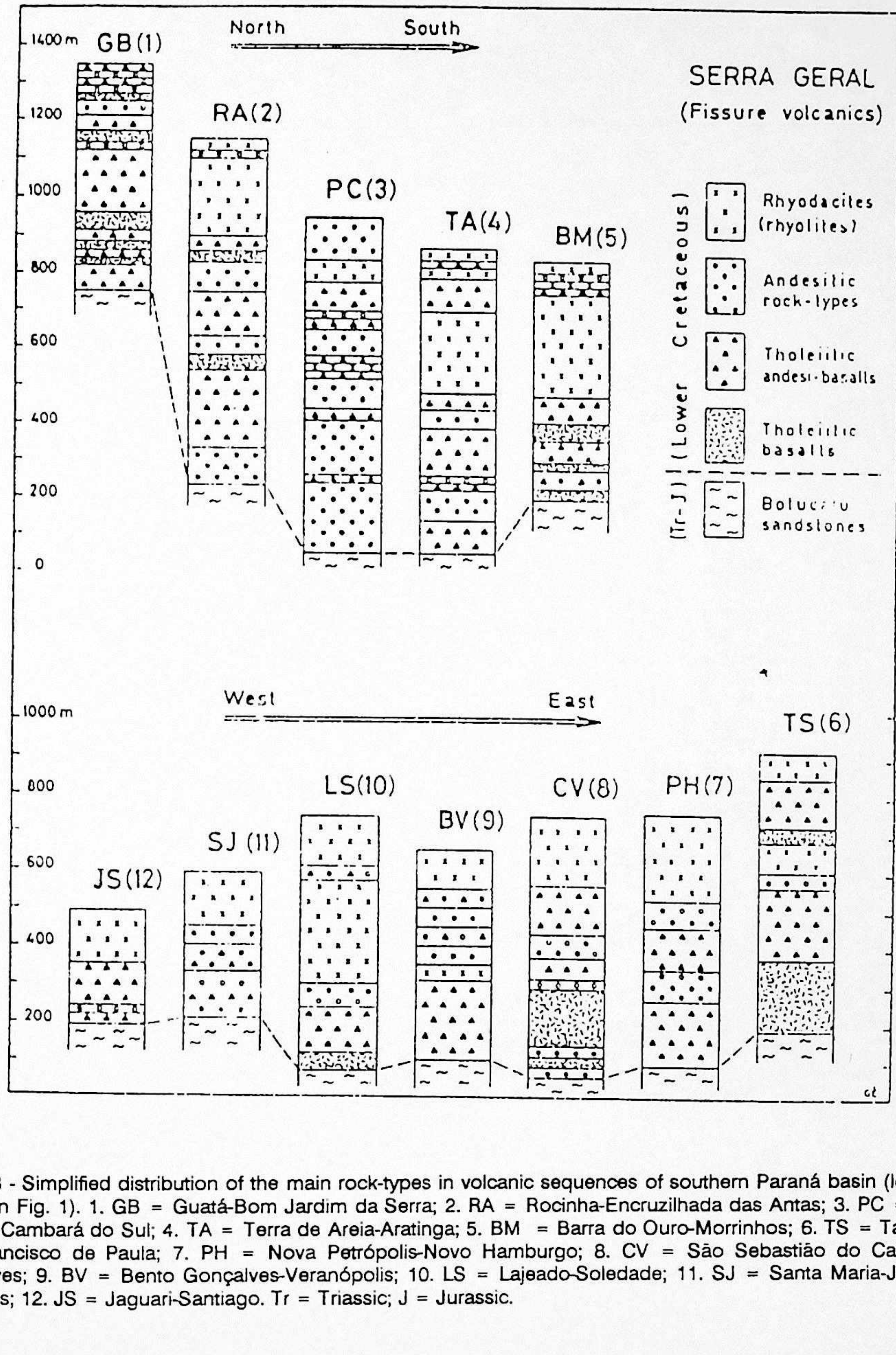


Figure 3 - Simplified distribution of the main rock-types in volcanic sequences of southern Paraná basin (location shown in Fig. 1). 1. GB = Guatá-Bom Jardim da Serra; 2. RA = Rocinha-Encruzilhada das Antas; 3. PC = Praia Grande-Cambará do Sul; 4. TA = Terra de Areia-Aratinga; 5. BM = Barra do Ouro-Morrinhos; 6. TS = Taquara-São Francisco de Paula; 7. PH = Nova Petrópolis-Novo Hamburgo; 8. CV = São Sebastião do Caí-Bento Gonçalves; 9. BV = Bento Gonçalves-Veranópolis; 10. LS = Lajeado-Soledade; 11. SJ = Santa Maria-Júlio de Castilhos; 12. JS = Jaguari-Santiago. Tr = Triassic; J = Jurassic.

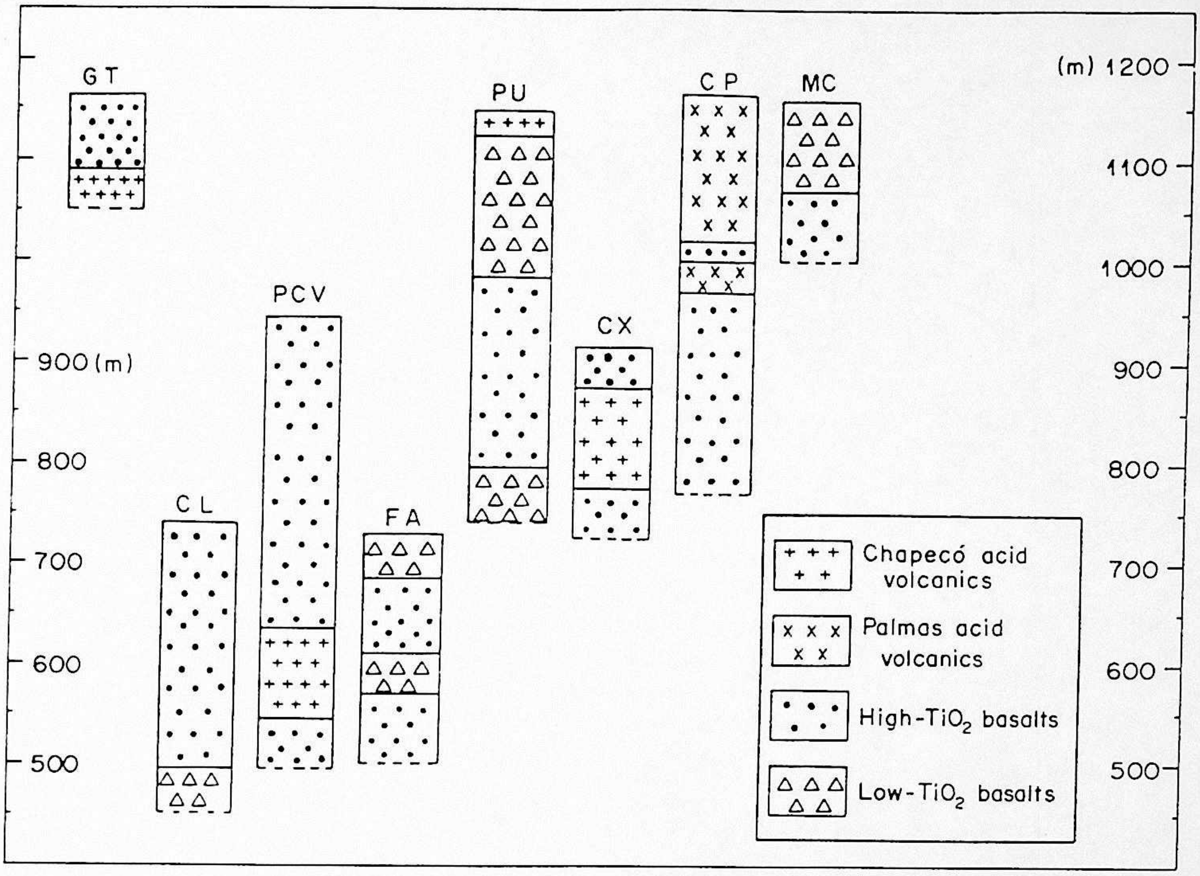


Figure 4. Simplified distribution of the main rock-types in volcanic sequences of central Paraná basin (latitude: 25-27°S; longitude: 51-53°W). GT = Guarapuava-Turvo; CL = Chopinzinho-Laranjeiras do Sul; PCV = Três Pinheiros- Coronel Vivida; FA = Foz do Areia borehole; PU = Três Pinheiros-Rio Iguaçu; CX = Clevelândia-Xanxerê; CP = Clevelândia-Palmas; MC = Matos Costa-Caçador.

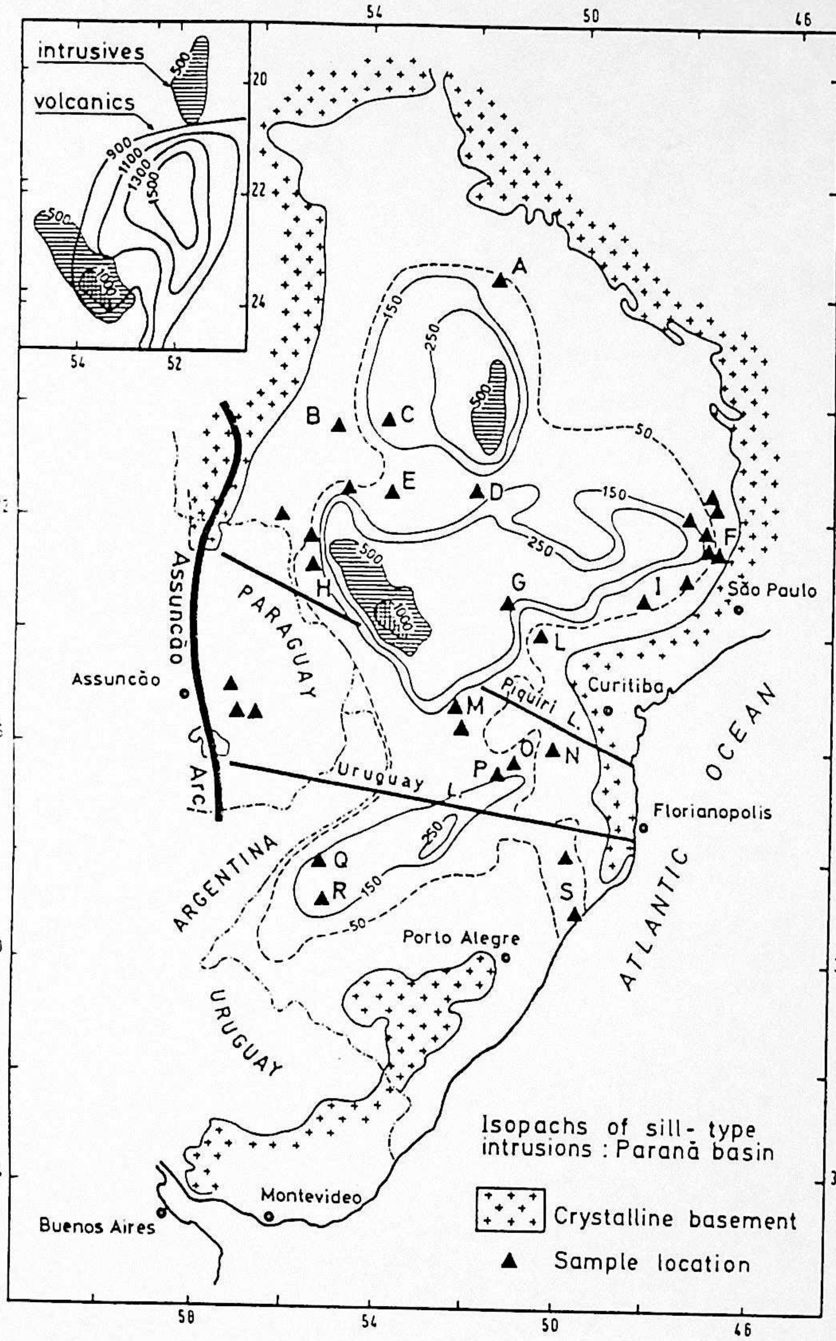


Figure 5. Isopachs (total thickness) of sill-type intrusions in the Brazilian territory of the Paraná basin. Inset: relationships between the maximun total thickness of intrusives and that of the volcanics. A-S = studied sills (Bellieni et al., 1984).

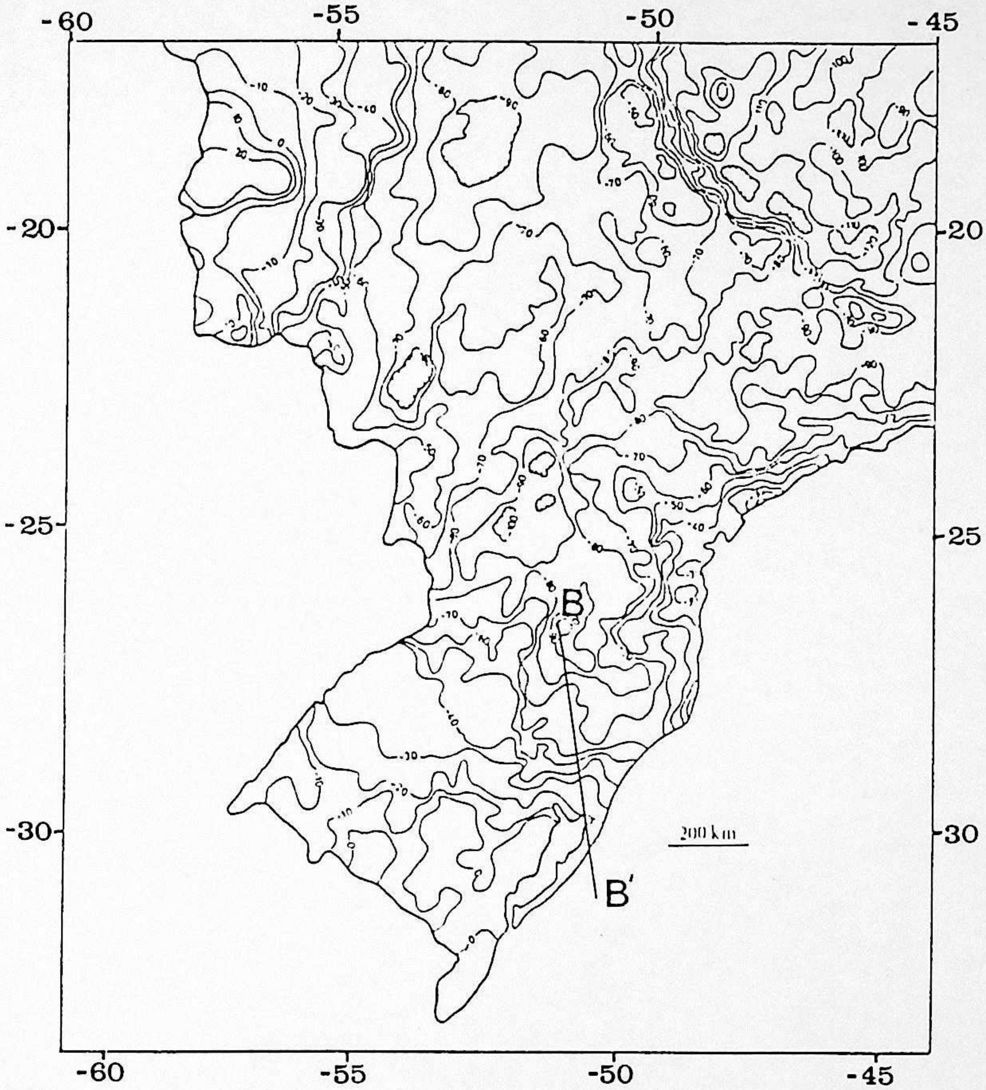


Figure 6 - Bouguer anomaly map of Paraná basin. Latitude correction GRS 67 and 2.67 g.cm$^{-3}$ Bouguer density. Contour interval 10 mgal. After Ussami et al. (1990).

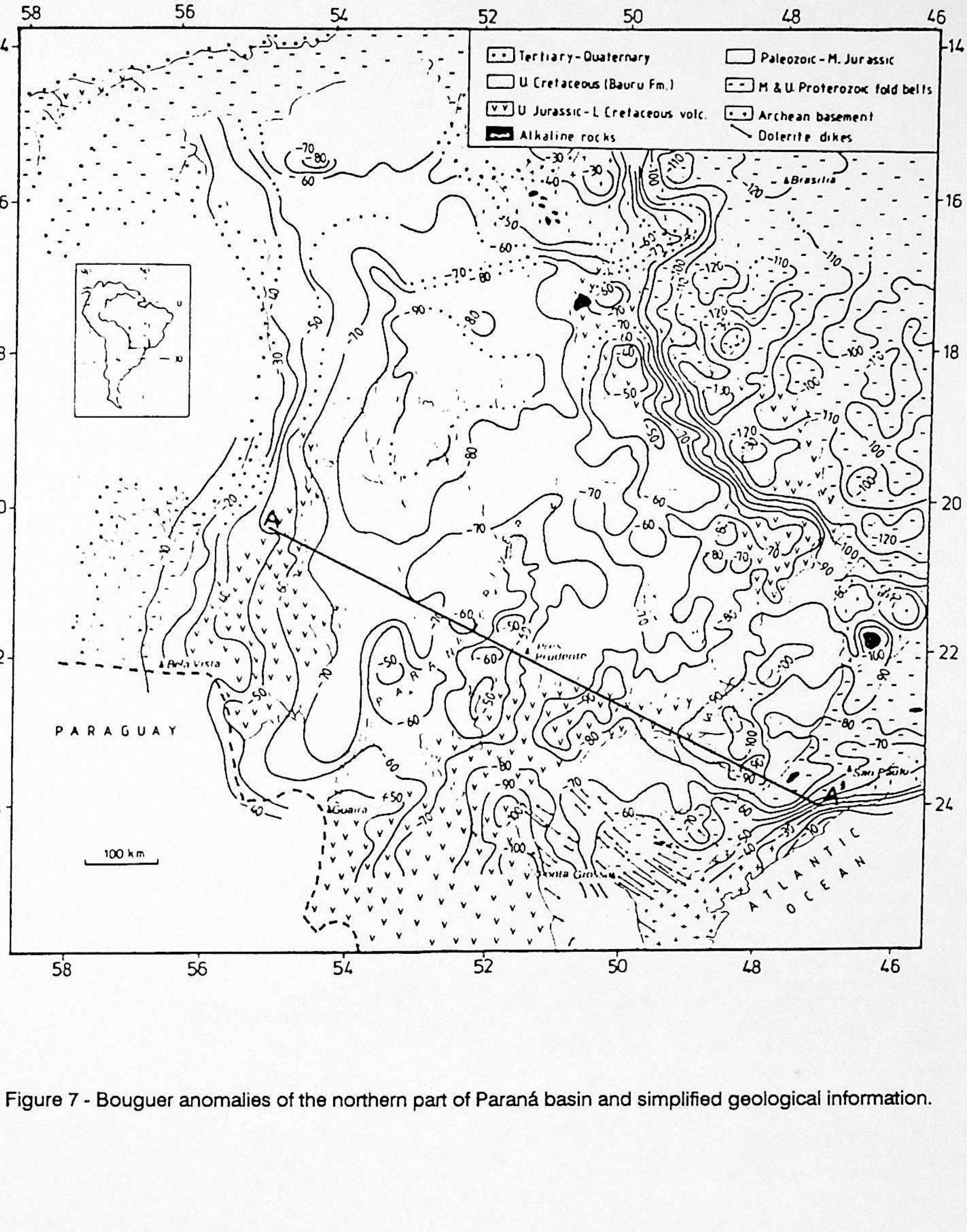


Figure 7 - Bouguer anomalies of the northern part of Paraná basin and simplified geological information.

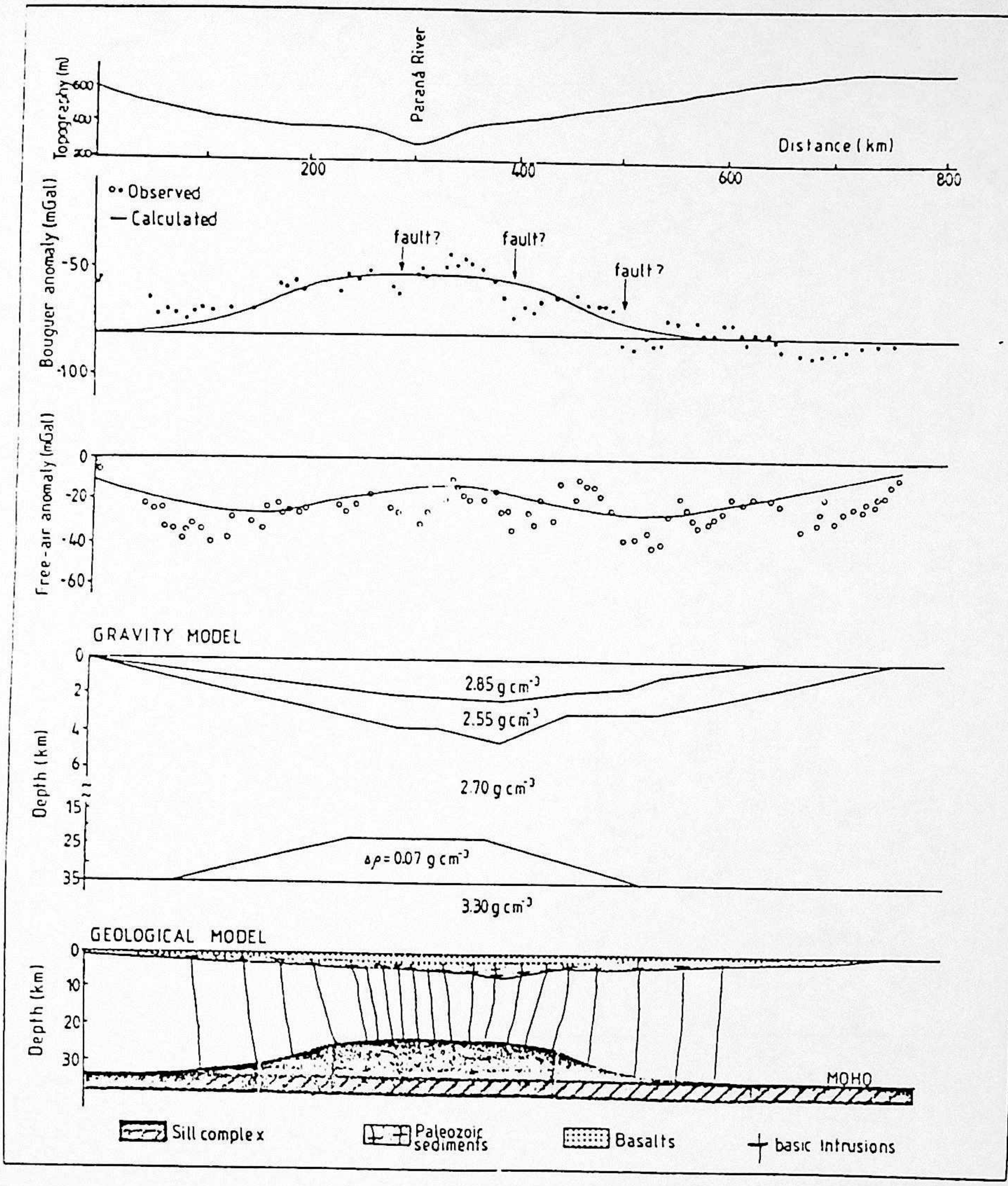


Figure 8 - Gravity and geological models under the northern Paraná basin, along profile A-A' of Figure 7.

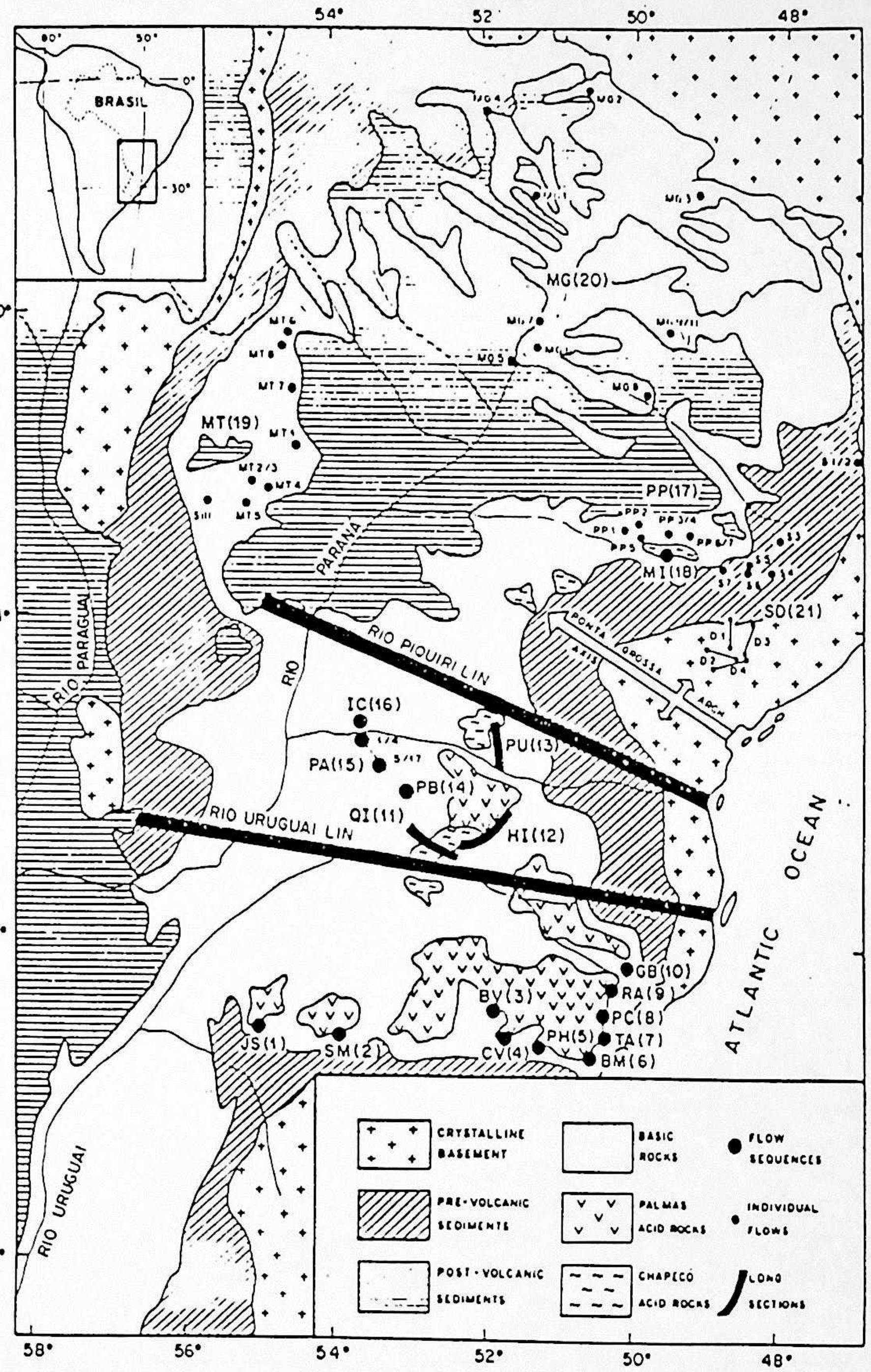


Figure 9 - Location map for the Paraná basin showing the paleomagnetic sampling sites.

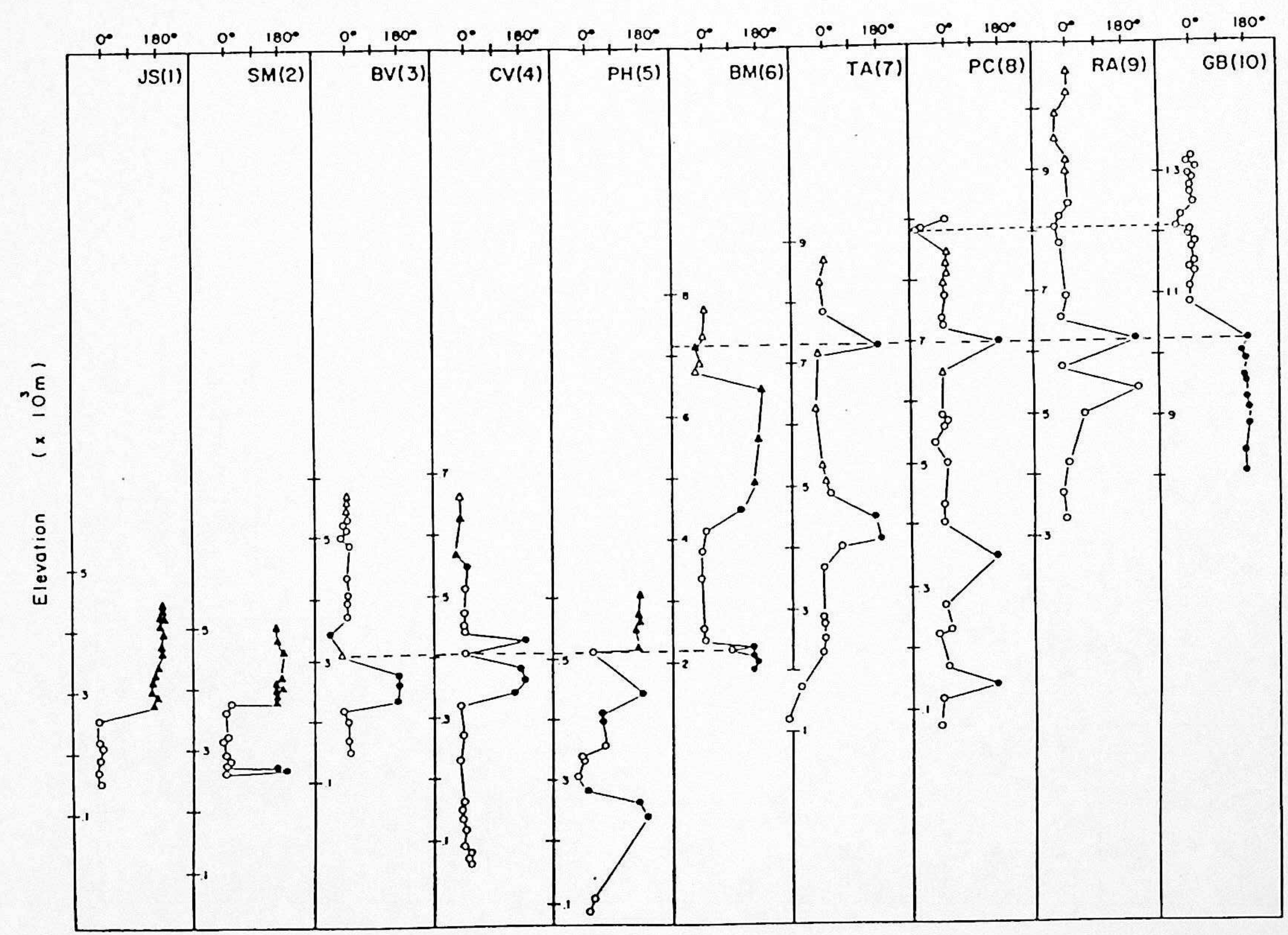


Figure 10 - Magnetic declination variations in the sections from southern Paraná basin. Solid symbols = positive inclinations; open symbols = negative inclinations; circles = basic floes; triangles = Palmas acid flows. Sequences have been adjusted in order to fit the common features they display (broken lines).

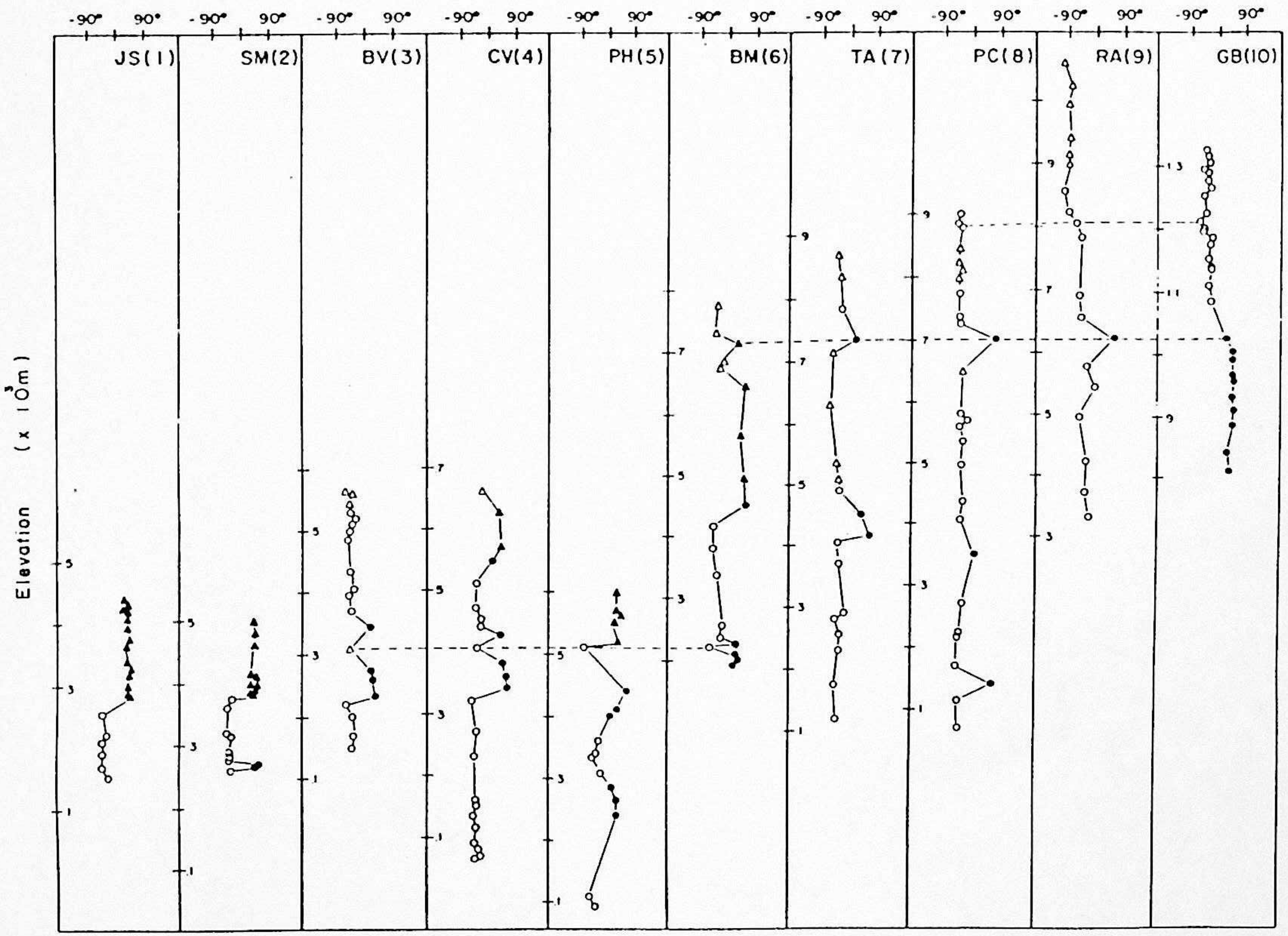


Figure 11 - Magnetic inclination variations in the section from the southern Paraná basin. Explanations as in Fig. 10.

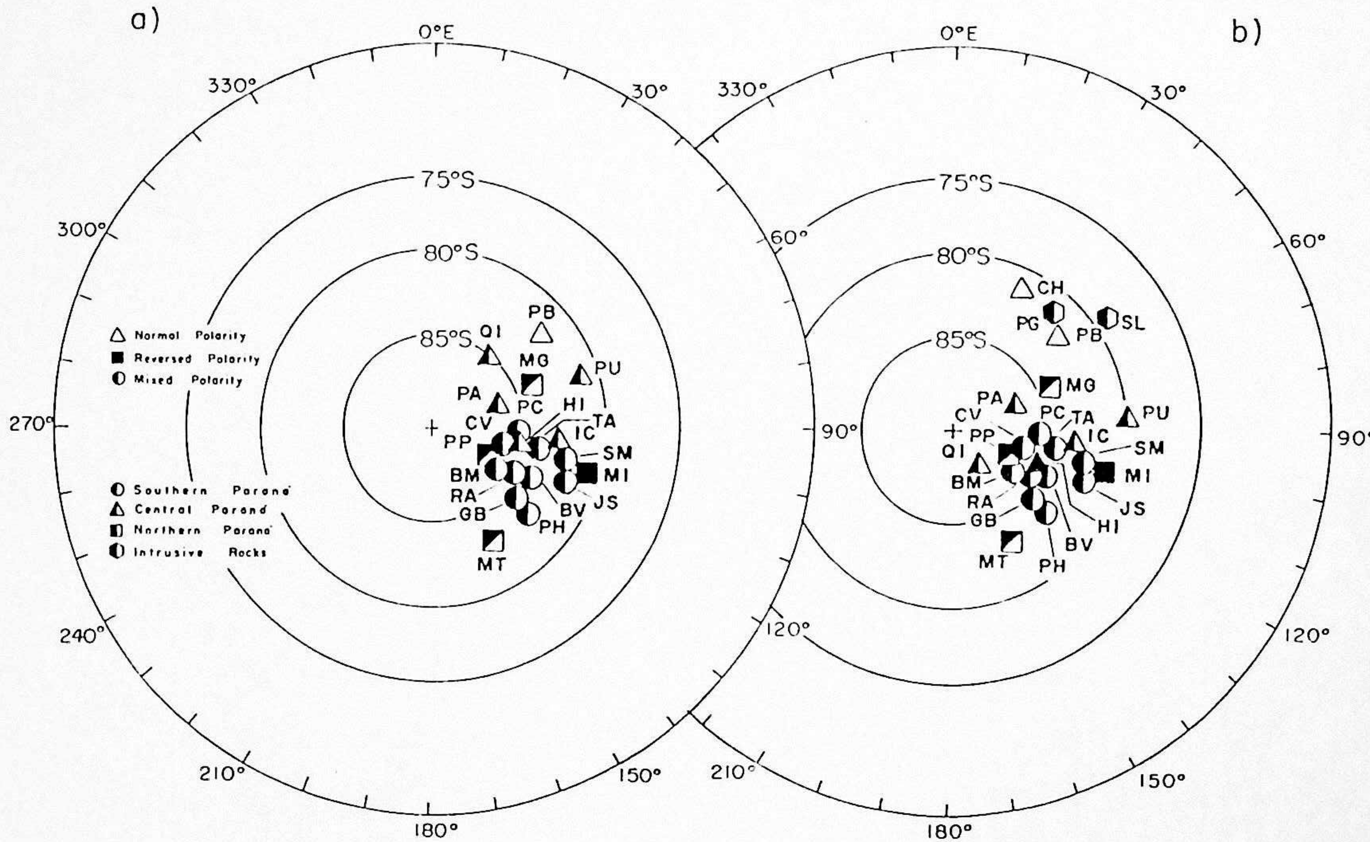


Figure 12 - a) Paleomagnetic poles for volcanic sequences of the Serra Geral Formation. b) Same as in a) but with QI(11), HI(12) and PU(13) poles recalculated in order to exclude the Chapecó acid flows (CH); pole PG= Ponta Grossa dykes; SL= sills from northeastern Paraná basin.