

I.2. GEOCHEMICAL STRATIGRAPHY OF PARANÁ CONTINENTAL FLOOD BASALTS : A CONTRIBUTION FROM BOREHOLE SAMPLES

M.S.M. MANTOVANI, D.W. PEATE and C.J. HAWKESWORTH

ABSTRACT : Oil exploration boreholes from a N-S profile across the Paraná basin provide critical information about the chemical stratigraphy of the Serra Geral formation volcanics. Geochemical characteristics of the analysed samples are consistent with those from surface samples, and define three groups according to their TiO_2 content (high end intermediate $\geq 2\% \text{TiO}_2$ and low $< 2\% \text{TiO}_2$). The vertical sections provided by the boreholes confirm that low TiO_2 magmas predominate in the south, with high TiO_2 in the north along the profile, and they further demonstrate that the southernmost lavas were erupted earlier and overlain by high TiO_2 basalts which in turn were covered by the group with intermediate TiO_2 . Preliminary results are presented in a N-S cross-section through the analysed boreholes, linked with surface samples from the southernmost extremity of the profile.

INTRODUCTION

Much attention has been devoted recently to the Serra Geral formation, a thick stack of lavas that comprise one of the world's major continental flood basalt (CFB) provinces. The lavas were erupted during the early Cretaceous, covering the Jurassic sediments of the Paraná basin, and were associated with the break-up of Gondwanaland.

Extensive geochemical work has been carried out on volcanic rocks collected both for wide-ranging regional studies over the whole Paraná basin, as well as from detailed sections along the exposed pile of lavas which constitute the "Serra Geral" escarpment in the south-east of Paraná basin (Rüegg and Amaral, 1976; Atalla et al., 1982; Bellieni et al., 1983, 1984a,b, 1986a,b; Mantovani, 1985; Mantovani et al., 1985a, 1988; Hawkesworth et al., 1986; Petrini et al., 1987; Piccirillo et al., 1987, 1988, this volume).

Earlier published results subdivided the basalts into two groups on the basis of their Ti (and P) contents (Atalla et al., 1982; Bellieni et al., 1984a; Mantovani et al., 1985). Here, the two groups are defined as HTi ($\text{TiO}_2 >$

2%) and LTi ($\text{TiO}_2 < 2\%$) consistent with usage throughout this volume. Furthermore, the HTi rocks are enriched in LREE, Sr, Ba, Zr and Nb compared to LTi rocks of similar MgO, and also have a remarkably different Sr, Nd and Pb isotopic signature (Mantovani, 1985; Mantovani et al., 1985a; Hawkesworth et al., 1986, 1988; Petrini et al., 1987; Piccirillo et al., 1988; see also Cordani et al., this volume). More recent work (Bellieni et al., 1986b; Piccirillo et al., 1988) has recognised a third significant group (ITi) with Ti contents intermediate between the LTi and HTi i.e. TiO_2 2-3%. The large range of Sr isotopic composition and the trace element variability which characterises the LTi group of southern Paraná has been interpreted as being due to extensive contamination by crustal material, which is clearly not the case for the other groups (Mantovani, 1985; Mantovani et al., 1985a; Petrini et al., 1987; Piccirillo et al., 1987a,b; Hawkesworth et al., 1988).

Bellieni et al. (1984a) emphasised the marked spatial distribution of the geochemical groups, with the HTi lavas being dominant in the northern parts of the Paraná basin and the LTi in the south. A similar distribution of low-Ti and high-Ti lavas was noted by Cox (1983) for the earlier

(190 Ma) Karoo province in Southern Africa. This suggests a large scale lateral variation within the upper mantle beneath Brazil, and more widely, beneath Gondwanaland before the time of its disruption (Cox, 1983; Bellieni et al., 1984a). The existence of these distinct geochemical groups encouraged a systematic stratigraphic investigation within the basin to explain the geodynamic and magmatic evolution of the Paraná CFB province.

Apart from several stratigraphic sections confined to roads cutting the "Serra Geral" escarpment in the south-east, most sampling of the Paraná lavas has been of surface samples with little stratigraphic control. The general lack of topographic relief over most of the basin, as well as the cover of Late Cretaceous sediments (Bauru formation) that obscures the lavas in the N.E. and N.W. (Mato Grosso and São Paulo states) and S. in Argentina, has limited the available stratigraphic data to a restricted area.

Between 1979 and 1982, 33 new oil exploration boreholes were drilled in the Paraná basin (PAULIPETRO, 1982) in addition to the previous 71 boreholes described by Northfleet et al. (1969) and Schneider et al. (1974). Samples from ten of these recently drilled boreholes were made available by PETROBRÁS, through PAULIPETRO. After taking the availability of suitable material into account, the boreholes were chosen in order to give a north-south section, roughly parallel to the main axis of lava thickness. The profile starts from the thickest accumulation of lavas (> 1.5 km; ca. 22°S, 52°W) moving south towards the northernmost sampled road section on the "Serra Geral" escarpment (ca. 28°S, 51°W) (see Fig. 1.11 and Table 1.1). The geochemical data from these samples should reveal the chemical stratigraphy of this otherwise inaccessible area, and the preliminary results are presented here.

SAMPLING AND ANALYTICAL DATA

Selection of samples from a given borehole was made after a detailed analysis of the geophysical well-logs in order to identify, or at least to estimate, the position of the contact between consecutive lava flows or pyroclastics. Unfortunately the Serra Geral formation was not cored during drilling due to the high cost and time involved, and hence the available samples are in the form of rock chips 0.1 to 1 cm in size. Each sample of rock chips

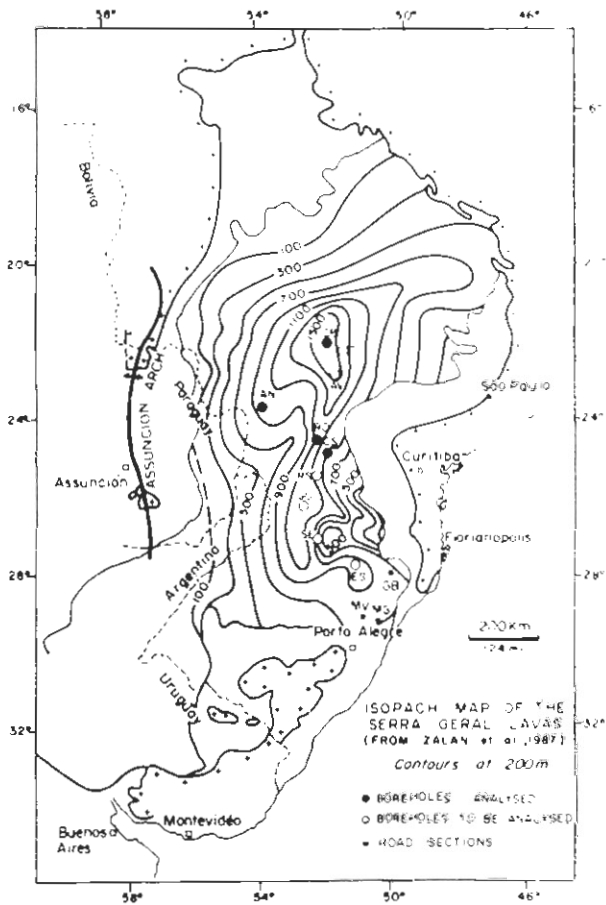


Fig. 1.11. Isopach map of lava thickness and areal extent, from Zalan et al., 1987. Locations of the studied boreholes (solid circles), and those being analysed (open circles), are shown.

was carefully handpicked, under optical magnification, to remove fragments with vesicular filling or that showed visible alteration, as well as trying to ensure that all of the sample analysed belonged to the same lithological unit. The selected fragments were washed several times with distilled water in an ultrasonic bath to remove any surface dust and drilling mud. The final product was crushed in an agate ball-mill.

A subset of 68 lavas samples was selected initially from four boreholes ('CB'-40, 'AN'-10, 'RO'-9, 'CS'-9) to test the reliability of geochemical data from such rock chip material. The 'CB' borehole lies over the deepest known part of the Paraná lavas and was sampled in greater detail, the average distance between successive samples being about 40 m. Samples were analysed by X-ray fluorescence for major oxides (Open University) and trace elements (Rb, Sr, Y, Zr, Nb, Ba, Ni, V, Cr: Nottingham University). For a smaller selection of

Table 1.1. Location of borehole studied; elevations in metres above sea level. Thickness of Serra Geral formation (basalts) and the overlying Bauru formation (siltstones/sandstones) in metres (taken from geophysical well-logs). Depth down borehole to sills within the Palaeozoic sediments of the Paraná basin. In all boreholes, the Serra Geral basalts overlie the Botucatu formation (aeolian sandstones).

Borehole	Location		Elevation (m)	Thickness (m)		Sills at (m) (from-to)
	Town	Lat. Long.		Fm. Bauru	Fm. S. Geral	
CB 2-CB-1-SP	Cuiabá Paulista (São Paulo state)	22°18'11,9"S 52°02'21,6"W	396	207	1722	3018-3115; 3245-3350; 4416-4430; 4453-4796; 5125-?
AN 2-AN-1-PR	Altonia (Paraná state)	23°51'16,0"S 53°48'27,0"W	410	260	1072	2870-3050; 3120-3235; 3408-3415; 3420-3645; 4735-5005; 5425-5455; 5215-< 5m; 5425-< 5m
RO 1-RO-1-PR	Roncador (Paraná state)	24°36'33,0"S 52°14'48,0"W	748	absent	1248	3535-3555; 3708-3772; 3835-3957; 4015-4045; 4170-4295
CS 1-CS-2-PR	Chapéu do Sol (Paraná state)	24°58'50,0"S 51°56'35,0"W	913	absent	933	2468-2585; 3035-3080; 3658-3748; 1980-< 5m; 2162-< 5m; 3008-< 5m; 3092-< 5m
TI 1-TI-1-SP	Tarabai (São Paulo state)	22°21'07,0"S 51°40'23,0"W	393	194	1537	2855-2975; 2975-3140; 3183-< 5m; 3190-3257; 4612-< 5m
GO 1-GO-1-SC	Galvão (Santa Catarina state)	26°22'58,0"S 52°42'35,0"W	916	absent	1236	2334-2355; 2593-2622; 2633-2643; 2662-2735
SE 1-SE-1-SC	Seara (Santa Catarina state)	27°08'39,0"S 52°18'04,0"W	676	absent	642	1647-1814; 1919-1923; 1927-1950; 2104-2119; 2470-2490; 3012-3074; 3773-3785
ES 1-ES-2-RS	Esmeralda (Rio Grande do Sul state)	28°05'36,3"S 51°09'13,8"W	941	absent	1000	2350-2370; 2387-2395
AV 1-AV-1-PR	Água da Valença (Paraná state)	23°05'36,2"S 51°54'46,5"W	517	110	1664	2438-< 5m; 2450-2465; 2735-2750
RS 1-RS-1-PR	Rio Segredo (Guarapuava - Paraná state)	25°42'09,4"S 52°06'59,8"W	847	absent	723	0745-0749; 1715-1783; 2027-2094; 2105-2194; 2352-< 5m; 2368-< 5m; 2433-< 5m; 2498-2520; 3288-< 5m; 3312-3327; 3330-3375; 3394-3402; 3595-3627; 3675-3737

samples, additional trace elements (REE, Th, U, Ta, Hf) were determined by neutron activation (Potts et al., 1985) as well as Sr and Pb isotopic compositions, both carried out at the Open University.

All of the analysed samples fall in the range of basalts and basaltic andesites, having between 48.5% and 55% SiO₂, and MgO ranging from 2.7% to 6.5%. Their low Mg# (< 55) and low Ni content (< 100 ppm) indicates the differentiated nature of the lavas. On the TiO₂ vs. MgO plot (Fig. 1.12), the data define three distinct geochemical groups with low, intermediate and high TiO₂, that are analogous to the LTi, ITi and HTi groups recognised in the surface lavas. Figure 1.12 also shows an example of the good agreement between the borehole data and average compositions of surface lavas of the three groups sampled in the central area of the Paraná basin (Piccirillo et al., 1988), emphasising the reliability of geochemical analysis of this borehole material. Furthermore, the good correlation observed among Ba, Rb, K₂O and Na₂O (see Figs. 1.13a,b,c) suggest that variations in these elements are inherent features of the different magma types, and that the effects due to alteration are negligible, or at least, of secondary importance (Marsh and Eales, 1984). Table 1.2 summarises the more useful criteria used to distinguish

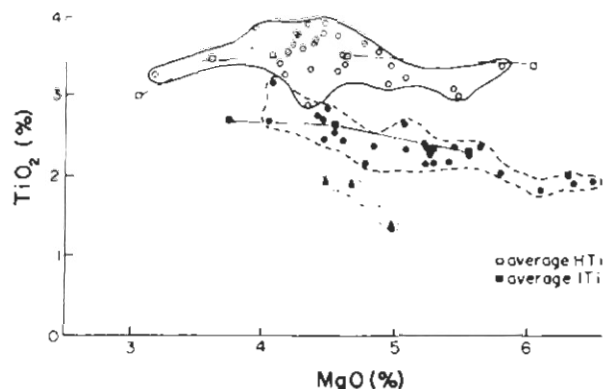


Fig. 1.12. Variation of TiO₂ vs. MgO for the borehole lavas, used to delineate the three main magma types; LTi (solid triangles), ITi (solid circles) and HTi (open circles). Squares are the averages of surface lavas from central Paraná in Piccirillo et al. (1988). Representative compositions are reported in Table 1.3.

the various borehole geochemical units.

A consistent stratigraphy is observed within each borehole, and the pattern of ITi lavas overlying a sequence of HTi flows is seen in all four analysed boreholes. Lavas of a given magma type occur as a packet of sequential flows, forming distinct stratigraphic units (Fig. 1.14). In the 'CB' borehole, the boundary

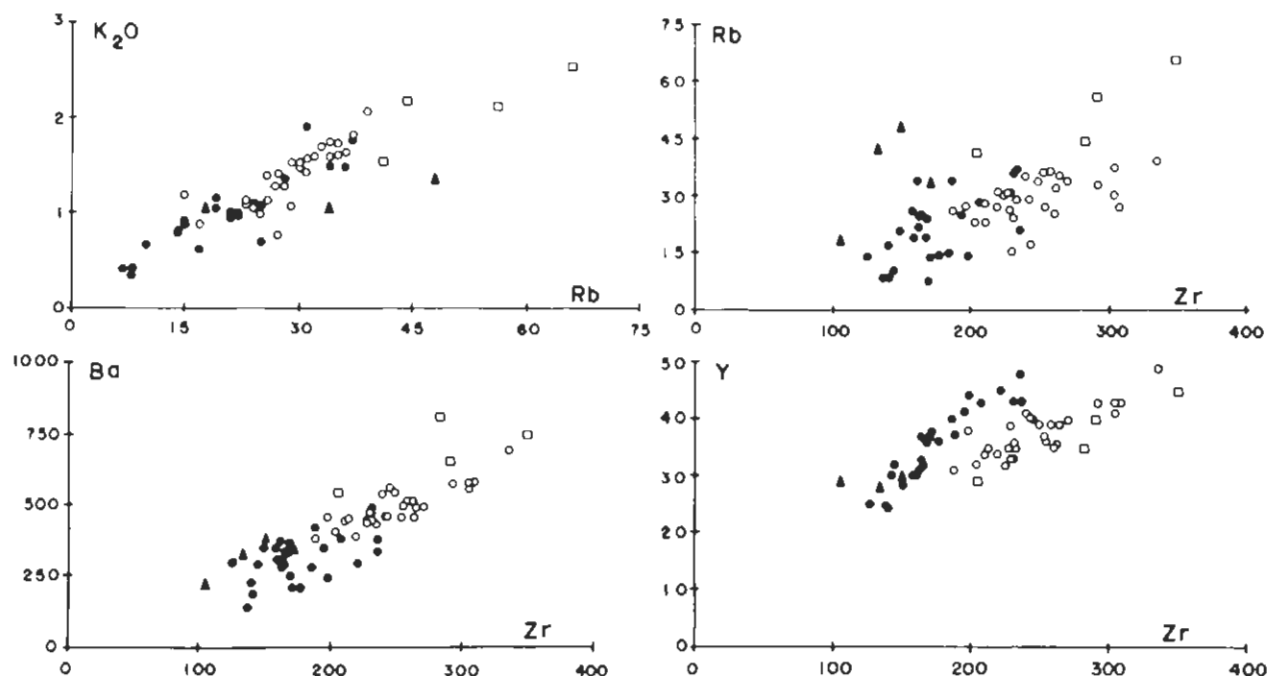


Fig. 1.13. Trace element variation diagrams for the borehole lavas. (a) K₂O (wt%) vs. Rb (ppm), (b) Rb vs. Zr, (c) Ba vs. Zr, (d) Y vs. Zr. Symbols are as for Fig. 1.12 except HTi LIL-enriched group (open squares).

Table 1.2. Geochemical criteria used to characterise the various borehole magma types.

	TiO ₂ wt %	SiO ₂ wt %	Sr ppm	Zr/Nb	Zr/Y	Ba/Y
LTI	<2.0	>52.0	-	>13	-	<12.5
ITi	1.8 - 3.2	<51.5	<375	<13	4.0 - 6.0	<12.5
HTi	>2.9	-	>375	<13	5.5 - 7.5	11.0 - 14.5
HTi	>3.0	-	>440	<13	7.0 - 8.1	>16.0
LIL - enriched						

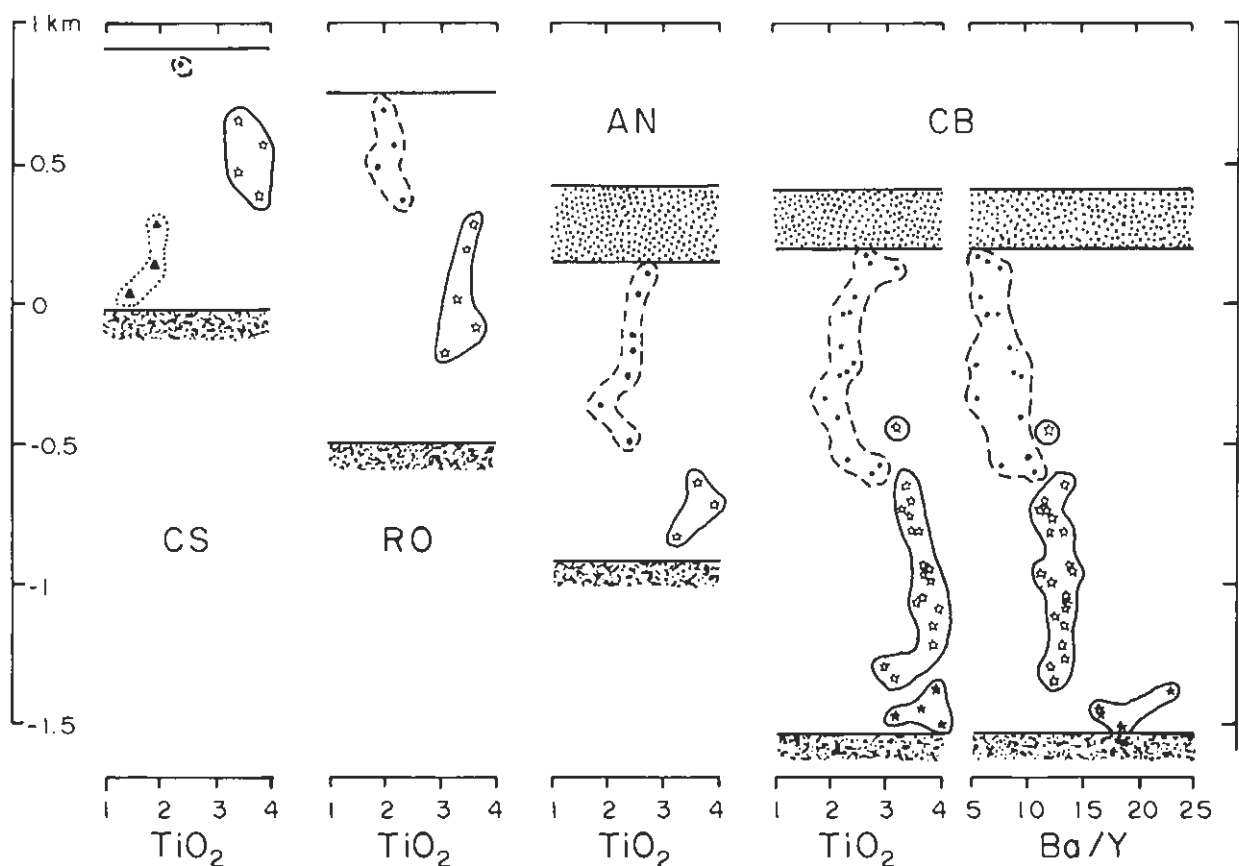


Fig. 1.14. Variation of TiO₂ with elevation above sea level for the four boreholes 'CB', 'AN', 'RO', 'CS'. For the 'CB' borehole the variation of Ba/Y is also shown, to highlight the difference between the HTi (open stars) and HTi LIL-enriched (solid stars) types. LTI and ITi symbols as Fig. 1.12. For 'AN' and 'CB' boreholes, stippled area represents the overlying Upper Cretaceous Bauru formation sediments.

between the two major units ITi and HTi is not clearly defined as lava flows of both types appear interbedded. Four samples at the base of the 'CB' borehole form a unit nearly 200 m thick and although they have high TiO₂

content (3.1-3.9%), they are distinguished from the main HTi group by their higher Ba, Rb and K contents, being characterised by Rb/Y > 1.2 and Ba/Y > 16 (see Table 1.2). To date this type has not been found in any of the

Table 1.3. Selected geochemical analyses of the units encountered in the boreholes. Sample names consist of the borehole name followed by the depth of collection in meters down the borehole. (after Peate et al., 1988).

Boreholes	CS900 LPT	CS657 LPT	AN783 IPT	RO57 IPT	RO361 IPT	AN657 IPT	AN585 IPT	CB276 IPT	CB1002 IPT	CB846 HPT	CB1382 HPT	CB1110 HPT	RO759 HPT	CB1902 HPTen	CB1776 HPTen
SiO ₂	54.58	52.58	50.42	50.27	49.51	50.43	50.41	50.79	50.70	49.75	49.79	51.27	52.43	49.27	49.75
TiO ₂	1.41	1.96	1.82	2.01	2.34	2.39	2.47	3.17	2.75	3.15	3.66	3.35	3.28	3.91	3.88
Al ₂ O ₃	13.95	13.09	13.82	13.56	13.52	13.06	13.00	11.80	12.81	13.09	12.84	12.70	12.33	12.81	14.39
Fe ₂ O ₃	12.14	15.06	13.45	13.99	14.29	15.23	15.31	17.03	15.43	15.31	15.22	14.96	15.05	14.79	13.97
MnO	0.20	0.22	0.20	0.22	0.22	0.23	0.21	0.26	0.22	0.23	0.21	0.23	0.22	0.19	0.17
MgO	4.96	4.46	6.06	6.28	5.27	4.82	4.45	4.06	4.39	4.92	4.75	4.34	3.17	5.75	4.17
CaO	8.75	8.84	10.60	10.35	9.66	9.21	8.47	8.02	8.60	9.34	9.13	8.56	7.44	8.46	7.83
Na ₂ O	2.76	2.47	2.63	2.34	3.34	3.22	3.69	2.77	3.00	2.50	3.18	3.02	3.14	2.83	3.11
K ₂ O	1.33	1.04	0.80	0.65	1.50	1.06	1.46	1.72	1.44	1.25	0.74	1.05	2.04	1.51	2.16
P ₂ O ₅	0.21	0.28	0.20	0.32	0.36	0.31	0.31	0.38	0.65	0.48	0.47	0.54	0.92	0.49	0.55
Li ₂ O _j	0.40	0.58	0.56	0.72	0.75	0.81	0.34	0.37	0.49	0.54	0.73	1.04	1.11	0.58	1.43
Mg*	48.8	40.8	51.2	51.1	46.2	42.4	40.1	35.7	39.9	42.8	42.1	40.3	32.9	47.5	41.0
Ni	38	46	59	66	58	35	29	35	33	37	28	21	14	74	41
Cr	42	53	126	205	136	132	54	180	66	76	86	46	24	264	84
V	295	318	340	320	357	383	374	459	281	367	462	405	259	375	381
Rb	48	18	14	10	34	24	34	37	36	27	27	29	39	41	44
Sr	215	176	346	267	329	288	274	208	365	389	485	449	493	523	599
Y	30	29	25	32	31	37	37	48	43	38	34	40	49	29	35
Zr	150	106	127	145	163	169	188	236	232	198	220	242	336	205	283
Nb	11	7	11	14	15	16	17	19	20	19	22	23	31	21	23
Ba	365	217	299	285	364	355	414	369	481	454	381	465	685	534	802
Th	-	-	2.09	2.48	3.05	2.84	3.11	3.33	4.31	3.31	3.42	3.67	5.14	4.34	4.25
U	-	-	-	0.66	0.67	1.62	1.29	-	1.47	1.16	-	1.00	1.21	1.10	-
Ta	-	-	0.81	0.83	1.01	1.04	1.13	1.48	1.57	1.49	1.65	1.58	2.44	1.66	2.03
Hf	-	-	3.47	3.80	4.44	4.90	5.24	6.29	5.83	5.39	6.34	7.13	9.14	5.92	7.78
La	-	-	16.4	17.5	21.4	21.7	23.9	26.3	34.5	29.1	29.4	33.4	47.8	34.1	37.3
Ce	-	-	38.2	41.1	52.9	50.5	56.0	61.8	73.9	62.2	71.0	76.3	112	71.7	90.2
Nd	-	-	22.1	23.0	29.4	28.3	30.8	35.6	43.0	34.2	43.2	48.0	54.3	42.2	46.4
Sm	-	-	4.63	5.31	6.44	6.32	6.83	8.25	9.44	7.12	-	-	-	6.79	-
Eu	-	-	1.61	1.75	2.04	2.05	2.13	2.45	2.95	2.52	2.82	2.94	4.10	2.69	3.56
Tb	-	-	0.82	0.92	0.99	1.16	1.15	1.56	1.51	1.28	1.29	1.34	1.95	1.19	1.56
Tm	-	-	0.26	0.52	0.56	0.57	0.53	0.48	0.67	0.31	0.61	0.68	0.85	0.60	0.68
Yb	-	-	2.47	3.21	3.19	3.78	3.82	4.94	4.15	3.65	3.36	3.53	4.48	2.69	2.90
Lu	-	-	0.40	0.53	0.53	0.62	0.63	0.84	0.72	0.58	0.48	0.59	0.84	0.47	0.39
Rb/Sr	0.223	0.102	0.040	0.037	0.103	0.083	0.124	0.178	0.099	0.069	0.056	0.065	0.079	0.078	0.073
Rb/Y	1.60	0.62	0.56	0.31	1.10	0.65	0.92	0.77	0.84	0.71	0.79	0.73	0.80	1.41	1.26
Ba/Y	12.2	7.5	12.0	8.9	11.7	9.6	11.2	7.7	11.2	11.9	11.2	11.6	14.0	18.4	22.9
Zr/Y	5.00	3.66	5.08	4.53	5.26	4.57	5.08	4.92	5.40	5.21	8.47	6.05	6.86	7.07	8.09
Zr/Nb	13.6	15.1	11.5	10.4	10.9	10.6	11.1	12.4	11.6	10.4	10.0	10.5	10.8	9.8	12.3
La/Yb	-	-	6.6	5.5	6.7	5.7	6.3	5.3	8.3	8.0	8.7	9.5	10.7	12.7	12.9
⁸⁷ Sr/ ⁸⁶ Sr	-	0.70659	0.70594	0.70568	0.70567	0.70587	0.70575	-	-	0.70566	0.70550	0.70546	-	-	0.70561

other boreholes. LTi rocks are only encountered at the base of the 'CS' borehole which is the southernmost studied hole.

Selected geochemical data (Table 1.3) are included with a more detailed discussion of the Paraná geochemical stratigraphy and its implications for the geodynamic evolution of the province, in Peate et al. (1988).

DISCUSSION

Preliminary results are presented in Figure 1.15, as a schematic S-N cross section through the CFB province along latitude 52°W. The profile of lava thickness and depth is taken from Northfleet et al. (1969). LTi rocks are generally restricted to the southern half of the section with HTi and ITi concentrated in the central and northern Paraná.

The northern half of the cross section is constrained by the available borehole coverage. In this segment, the geochemical formations form a sequence of northwardly dipping units, with ITi lavas overlying HTi which in turn overlie LTi in the southernmost borehole. The HTi/ITi boundary is inferred to have an approximate dip of 0.3° to the north. This lithostratigraphic pattern implies; (i)

that the dominant magma type has evolved from LTi to HTi to ITi with time, and (ii) that the source of magmatism may have migrated north.

One difficulty arises in relating the stratigraphy revealed by the boreholes, which are presently restricted to a narrow N-S axis, to the broad distribution of surface samples. The borehole stratigraphy indicates that the uppermost lava flows over most of the northern half of the basin should have ITi signature. Nevertheless, according to Petrini et al. (1987), extensive HTi and the occasional LTi flows have been recorded in this area. Boreholes lying off this S-N axis (such as 'AN' to the west) would help in better constraining the E-W structure within the lava pile.

Stratigraphic work in the south has been confined to the "Serra Geral" escarpment in Santa Catarina and Rio Grande do Sul states (Bellieni et al., 1983; Mantovani, 1985; Mantovani et al., 1985a; Bellieni et al., 1986a; Mantovani and Hawkesworth, 1987, 1988). It is not certain how representative the road sections are of the internal stratigraphy of the South Paraná as a whole. In the transition zone (28°-29°S) thick mixed sequences of lavas of both magma types are developed (Bellieni et al., 1986b), and moving north along the escarpment the

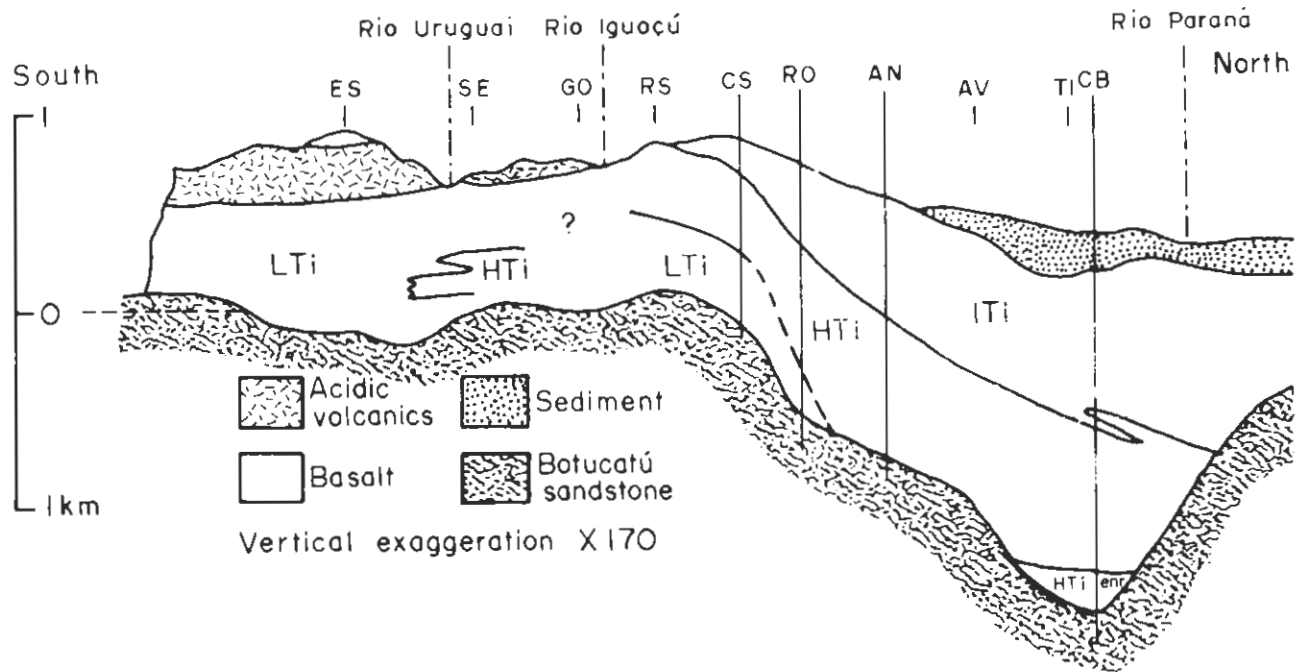


Fig. 1.15. Summary cross-section through the Paraná CFB province, along latitude 52°W, highlighting the lithostratigraphic configuration of the various geochemical units (vertical exaggeration x 170). Positions of the boreholes and the three major rivers of the basin (Rio Paraná, Rio Iguoçu, Rio Uruguai) are shown.

dominant magma type within the sequence changes from LTi to HTi. This side-by-side arrangement of the two units is consistent with the existence of two separate and simultaneously active vent systems to the north and south of the area, producing the local interfingering of the LTi and HTi lavas.

Further boreholes to the south ('RS', 'GO', 'SE' and 'ES') are being analysed in an effort to unravel the poorly constrained link between the contrasting stratigraphies of central Paraná (this study, Melfi et al., this volume) and the coastal road sections of the south-east.

Low-Ti acidic volcanics (rhyodacites and rhyolites) are observed in the uppermost horizons of the S.E. road sections, reaching thicknesses of up to 400 m (Bellieni et al., 1985a, 1986a; Mantovani, 1985; Mantovani and Hawkesworth, 1987, 1988; 'Palmas' type of Bellieni et al., 1986a). These rocks are associated with the LTi basic rocks, either as a product of complex AFC processes (Mantovani, 1985; Mantovani et al., 1985a; Bellieni et al., 1986a; Mantovani and Hawkesworth, 1988) or as anatectic crustal melts related to intensive volcanism (Cordani et al., 1980; Bellieni et al., 1986a; Hawkesworth et al., 1988). The rhyodacites and rhyolites related to the HTi basaltic lavas outcrop further north, and are referred to as 'Chapecó'-type by Bellieni et al. (1986a; see also Mantovani et al., 1985b). Piccirillo et al. (1987, 1988) interpreted them as a product of partial melting of lower crustal basic material (high-Ti basalts, or mafic granulites), similar to the origin proposed for the Lebombo rhyolites of the Karoo province by Cleverly et al. (1984). It is notable that all silicic volcanism was concentrated towards the present continental margin (Bellieni et al., 1986a; see also Cordani et al., this volume).

The gross spatial distribution of the two main geochemically distinct groups (HTi and LTi) within the Paraná province, has been attributed to different degrees of melting and compositional variations within the upper mantle (Piccirillo et al., this volume). The more detailed stratigraphic data presented here constrain firstly the relationship between the lava stratigraphy to the disruption of Gondwanaland and secondly the compositional heterogeneity of its upper mantle.

The open system differentiation of the LTi basaltic andesites, and the suggested crustal anatectic origin for the related acidic rocks, require elevated temperatures at or near the base of the crust as well as a relatively long residence time for this thermal anomaly (Cordani et al., 1980; Bellieni et al., 1986a; Fodor, 1987). Regardless of the

mechanism which may have produced this thermal anomaly, LTi acid rocks would appear to represent the centre from where the southernmost separation between Brazil and Africa was initiated, which corresponds to the incipient southern South Atlantic ocean.

Fodor (1987) attributes all chemical and isotopic characteristics observed, within the Paraná volcanics, to such a thermal anomaly, represented by the Tristão da Cunha plume, which would melt an homogeneous mantle, the degree of melting decreasing with distance from the centre of the plume. In the N-S section considered here, the model would predict that the hot-spot was located to the south, where crustal contamination can be demonstrated. However, if higher degrees of melting are attributed to the LTi magmas, ITi would be sequentially the next type formed, followed by HTi. Such a sequence is not borne out by our N-S section, since ITi overlie the HTi. Moreover, the model is also inconsistent with regional studies which identify a sharp boundary between HTi in the north and LTi in the south (Erlank et al., 1987). This boundary can be traced from our section where HTi lavas predominate to the north of CS borehole, and such a regional variation may reflect the role of mantle heterogeneities in the petrogenesis of Paraná flood basalts.

ACKNOWLEDGEMENTS

PETROBRÁS* (SUPEX-5148/85) and PAULIPETRO (Dr. Julio A. Bruno) for sample donation and for providing essential information through internal reports. Tim Brewer (Nottingham) and John Watson (Open University) for XRF, and Nick Rogers (OU) for INAA analyses. Umberto G. Cordani and Nigel Harris for fruitful discussions. CNPq and the British Council for travel and subsistence for MSMM and CJH, and NERC for a studentship for DWP.

REFERENCES

- ATALLA, L.T., CIVETTA, L., INNOCENTI, F., MANTOVANI, M.S.M., MARQUES, L.S. & SOUSA, M.A. de, 1982. Geochemistry of Paraná plateau basalts (Southern Brazil). Abstracts: Generation of major basalt types, IAVCEI-IAGC Scientific Assembly, August 15-22, No. 62, Reykjavik, Iceland.
- BELLIENI, G., BRQTZU, P., COMIN-CHIARAMONTI, P.,

- ERNESTO, M., MELFI, A.J., PACCA, I.G., PICCIRILLO, E.M. and STOLFA, D., 1983. Petrological and palaeomagnetic data on the plateau basalt to rhyolite sequences of the southern Paraná basin (Brazil). *An. Acad. brasil. Ciênc.*, **55**, 355-383.
- BELLIENI, G., COMIN-CHIARAMONTI, P., MARQUES, L.S., MELFI, A.J., PICCIRILLO, E.M., NARDY, A.J.R. and ROISENBERG, A., 1984a. High- and low- TiO_2 flood basalts from the Paraná plateau (Brazil): petrology and geochemical aspects bearing on their mantle origin. *N. Jb. Miner. Abh.*, **150**, 273-306.
- BELLIENI, G., BROTZU, P., COMIN-CHIARAMONTI, P., ERNESTO, M., PACCA, I.G. and PICCIRILLO, E.M., 1984b. Flood basalt to rhyolite suites in the southern Paraná plateau (Brazil): palaeomagnetism, petrogenesis and geodynamics implications. *J. Petrol.*, **25**, 579-618.
- BELLIENI, G., COMIN-CHIARAMONTI, P., MARQUES, L.S., MELFI, A.J., NARDY, A.J.R., PAPATRECHAS, C., PICCIRILLO, E.M., ROISENBERG, A. and STOLFA, D., 1986a. Petrogenetic aspects of acid and basaltic lavas from the Paraná plateau (Brazil): geological, mineralogical and petrochemical relationships. *J. Petrol.*, **27**, 915-944.
- BELLIENI, G., COMIN-CHIARAMONTI, P., MARTINEZ, L.A., MARQUES, L.S., MELFI, A.J., NARDY, A.J.R., PICCIRILLO, E.M. and STOLFA, D., 1986b. Continental flood basalts from the central-western regions of the Paraná plateau (Paraguay and Argentina): petrology and petrogenetic aspects. *N. Jb. Miner. Abh.*, **154**, 111-139.
- CLEVERLY, R.W., BETTON, P.J. and BRISTOW, J.W., 1984. Geochemistry and petrogenesis of the Lebombo rhyolites. *Spec. Publ. geol. Soc. S. Afr.*, **13**, 171-194.
- CORDANI, U.G., SARTORI, P.L.P., KAWASHITA, K., 1980. Geoquímica dos isótopos de estrôncio e a evolução da atividade vulcânica na Bacia do Paraná (sul do Brasil) durante o Cretáceo. *An. Acad. brasil. Ciênc.*, **52**, 811-818.
- COX, K.G., 1983. The Karoo province of southern Africa: origin of trace element enrichment patterns. In: "Continental basalts and mantle xenoliths", Eds. C.J. Hawkesworth and M.J. Norry, Shiva Press, 139-157.
- FODOR, R.V., 1987. Low- and high- TiO_2 flood basalts of southern Brazil: origin from picritic parentage and a common mantle source. *Earth Planet. Sci. Letters*, **84**, 423-430.
- HAWKESWORTH, C.J., MANTOVANI, M.S.M., TAYLOR, P.N. and PALACZ, Z., 1986. Evidence from the Paraná of south Brazil for a continental contribution of Dupal basalts. *Nature*, **322**, 356-359.
- HAWKESWORTH, C.J., MANTOVANI, M.S.M. and PEATE, D.W., 1988. Lithosphere remobilisation during Paraná magmatism. *J. Petrol.* (in press).
- MANTOVANI, M.S.M., 1985. Caracterização isotópica do magmatismo da bacia do Paraná, sua correlação com a crosta continental subjacente e com a abertura do Atlântico Sul. Thesis, IAG/USP, (unpubl.).
- MANTOVANI, M.S.M., MARQUES, L.S., SOUSA, M.A. de, CIVETTA, L., ATALLA, L. and INNOCENTI, F., 1985a. Trace element and strontium isotope constraints on the origin and evolution of Paraná continental flood basalts of Santa Catarina state (southern Brazil). *J. Petrol.*, **26**, 187-209.
- MANTOVANI, M.S.M., CORDANI, U.G., ROISENBERG, A., 1985b. Geoquímica isotópica em vulcânicas ácidas da bacia do Paraná, e implicações genéticas associadas. *Rev. Bras. Geociências*, **15**, nº 1, 61-65.
- MANTOVANI, M.S.M. & HAWKESWORTH, C.J., 1987. Inversão de dados geoquímicos e isotópicos, com aplicação às vulcânicas da bacia do Paraná. 1º Congresso Brasileiro de Geoquímica, Porto Alegre, RS, 30 out./02 nov., Resumos.
- MANTOVANI, M.S.M. and HAWKESWORTH, C.J., 1988. Crustal contamination inverted: some preliminary results. *Rev. Bras. Geoc.*, **18**, 27-32..
- MARSH, J.S. and EALES, H.V., 1984. The chemistry and petrogenesis of igneous rocks of the Karoo central area, southern Africa. *Spec. Publ. geol. Soc. S. Afr.*, **13**, 27-67.
- NORTHFLEET, A.M., MEDEIROS, R.A., MUHLMAN, H., 1969. Reavaliação dos dados geológicos da bacia do Paraná. *Bol. Tec., Petrobrás*, **12**, 291-346.
- PAULIPETRO, 1982. Geologia da bacia do Paraná: reavaliação da potencialidade e prospectividade em hidrocarbonetos. Consórcio CESP/IPT, 198 pp.
- PEATE, D.W., MANTOVANI, M.S.M. and HAWKESWORTH, C.J., 1988. Geochemical stratigraphy of the Paraná CFB: borehole evidence. *Rev. Bras. Geoc.*, **18**(2), 212-221.
- PETRINI, R., CIVETTA, L., PICCIRILLO, E.M., BELLINI, G., COMIN-CHIARAMONTI, P., MARQUES, L.S. and MELFI, A.J., 1987. Mantle heterogeneity and crustal contamination in the genesis of low-Ti continental

- flood basalts from the Paraná plateau (Brazil): Sr-Nd isotope and geochemical evidence. *J. Petrol.*, **28**, 701-726.
- PICCIRILLO, E.M., RAPOSO, M.J.B., MELFI, A.J., COMIN-CHIARAMONTI, P., BELLINI, G., CORDANI, U.G. and KAWASHITA, K., 1987. Bimodal fissural volcanic suites from the Paraná basin (Brazil): K-Ar age, Sr-isotopes and geochemistry. *Geochimica Brasiliensis*, **1**, 53-69.
- PICCIRILLO, E.M., MELFI, A.J., COMIN-CHIARAMONTI, P., BELLINI, G., ERNESTO, M., MARQUES, L.S., NARDY, A.J.R., PACCA, I.G., ROISENBERG, A. and STOLFA, D., 1988. Continental flood volcanism from the Paraná basin, Brazil. In: "Continental Flood Basalts", ed. Macdougall J.D., Kluwer Academic Publ., Dordrecht (The Netherlands), 195-238.
- POTTS, P.J., WILLIAMS-THORPE, O., ISAACS, M.C. and WRIGHT, D.W., 1985. High-precision instrumental neutron-activation analysis of geological samples employing simultaneous counting with both planar and coaxial detectors. *Chem. Geol.*, **48**, 145-155.
- RÜEGG, N.R., AMARAL, G., 1976. Variação regional da composição química das rochas basálticas da bacia do Paraná. *Bol. IG/USP*, **7**, 131-147.
- SCHNEIDER, R.L., MUHLMAN, H., TOMAZI, E.K., MEDEIROS, R.A., DAEMON, R.F., NOGUEIRA, A.A., 1974. Revisão estratigráfica da bacia do Paraná. *An. 28º Congr. Bras. Geol.*, **1**, 41-65.
- ZALAN, P.V., WOLFS, S., CONCEIÇÃO, J.C. de J., ASTOLFI, M.A.M., VIEIRA, I.S., APPIS, V.T., ZANNOTTO, O.A., 1987. Tectônica e sedimentação da bacia do Paraná. *Anais do III Simpósio Sul Brasileiro de Geologia*, Curitiba, PR.