GEOCHEMICAL VARIABILITY IN THE GREENSTONE BELTS OF GOIÁS (BRAZIL): THE HIDROLINA AND ORIXÁS SEQUENCES

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RESUMO VARIAÇÃO GEOQUÍMICA NOS CINTURÕES VERDES DE GOIÁS (BRASIL): AS SEQÜÊNCIAS DE HIDROLINA E CRIXÁS. Os cinturões verdes de Crixás e Hidrolina situados no Estado de Goiás podem representar componentes desmembrados de um mesmo corpo ou cinturões adjacentes. Suas seqüências estratigráficas e evoluções tectono-metamórficas são semelhantes, assim como seus componentes ígneos (metakomatiítos, metabasaltos e metavulcânicas félsicas). Quimicamente, eles diferem no comportamento das relações entre CaO e Al_2O_3 com MgO, e na conduta de vários elementos compatíveis e incompatíveis (Cr, Ni, Ti, Sc, Y, Zr, P). O comportamento de Ca e Al, anômalo em Crixás, é tentativamente atribuído a um processo de cristalização cujos controles não estão esclarecidos. Tal processo, atuante em Crixás, e não existente em Hidrolina, implicaria na formação de clinopiroxênio em meio a uma massa constituída principalmente por olivina. Ás diferenças no comportamento dos elementos traços foram atribuídas principalmente à heterogeneidade composicional e modal da fonte mantélica, que foi provavelmente mais rica em espinélio em Crixás do que em Hidrolina.

Palavras-chaves: Cinturão de rochas verdes, heterogeneidade mantélica Crixás, Hidrolina, Goiás.

ABSTRACT The greenstone belts of Crixás and Hidrolina of Goiás, Brazil, are dismembered components of the same body or of originally adjacent belts. Their tectono-metamorphic history and stratigraphy is similar, as well as their igneous components (meta-komatiites, meta-basalts and felsic meta-volcanics). Chemically, they differ for the CaO and Al_2O_3 versus MgO trends and for the behaviour of many incompatible and compatible trace elements (Cr, Ni, Ti, Sc, Y, Zr, P). The difference in the Ca and Al behaviour, wich is anomalous at Crixás, is tentatively attributed to an unconstrained igneous crystallization process. This process should imply the growth of clinopyroxene into an olivine-dominated crystal mush, and has acted at Crixás and not at Hidrolina. The difference in the trace element behaviour has been mainly attributed to a compositional and modal heterogeneity of the mantle source, which was probably spinel-richer at Crixás than at Hidrolina.

Keywords: Greenstone belts, mantle heterogeneity, Crixás, Hidrolina, Goiás.

INTRODUCTION An important feature of greenstone belts are the regional compositional variations of their stratigraphic units. These variations, if primary, may give indications on the variability of the environment of emplacement or of the source of the materials and, if secondary, may be an useful indicator of postgenetic processes.

Regional differences within single units of one greenstone sequence are well documented, for instance, in South-African greenstone belts: Viljoen *et al.* (1982) have pointed out differences in the Onverwacht group of Barberton between the Sandspruit, Komati, Geluk, Badplaaas and Barberton types.

Two occurrences of Central Goiás (Brazil), the Crixás and Hidrolina greenstone belts are here examined. They are components of the same geological unit: the Pilar de Goiás Group (Ribeiro Filho 1978, Danni & Ribeiro 1978, Saboia & Teixeira 1983). Most probably, they belong to the same greenstone belt, dismembered by effect of a complicated tectono-metamorphic history consisting of several deformation episodes, metamorphism and intrusion of granites (Danni *et al.* 1986). It is also possible that they originally occurred in adjacent but separated belts. They are now divided by intrusive granites about 50 km apart. They are covered probably in discordance by the Proterozoic formation of the Araxá schists and rest unconformably on an Archaean basement (2.9-3.1 Ga, Almeida & Hasui 1969, Hasui & Almeida 1970, Tassinari & Montalvão 1980) of granitoid,

gneisses, migmatites and amphibolites (Danni *et al.* 1986, Montalvão 1986). Their age is Archaean and probably of 2.7 - 2.8 Ga(Arndt *et al.* 1989).

Literature data (Saboia & Teixeira 1983) and references therein) and field inspections show that the Hidrolina and Crixás belts have similar stratigraphies. Recent geochemical work, however, has shown that rocks of the same stratigraphic unit in the two sequences may show considerable differences. For instance, Rivalenti *et al.* (1989) have concluded that the Hidrolina belt has undergone an essentially isochemical metamorphism (except for alkaline elements and alkaline earths) and have proposed an igneous genetic model on this base; on the contrary, Arndt *et al.* (1989) at Crixás have concluded that the komatiites have undergone extensive element mobilization and that little is leff of the original composition. These differences have prompted us to a comparative study of the two sequences. For this reason, 120 new analyses of the Crixás sequence have been carried out, which are available by request.

Although in the text the prefix "meta-" has been omitted in the terminalogy, obviously all the rocks are metamorphic.

STRATIGRAPHY The stratigraphy of Hidrolina belt is reported in Danni *et al.* (1986) and Rivalenti *et al.* (1989) and that of Crixás in Saboia *et al.* (1979). Rivalenti *et al.* (1989) have divided the Hidrolina belt into a lower and an upper sequence (LS and US). The LS consists of a basal portion dominated by ultramafic flows intercalated with thin chemical

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sediments (LS1), grading upwards into a zone where the ultramafic flows decrease and the mafic flows increase (LS2) until the ultramafics disappear (LS3). Concomitantly the sedimentary component increases. At the roof of LS3 an horizon of marbles occurs and separates the lower unit from US. US igneous componet consists of intercalated basaltic and felsic volcanics. Sediments are pelites and quartzites. The pelitic rocks dominate in the uppermost part where the main Au mineralizations occur (Magalhães *et al.* 1984, Ribeiro Filho 1984).

At Crixás, Saboia & Teixeira (1983) ditinguish three units (called by them "formations"): a. the Córrego Alagadinho unit, constituted by ultramafic flows preserving primary features, without sediments; b. the Rio Vermelho unit, with dominant basaltic rocks preserving sometimes pillow structures; c. the Ribeirão das Antas unit, dominantly sedimentary (chlorite-quartz schists, quartzites,, grafite schists, B IF) and metabasalts interlay ered with felsic metavolcanics.

Recently Jost & Oliveira (1990) compared the stratigraphy of the three greenstone belts named by them Pilar de Goiás, Guarinos and Crixás. They proposed a new stratigraphy for the supracrustal units and concluded that the differences among them can be explained either by paleogeography or by tectonism. Jost *et al.* (1989) also described a new stratigraphic unit called Morro Vermelho sequence, which overlays the greenstone units in the Crixás area.

The two stratigraphic successions compare favourably: the Alagadinho unit may correspond with LS1 and LS2, the Rio Vermelho unit is probably analogous to LS3 and the Ribeirão das Antas corresponds with US. A difference is the absence of metasediments in the Crixás basal zone, while the presence of marbles at the top of the Rio Vermelho unit is dubious.

PETROGRAPHY *Komatiites* The field characteristics and petrology of lhe Crixás komatiites have been been described by Saboia & Teixeira (1983) and Arndt *et al.* (1989) and of those of Hidrolina by Danni *et al. (1986) and Rivalenti* et al. (1989). They have the typical characteristics of ultramafic volcanics metamorphosed under greenschist facies. At Hidrolina, and in a large part of the Crixás field, they are ultramafic schists composed by serpentine, chlorite, tremolite, and variable amounts of carbonate, talc and opaque minerals. Relic primary features are exceptional at Hidrolina (only one pillow occurence) and more common at Crixás in the Córrego Alagadinho section, where individual flows show spinifex textures, olivine cumulates at the bottom of the flows, porphyritic textures, and polyhedral jointing. In the spinifex-textured samples, olivine needles are replaced by tremolite and chlorite with minor carbonate; serpentine occurs in the interstitial matrix. Relics of primary minerals are vey rare and consist of olivine and clinopyroxene. Arndt *et al.* (1989) mention the occurrence of metamorphic recrystallized olivine.

Basalts They consist in both localities of amphibolites composed by randomly oriented blue-green to yellow-green hornblende, plagioclase, quartz, and sometimes epidote, sphene, carbonate. Opaques and zircon are accessories. Primary volcanic structures (pillow) have been found only at Crixás in the Rio Vermelho section.

CHEMISTRY The XRF analytical methods employed for major and trace elements determinations on the 120 Crixás samples were the same as used at Hidrolina. Details on the methods, accuracy and precision data are reported in Rivalenti *et al.* (1989).

Average composition of Hidrolina and Crixás komatiites and basalts are reported in tables 1 and 2, respectively. The geochemical trends for major and trace elements of the two

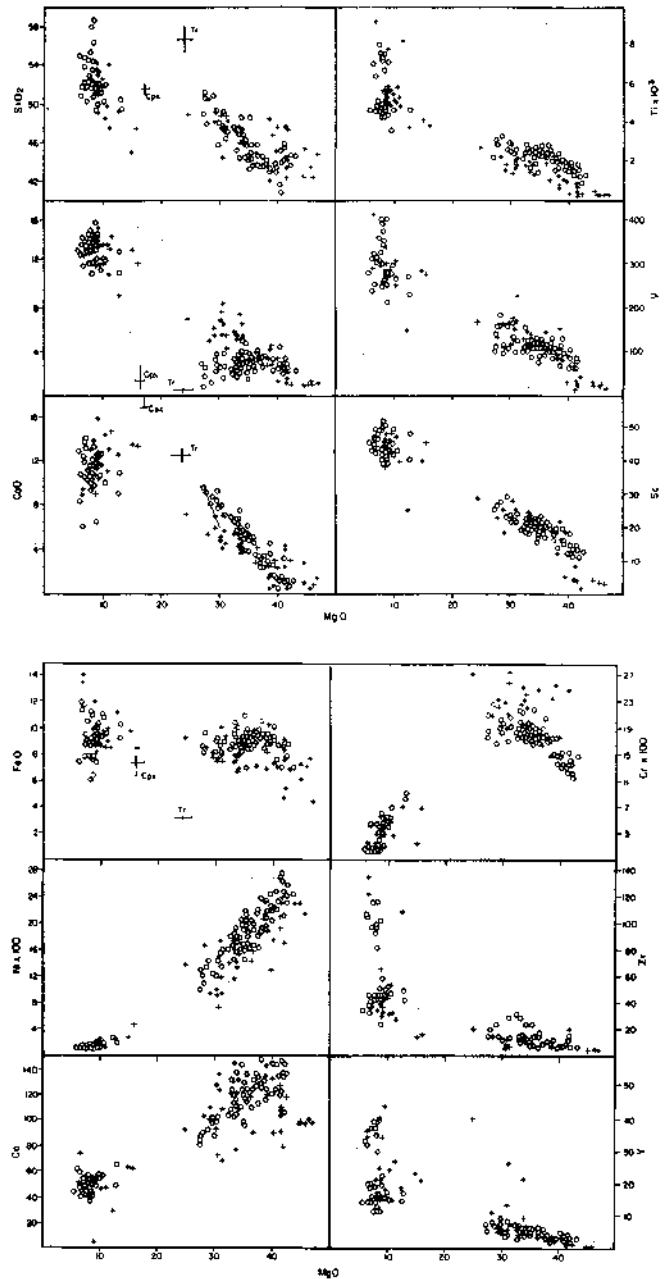localities are compared in the plots of figures 1 to 6.

Figure 1 - Plot of MgO versus SiO₂, Al₂O₃, CaO, FeO (wt%), and Ti, Zr, Y, Sc, V, Ni, Co, Cr (ppm)for the samples from the Hidrolina (crosses) and Crixás (circles) greenstone belts, the analyses are recalculated anhydrous. Samples of Hidrolina enriched in cumulus phases (Rivalenti et al. *1989), except those of the komatiites, have been omitted. The compositional range of clinopyroxene relics and of tremolite at Crixás is reported in the SiO₂, CaO, Al₂O₃ plots*

Figura 1 - Relação entre MgO e os óxidos SiO₂, Al₂O₃, CaO, FeO (% peso) e Ti, Zr, Y, Sc, V, Ni, Co, Cr (ppm) para as amostras dos cinturões verdes de Hidrolina (cruzes) e Crixás (círculos). As análises foram recalculadas anidras. As amostras ricas em fases cumulus de Hidrolina (Rivalenti *et al.* 1989), exceto as dos komatiftos, foram omitidas. As variações composicionais dos relidos de clinopiroxênio e de tremolita de Crixás estão expressas nos diagramas de SiO₂, CaO e Al₂O₃

Komatiites Figure l shows that the two occurrences behave for most major elements in the same way, except for Al₂O₃

Table l - *Averages of chemical analysis of the Hidrolina komatiites and basalts (Rivalenti* et al.
Tabela 1 - Média de análises químicas dos komatiítos e basaltos de Hidrolina (Rivalenti ei *al.* 1989)

Str. Unit	Komatiites				Basalts				
	Mg 29-31 LS 1	Mg 33-34 LS 1	Mg 38-40 LS 1	Mg 24 LS 2	Mg 7-10 LS 2	Mg 8-11 LS 3	Mg 14-16 LS 3	Mg 6-7 US	Mg 8-11 US
SiO_2	47.65	46.80	45.35	48.91	52.19	51.01	46.09	51.01	51.69
TiO_2	0.28	0.27	0.19	0.44	0.92	0.87	0.65	1.61	0.88
Al_2O_3	6.02	5.67	3.54	6.76	11.65	13.64	12.08	12.13	12.92
Fe_2O_3	1.82	1.69	1.85	2.07	2.12	1.87	2.04	3.07	2.12
FeO	8.21	7.59	8.34 .	9.32	9.53	8.40	9.18	13.82	9.52
MnO	0.15	0.13	0.12	0.19	0.17	0.21	0.22	0.21	0.18
MgO	30.30	33.41	38.91	24.40	8.70	8.93	15.25	6.40	8.93
CaO	5.38	4.32	1.68	7.31	12.81	13.61	13.44	9.17	11.18
Na_2O	0.12	0.07	0.00	0.46	1.56	1.09	0.74	2.05	2.16
K_2O	0.03	0.02	0.00	0.08	0.19	0.25	0.23	0.26	0.28
P_2O_5	0.04	0.03	0.02	0.07	0.15	0.12	0.10	0.26	0.14
CaO/Al_2O_3	0.93	0.77	0.47	1.08	1.10	1.00	1.12	0.76	0.87
Al_2O_3/TiO_2	22.51	21.80	17.72	15.36	12.66	15.70	18.56	7.56	14.79
P	135	83	80	305	666	539	419	1156	612
Sc	23	21	18	29	44	44	43	47	44
Ti	1659	1500	1110	2637	5515	5231	3899	9651	5260
V	152	127	99	167	282	287	276	353	272
Cr	2733	2363	2568	2820	627	477	485	239	357
Co	103	118	139	92	53	37	62	62	48
Ni	1081	1433	1853	1370	177	151	360	91	131
Y	8	5	2	40	35	18	22	35	16
Zr	9	6	–	20	45	39	14	130	44
Ti/P	11.5	17.7	16.5	8.6	8.2	9.8	9.3	8.6	8.4
Ti/Sc	74	66	64	90	124	116	91	297	120
Ti/V	11.2	12.5	11.2	15.7	19.5	18.2	14.1	27.9	19.3
Ti/Y	285	283	371	65	141	290	177	275	334
Ti/Zr	338	231	–	131	121	137	280	74	120
Zr/Sc	0.25	0.30	–	0.69	1.02	0.33	0.19	2.79	1.01

Analysis are recalculate anhydrous. Fe_2O_3 has been calculated from total Fe assuming $Fe_2O_3 = 0.2$ FeO. The analyses are averages of the MgO range indicated in the labels. For instance sample Mg 29- 31 is the average of the samples in the range 29 < MgO< 31%

and CaO: in Crixás, the first slightly increases at increasing MgO in the MgO range 27%-35%, while at Hidrolina it decreases; the second is higher and decreases more sharply at decreasing MgO in Crixás than in Hidrolina. Figure 2 shows that the CaO and AL_2O_3 trends of the Crixás komatiites occur in single flows: CaO reaches a maximum concentration in the spinifex-textured centre of the flow; $A1_2O_3$ varies little, but decreases slightly at the centre, as does also MgO.

Other differences between Crixás and Hidrolina are a higher content of Ni, Ti and Y in the first locality at a given MgO content. So behaves also Zr, but its content spreads much in the komatiites of Crixás. Cr shows a hump-shaped trend at Crixás, with a maximum at about 35% MgO, and is tendentiously lower than in Hidrolina, where it exhibits a dispersed array.

All the ratios where Ti is involved (Ti/Zr, Ti/Y, Ti/V and Ti/Sc) are different in the two localities. Figure 3,4 and 5 and tables 1 and 2 show that in the komatiites of Crixás the ratios Ti/Zr, Ti/Y, Ti/V and Ti/Sc are higher than chondritic, Zr/Sc is lower and Zr/Y and Sc/Y are at about chondritic. At Hidrolina, in Pk Ti/Zr is higher, Ti/V and Zr/Sc are lower, while all the other ratios are at about chondritic. The Al_2O_3/TiO_2 ratio (Tabs. 1 and 2) is much lower than the chondritic values of 20 in all the Crixás rocks, whereas at Hidrolina, it is chondritic or slightly lower than chondritic.

The differences between the two localities are stressed by the zero intercepts on the MgO axis incompatible elements and by the molecular proportion ratio (MPR) plots of figure 6. The zero intercepts for CaO, Ti, Y and Sc are at MgO 43%, 48%, 56% and 58%, respectively in Crixás and at 47%, 46%, 36% and 46% in Hidrolina. While in Hidrolina they are closer, except for Y, to a possible olivine control line (which would give intercepts at about MgO 47%-50%), this is not the case in Crixás, except for Ti.

MPR trends (for their use, see Pearce 1968,1987, Beswick 1982, Rollinson & Roberts 1986, Russel & Nicholls 1988) are compared in figure 6. Although fairly parallel, the trends of the komatiites of the two localities are clearly distinguished, thus suggesting a control of the same phase (s), but different initial compositions. The controlling assemblage of the komatiite trend appears to be olivine dominated.

Basalts The basaltic rocks of Crixás, as those of Hidrolina, have the characteristics of tholeiites (Tabs. 1 and 2). They cluster into two groups distinguished by a Ti content higher and lower than 0.6% (Figs. 1 and 3). The higher Ti correlates with higher P, Zr, V and Y and lower Sc. These clusters apparently do not correspond with any stratigraphic division. Samples enriched in Ti are found also at Hidrolina in the US unit. At Hidrolina, in the MgO range 9%-12%, the basalts contain more Ti (Fig. 1 and Tabs. 1 and 2). In the same range, the rocks of Crixás have lower Ti/Sc and higher Zr/P than those of Hidrolina, while Ti/P, Ti/Zr, Ti/Y, Zr/Sc and Zr/Y are similar and Ti/V is slightly lower (Figs. 2 to 4). Ti/P and Sc/Y are lower than chondritic, while Ti/Zr, Ti/Y, Zr/Y are at about chondritic and Zr/Sc is higher. In the high Ti

Table 2 — Averages of chemical analysis of the Crixás komatiites and basalts
Tabela 2 - Médias das análises químicas de komatiítos e basaltos de Crixás

| Str. Unit | Komatiites | | | | | | Basalts | | | | |
| | Córrego Alagadinho | | | | | | Rio Vermelho and Ribeirão das Antas | | | | |
	Mg 27-29	Mg 29-31	Mg 31-33	Mg 33-36	Mg 36-38	Mg 38-40	Mg 7-9 Low Ti	Mg 9-11 Low Ti	Mg 11-13 Low Ti	Mg 6-7 High Ti	Mg 7-8 High Ti
SiO_2	47.79	47.81	45.71	45.81	44.34	43.33	53.51	51.46	49.97	51.65	51.85
TiO_2	0.45	0.43	0.40	0.35	0.35	0.27	0.73	0.84	0.70	1.44	1.22
Al_2O_3	2.80	2.66	3.34	3.28	3.02	2.85	13.01	11.59	11.76	13.17	13.20
Fe_2O_3	2.14	1.93	2.17	1.93	2.08	2.09	1.93	2.31	2.21	2.65	2.28
FeO	9.65	8.67	9.78	8.68	9.37	9.40	8.67	10.39	9.93	11.92	10.25
MnO	0.14	0.14	0.15	0.16	0.18	0.19	0.18	0.18	0.17	0.20	0.17
MgO	27.77	30.00	32.06	34.56	37.03	39.10	8.11	9.89	12.83	6.23	7.86
CaO	9.06	8.24	6.32	5.15	3.59	2.72	10.87	11.14	9.96	8.46	10.40
Na_2O	0.12	0.04	0.00	0.03	0.00	0.01	2.67	1.96	2.26	3.73	2.29
K_2O	0.03	0.02	0.02	0.01	0.01	0.01	0.21	0.13	0.10	0.26	0.30
P_2O_5	0.04	0.07	0.06	0.03	0.03	0.03	0.11	0.11	0.11	0.29	0.19
CaO/Al_2O_3	3.62	3.33	1.89	1.73	1.24	0.99	0.84	0.96	0.85	0.64	0.79
Al_2O_3/TiO_2	6.08	6.08	8.23	9.39	8.76	10.51	17.78	13.84	16.84	9.15	10.82
P	187	287	243	138	121	110	461	486	478	1261	834
Sc	25	24	23	20	19	16	46	45	44	40	43
Ti	2713	2604	2425	2091	2106	1636	4387	5020	4187	8633	7309
V	145	118	136	105	101	82	274	279	251	289	356
Cr	2268	1982	2210	1932	1904	2044	335	647	993	168	190
Co	91	98	116	113	122	130	48	54	57	57	52
Ni	1158	1281	1505	1732	1844	2065	115	137	180	111	150
Y	5	5	4	5	4	3	14	29	16	42	37
Zr	22	7	20	11	14	6	39	48	45	167	101
Ti/P	14.4	9.1	10.0	15.1	17.3	14.8	9.5	10.3	8.7	6.8	8.7
Ti/Sc	108	110	105	102	110	105	95	111	94	213	168
Ti/V	18.7	22.1	17.8	19.9	20.8	20.0	16.0	18.0	16.7	29.9	20.5
Ti/Y	542	504	692	429	481	545	308	175	265	207	199
Ti/Zr	121	363	121	184	146	284	112	104	93	51	72
Zr/Sc	0.89	0.30	0.87	0.56	0.76	0.37	0.85	1.07	1.02	4.13	2.32

Analysis are recalculate anhydrous. Fe_2O_3 has been calculated from total Fe assuming $Fe_2O_3 = 0.2$ FeO. The analyses are averages of the MgO range indicated in the labels. For instance sample Mg 27-29 is the average of the samples in the range 27 < MgO < 29%

samples Ti/Zr and Ti/Y become lower than chondritic, while Zr/Y is higher.

DISCUSSION The comparison of the chemical parameters between Crixás and Hidrolina has shown that the most significant differences involve CaO and Al_2O_3 for the major elements of the komatiites and many compatible and incompatible trace elements of komatiites and basalts. As will be discussed later on, the differences in the trace elements suggest a possible heretogeneity in the source of the two regions. Those concerning CaO and Al_2O_3 are not of easy interpretation. They are dependent on the "anomalous" behaviour of these elements at Crixás and, therefore, this point is to be discussed preliminarly.

CaO and Al_2O_3 **behaviour at Crixás** The "anomalous" CaO and Al_2O_3 trends of the komatiites at Crixás may depend on the metamorphic redistribution of these elements, or may be primary. In this last case it may be determinated either by mixing of magmas of different initial composition dependent on local heterogeneities of the source or by crustal contamination of the magmas or by the emplacement and crystallization processes.

Metamorphism   Arndt *et al.* (1989) have concluded that the Crixás komatiites have undergone a poorly understood metamorphic or metasomatic process during which the concentration of CaO and Al_2O_3, as well as that of many other elements generally considered as immobile, was drastically changed. There are, however, two main reasons suggesting that hardly metamorphic open system processes are responsible for a CaO and Al_2O_3 redistribution.

The first is a comparison with Hidrolina. The two localities, at a given MgO content of the rock, have similar mineral assemblages. Moreover, if metamorphic element redistribution has occured, it is more likely that it has taken place at Hidrolina, where primary features have been completely blurred, than at Crixás, where primary features are common.

The second reason rests on the following observations. In the Al_2O_3 and CaO plots, the Crixás samples plot towards the clinopyroxene or tremolite composition (Fig. 1). If controlled by tremolite, the system must have been opened at least for CaO and SiO_2, which could have been transported and enriched by hydrothermal solutions and reacted with serpentine or talc to form tremolite. However, the element distribution through single flows should imply that metasomatism has acted more at the centre than at the contacts, and no serious reason can be found for this process.

Mixing of magmas of different composition   The possibility that magmas coming from sources of different compositions
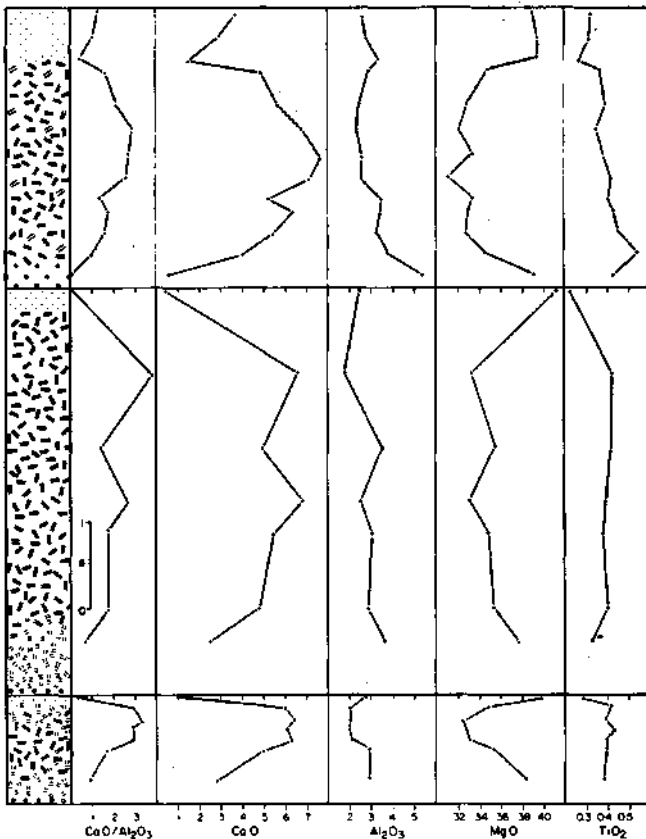
Figure 2 - Variation of CaO, Al₂O₃, MgO, TiO₂ (wt%) and of the CaO/Al₂O₃ ratio in three komatiite flows of Crixás (Córrego Alagadinho section). Each flow has an olivine-cumulate zone at the base, is spinifex-textured in the inner pan and has an aphanitic, sometimes polyhedrally-jointed, top. Spinifex dimension becomes decimetric at the centre of the flows

Figura 2 - Variação de CaO, Al₂O₃, MgO, TiO₂ (%peso) e da relação CaO/Al₂O₃ nos três derrames komatiíticos de Crixás (seção do Córrego do Alagadinho). Cada derrame tem cumulato de olivina na base, textura spinifex na parte central, e é afanítica, às vezes com disjunção poliedral no topo. As dimensões do spinifex tornam-se decimétricas no centro dos derrames

are mixed to give the actual variation patterns is ruled out by the fact that single flows display the whole CaO and Al₂O₃ variation range: as Arndt *et al.* (1989) claim, although it might be theoretically possible to mix magmas from different sources within a single flow, it seems highly improbable that this process is repeated at each flow.

Contamination In order to establish a possible contaminant, a mass balance calculation has been carried out. The average at 27%-20% MgO and 33%-36% MgO have been considered as end-members. As a constraint for the calculation, it has been assumed that neither the crystallizing phase (which, in this MgO range, can be only olivine) nor the contaminant contained CaO.

The lack of CaO in the contaminant is postulated on the basis of the rapid decrease of CaO at increasing MgO (Fig. 1), resulting in a much lower MgO zero intercept than that expected from olivine control.

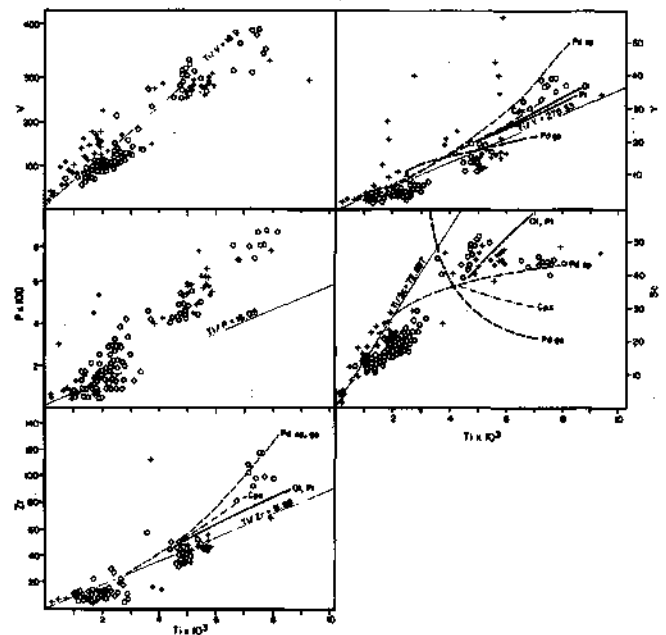The residue (Tab. 3) from subtracting the high MgO group from the low one, until CaO is minimized, can be recalculated

Figure 3 - Plot of Ti versus Zr, P, V, Sc and Y (ppm)for the rocks of Hidrolina (crosses) and Crixás (circles). Chondrite values (continuous line) are from Wänke et al. (1974), Jagoutz et al. (1979), Wood (1979) and Nesbitt & Sun (1980). The Zr, Sc, and Ti/Sc concentration calculated in liquids formed by non modal partial melting of mantle in garnet- or spinel-peridotite fades is also reported (dashed lines; ticks are intervals of 5% melting). Model mantle (asterisk) is that of Hofmann (1989). The formula used is: $C_l = C_O/[D=F (1-P)]$, where C, is the concentration of the element in the liquid; C_O is the concentration in the source, D is the bulk partition coefficient for the source; P is the bulk partition coefficient for the melting assemblage; F is the melting degree. Partition coefficients are from Rivalenti et al. (1989) Garnet-peridotite (Pd ga) - Modal composition: ol = 0.6, opx = 02; cpx— 0.1; ga= 0.1. Melting proportions: ol = 0.15, opx = 0.05; cpx = 0.4; ga = 0.4, Spinel-peridotite (Pd sp) - Modal composition: ol = 0.6; opx = 02; cpx = 0.15; sp = 0.05. Melting proportions: ol = 0.15, opx = 0.75, cpx = 0.4, sp = 03. Dash-dots lines are fractionation vectors for olivine, clinopyroxene and plagioclase. Ticks are 0,1 fractionation intervals. The formula used is: $C_l = C_O *F^{(D-1)}$,

Figura 3 - Diagrama de variação de Ti em relação a Zr, P, V, Sc e Y (ppm) para as rochas de Hidrolina (cruzes) e de Crixás (círculos). Os valores condríticos (linha contínua) são de Wänke *et al.* (1974), Jagoutz *et al.* (1979), Wood (1979) e Nesbitt & Sun (1980). As concentrações de Zr, Sc e Ti/Sc calculadas nos líquidos formados por fusão não-modal do manto nas facies de granada e espinélio peridotito são também representadas (linhas interrompidas; pequenas marcas são intervalos de fusão de 5%). O modelo de manto é extraído de Hofmann (1989). A fórmula usada e: $C_l = Co/ [D+F(1-P)]$, onde C, é a concentração do elemento no líquido, Co é a concentração da fonte, P é o coeficiente de partição total para a assembléia de fusão, F é o grau de fusão. Os coeficientes de partição são de Rivalenti *et al.* (1989). Granada-Peridotito (Pd ga) - Composição modal: ol= 0,6; opx= 0,2; cpx= 0,1; ga= 0,1. Proporções de fusão: ol= 0,15; opx= 0,05; cpx= 0,4; ga= 0,4. Espinélio peridotito (Pd sp) - Composição modal: ol = 0,6; opx - 0,2; cpx = 0,15; sp = 0,05. Proporções de fusão: 01 = 0,15; opx = 0,15; cpx = 0,4; sp = 0,3. Linhas interrompidas - pontílhadas são vetores de fracionamento para olivina, clinopiroxênio e plagioclásio. Pequenas marcas representam intervalos de fracionamento de 0,1. A fórmula usada é: $C_l = Co *F^{(D-1)}$.
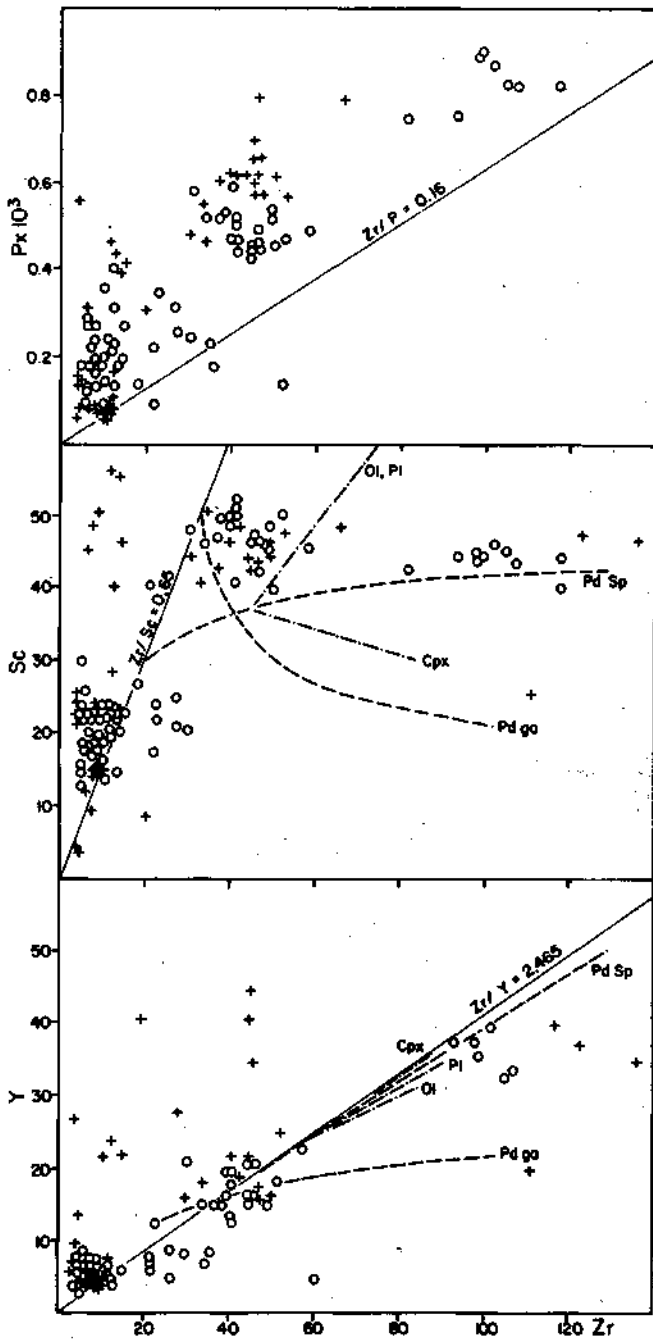
Figure 4 - Plot of Zr *versus P, Sc, and Y (ppm), for the samples from the Hidrolina (crosses) and Crixás (circles) greenstone belts. See the caption of figure 3 for the chondrite values, the model melting curves and for the fractionation vectors*

Figura 4 - Variação de Zr versus P, Sc e Y (ppm), para as amostras dos cinturões verdes de Hidrolina (cruzes) e de Crixás (círculos). Veja a legenda da figura 3 para os valores condríticos, para as curvas de modelo de fusão e para os vetores de fracionamento

as 88% olivine and 12% of a mixture of 9% clay (Si: Al = 1:2) + 3% quartz. The clay + quartz component could correspond to a normal lateritic rock assimilated by the komatiites during olivine fractionation. This mechanism is, however, unsuported by the trace elements behaviour: such a mixture whould contain negligible amounts of Y and Sc, and should produce for these elements MgO intercept sensibly lower than that determined by olivine fractionation, and not higher as in the present case.

Table 3 - *Mass balance calculation between the analyses in which MgO ranges from 27 to 29% and from 33 to 36% for the Crixás komatiites*

Table 3 - Cálculo de balanço de massa entre as análises nas quais MgO varia de 27 a 29% e de 33 a 36% para os komatiftos de Crixás

	Mg 27-29	Mg 33-36	Residue
SiO_2	47.79	45.81	43.24
TiO_2	0.45	0.35	0.22
Al_2O_3	2.80	3.28	3.90
Fe_2O_3	2.14	1.93	1.66
FeO	9.65	8.68	7.42
MnO	0.14	0.16	0.19
MgO	27.77	34.56	43.38
CaO	9.06	5.15	0.07

No CaO is assumed in the residue.

Emplacement and crystallization The trends towards the clinopyroxene composition (Fig. 1), as an alternative to tremolite, suggest its possible control. However, the examined single flows have an MgO content which prohibits early clinopyroxene crystallization either as cumulus or as spinifex. Virtually all the basaltic magmas with more than 12% MgO would have olivine as the only liquidus phase on a wide P range (Green *et al.* 1975, Arndt 1976, Kinzler & Grove 1985). Speculatively, a process consisting of the following steps could be proposed:

a. picritic magma crystallizes olivine during ascent;

b. effusion, with consequent chilling at the contacts, of a crystal mush of olivine and residual liquid retaining 10%-12% MgO;

c. crystallization of ol-spinifex, depleting further the residual liquid in MgO, and entry of clinopyroxene;

d. removal during flow of the basaltic residue, which continues crystallizing clinopyroxene.

The amount of clinopyroxene crystallized is in this model directly related to the amount of residual liquid with respect to the solid (olivine) and is expected to be maximum at the centre of the flow. Whether such a process is realistic is very doubtful as no natural occurrence where this happens has ever been described. An indirect support to the possibility that the liquid interstitial to olivine has a basaltic composition, capable of crystallizing clinopyroxene, comes, however, from the studies of Nisbet *et al.* (1987) and Aitken & Echeverria (1984), who show that in relatively fresh komatiites the interstitial glass has constantly a basaltic to andesitic composition. In any case, if operative at Crixás, there is no evidence that this process has been efficient also at Hidrolina.

Regional source heterogeneities The non-modal partial melting trends (parameters reported in the figure captions) of a mantle in spinel peridotite and garnet-peridotite fades, having the composition of the undepleted primitive mantle model of Hofmann (1988) ate reported in the plots of figures 3,4 and 5.

At Hidrolina, Rivalenti *et al.* (1989) have concluded that: a. the komatiites may have formed by mixing with, and assimilation of mantle material, by a liquid deriving from moderate melting degrees; b. melting involved a source in spinel-peridotite facies; c. the mantle source was slightly depleted in imcompatible elements.

Also at Crixás the samples follow a curve suggesting a spinel-, rather than garnet-facies source; the komatiites, plotting close to the source composition, may derive either by improbable extremely high melting degrees (50%-70%) or, like in Hidrolina, by mixing of liquid formed at moderate melting degrees with mantle material.With respect tcTthe model mantle of Hofmann (1988), the Crixás source was
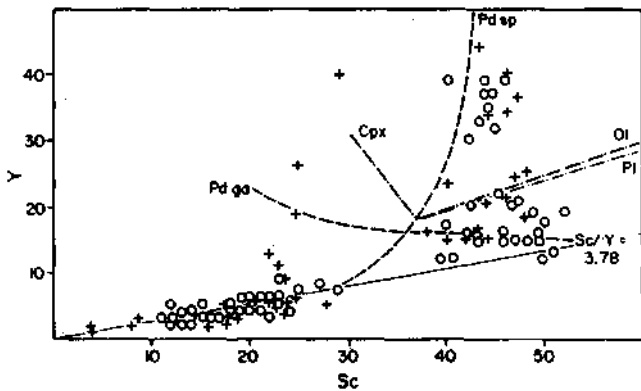
Figure 5 — Plot of Sc versus Y (ppm) for the samples the Hidrolina (crosses) and Críxás (circles) greenstone belts. See the caption of figure 3 for the chondritic values, the model melting curves and for the fractionation vectors
Figura 5 - Variação de Sc versus Y (ppm) para as amostras dos cinturões verdes de Hidrolina (cruzes) e Crixás (círculos). Veja a legenda da figura 3 para os valores condríticos, para as curvas de modelo de fusão e vetores de fracionatnento

probably depleted in Zr, Sc, Y and Ti.

The systematic differences from the Hidrolina suite, shown in the Ti-Sc, Ti-Zr, Ti-Y, Ti-V, Zr-Y, Zr-Sc and Zr-P plots, point to a different composition for the Crixás source. Of particular interest is the contrasting behaviour of the Ti/Sc, Ti/Y and Ti/Zr ratios between komatiites and basalts of Crixas and Hidrolina: in the Crixás komatiites they are higher, and in the basalts they are lower, with respect to Hidrolina. This fact may be accounted for a higher spinel content of the Crixás source: since partition coefficients for this phase are higher for Ti than for Zr, Y and Sc, liquids deriving from moderate (10%-30%) melting would be enriched in Sc, Zr and Y with respect to Ti, whereas the contrary happens in the melting residue. The different behaviour of V in the Crixás and Hidrolina komatiites is more difficult to be explained. The bulk partition coefficient for this element is strongly dependent, besides mineralogy, from fO_2 (Shervais 1982) and decreases by a factor of 100 for an increase of $\log fO_2$ from -12 to -6. The higher Ti/V ratio in the Crixás komatiites and slightly lower in the basalts with respect to Hidrolina suggests, therefore, a higher fO_2 in the first locality.

Like at Hidrolina, the low-Ti basaltic cluster of Crixás is compatible with a moderate degree (20%-30%) melting of the same source which gave the komatiites. Its Sc-Ti trend could, however, be consistent with olivine fractionation, but this is excluded as a main control by the small and random variation range of MgO in this group (Fig. 1). The high-Ti cluster of Crixás might represent lower melting degrees of the same mantle source as that of the low-Ti basaltic cluster (Figs. 3,4 and 5). The samples have, however, low *mg* numbers if compared with primary mantle-derived liquids. The fractionation vectors of figures 3, 4 and 5 indicate that they may derive by fractionation of clinopyroxene, accompanied by olivine and/or plagioclase, from the low-Ti group. A similar conclusion was reached also on the basalts of Hidrolina. For the rest, the differences between the basalts of the two localities may be accounted for the already discussed heterogeneities of the respective sources.

CONCLUSIONS Although remarkably similar in many stratigraphic and geochemical respects, the Crixás and Hidrolina greenstone belts show differences which are related in part to a regional variation of the mantle source composition.
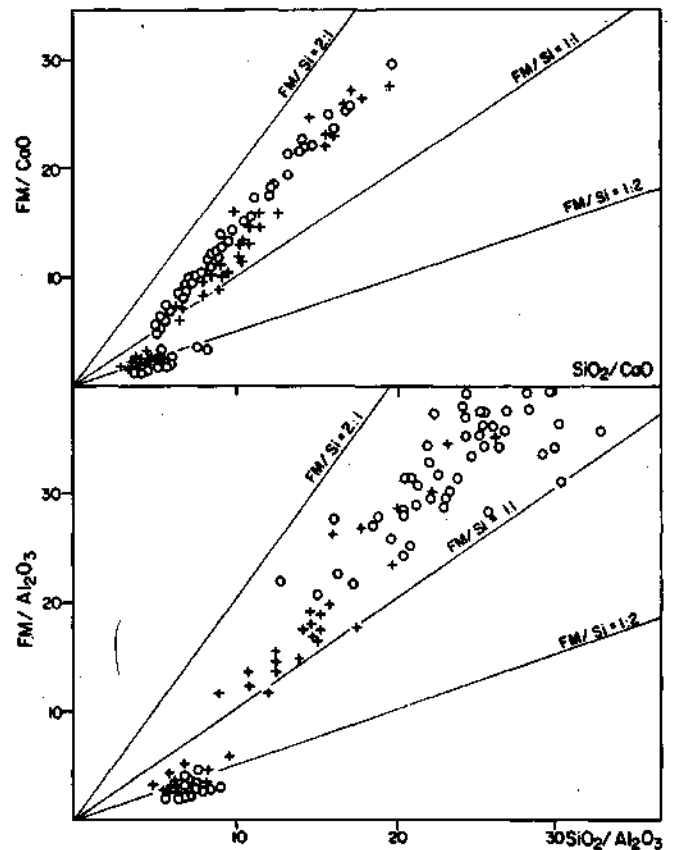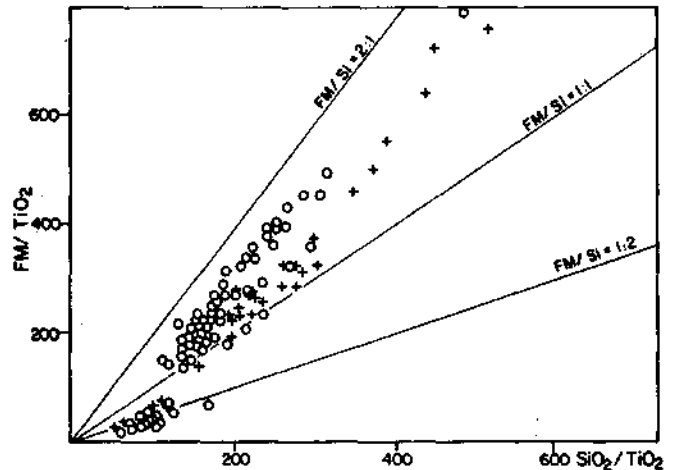

Figure 6 — Molecular proportion ratio plots (MPR or Pearce plots) of SiO₂/CaO versus FM/CaO, SiO₂/TiO₂ versus FM/TiO₂ and SiO₂O₃/Al₂O₃ versus Fm/Al₂O₃. FM = FeO+MgO. The lines FM/Si = 2:1,1:1, and 1:2 are reference lines for olivine, orthopyroxene and clinopyroxene respectively, drawn to pass through the origin, although this does not applies in natural cases. The komatiites of Crixás (circles) and Hidrolina (crosses, clearly show the influence of olivine as a control phase
Figura 6 - Diagramas de quocientes de proporções moleculares (Diagramas MPR ou de Pearce) de SiO₂/CaO versus Fm/CaO, SiO₂/TiO₂ versus FM/TiO₂ e SiO₂/Al₂O₃ versus FM/Al₂O₃. FM = FeO + MgO. As linhas FM/Si = 2:1,1:1 e 1:2 são linhas de referência para olivina, ortopiroxênio e clinopiroxênio respectivamente, desenhadas para passar pela origem , embora isto não se aplique em casos naturais. Os komatiftos de Crixás (círculos) e Hidrolina (cruzes) mostram claramente a influência da olivina como fase de controle

Mantle heterogeneities are evidenced by the behaviour of many incompatible or moderatey compatible trace elements (Ti, Y, Sc, Zr, V and P) and are probably consistent with a modal variation in the spinel content, higher in the Crixas than in the Hidrolina mantle.

The Crixás sequence shows many of the characteristics found in belts older than 3.5 Ga (Arndt *et al.* 1989 and references therein), such as low Al_2O_3/TiO_2 ratio, whereas the Hidrolina sequence is more similar in this respect to younger (2.7 Ga) belts.

A variability of the mantle source cannot, however, account for the differences in the CaO and Al_2O_3 behaviours (with respect to MgO). Their anomalous trends at Crixás have been tentatively attributed to a poorly constrained magmatic process, which implies clinopyroxene growth into an olivine mush. This process eventually has acted at Crixás and not at Hidrolina. Other possibilities, such as metamorphic open system, would imply differences in the metamorphism of the two areas, which is unsupported by the petrographic observations, whereas contamination of the magmas by crustal material is unsupported by the trace elements behaviour.

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