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LATERITIC EVOLUTION OF THE JACUPIRANGA ALKALINE COMPLEX, SP

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ABSTRACT

In the Jacupiranga alkaline complex, dunites and jacupirangites are the predominant rocks, covering an area of about 70% of the complex. Such rocks, altered by weathering, have developed a thick lateritic cover which can exceed 40 m. The dunite areas correspond to a plateau up to 190 m of altitude, whereas the jacupirangite areas present a more segmented morphology at lower topographic levels (15-50 m).

Overlying dunites (olivine, serpentine, chromite and magnetite), a profile down to 39 m depth has been sampled. It consists from bottom to top of a saprolite layer (serpentine, smectite and quartz), a Si-boxwork zone (quartz and goethite) and a laterite (goethite, kaolinite and quartz). The geochemical evolution of this profile can be characterized by total loss of Mg, retention of Si and residual concentration of Fe, Al, Cr, Ti, P and Zr are enriched towards the upper levels of the profile and Co, Ni, Mn, Ba and Ce show higher contents at intermediate levels. The weathering evolution from fresh rock to saprolite is lateritic. The Si-boxwork zone represents an episode of silicification and, finally, the lateritic cover, enriched in elements untypical of dunites (Al, Ti, Zr, V and P) must be the result of alloch tonous contribution.

Two weathering alteration profiles overlying jacupirangites (titanoaugite, magnetite and perovskite) have been investigated down to 30 and 40 m depth, respectively. In such profiles two horizons could be distinguished, from bottom to top: saprolite (titanoaugite, smectite, magnetite and anatase) and laterite (goethite, kaolinite, anatase and quartz). They have been formed by total loss of Ca and Mg, partial loss of Si and residual concentration of Fe, Al and Ti. V, Cr and Zr are gradually enriched from the fresh rock to the laterite. Ba, Zn, Cu, Ni, Co, Ce and Mn are concentrated in the early stages of weathering, being depleted onwards. This lateritic "in situ" evolution has had an initial stage of 2:1 phylosilicates formation, further replaced by the crystallization of 1:1 phylosilicates plus goethite. In the upper levels of the laterite, mechanical reworking of the soil by colluvial transport seems to have happened.

The investigation of weathering profiles overlying dunites and jacupirangites led to the hypotheses of a polycyclic weathering evolution for the Jacupiranga alkaline complex. During an initial phase of weathering under climatic conditions with alternating drier and more humid periods, the alteration of dunites led to the formation of a weathering profile with silica accumulation at its bottom, whereas the jacupirangites developed a smectitic cover. During a second phase, erosion processes related to a tectonic uplift removed the alteration blanket down to the Si-boxwork horizon in the case of dunites and to deeper levels in the case of jacupirangites. The weathering under a following period of humid climate resulted in very thick lateritic profiles. In this period, colluvial detritus of Al-Si-rich composition derived from more acid lithologies covered the "in-situ" weathering products. The intense intermixing led to the formation of the partially allochtonous blanket found today. Taking into account the supergene evolution of other ultramafic massifs in Brazil, the erosion cycle above mentioned can be correlated to the Velhas Cycle (Upper Tertiary), thus yielding a maximum age for the laterites of Jacupiranga.

RESUMO

No maciço alcalino de Jacupiranga, dunitos e jacupiranguitos são as litologias dominantes, perfazendo cerca de 70% de sua área total. Estas rochas, submetidas à alteração intempérica, geraram um espesso manto laterítico que ultrapassa 40 m. Os dunitos formam um platô pouco dissecado, com altitudes máximas da ordem de 190 m, enquanto que os jacupiranguitos, com uma morfologia mais segmentada, formam colinas de altitudes de até 50 m.

Sobre os dunitos (olivina, serpentina, cromita e magnetita), foi estudado um perfil de alteração de 38 m de profundidade, em posição de meia encosta. Este perfil apresenta da base para o topo 3 níveis de alteração: saprolito (serpentina, esmectita e quartzo), Si-boxwork (quartzo e goethita) e laterita (goethita, caolinita e quartzo). Quimicamente, ao longo do perfil, ocorre perda total de Mg, conservação de Si e concentração residual de Fe, Al, Cr, Ti, P e Zr encontram-se enriquecidos nos níveis superiores do perfil e Co, Ni, Mn, Ba e Ce mostram seus mais altos teores nos níveis intermediários. A evolução intempérica da rocha fresca ao saprolito é laterítica. O Si-boxwork representa um episódio de silicificação e, finalmente, a cobertura laterítica, enriquecida em elementos não típicos de dunitos (Al, Ti, Zr, V e P), deve ser resultado de contribuição alóctone.

Foram analisados 2 perfis de alteração sobre jacupiranguitos (titanoaugita, magnetita e perovskita), com 30 e 40 m de profundidade, situados no topo e na encosta de uma colina, respectivamente. Nestes perfis distinguem-se, da base para o topo: saprolito (titanoaugita, esmectita, magnetita e anatásio) e laterita (goethita, caolinita, anatásio e quartzo). Estes perfis, desenvolvidos essencialmente "in situ", evoluem por perdas totais ou parciais de Ca, Mg e Si e concentrações residuais de Fe, Al e Ti. V, Cr e Zr são gradualmente enriquecidos da rocha fresca à laterita. Ba, Zn, Cu, Ni, Co, Ce e Mn concentram-se nos estágios iniciais do intemperismo, sendo, em seguida, lixiviados. O processo de alte-

ração foi de natureza laterítica, com uma fase inicial de formação de argilo-minerais 2/1 que evoluem para 1/1. A porção superior do nível de laterita apresenta características mineralógicas e químicas que permitem identificá-la como proveniente de material parcialmente alóctone.

O estudo dos perfis de alteração sobre dunito e jacupiranguito permite emitir uma hipótese de evolução supérgena policíclica para o complexo alcalino de Jacupiranga. Assim, numa primeira fase de alteração, sob clima marcado por episódios de relativa aridez, a evolução dos dunitos conduziu à formação de um perfil de alteração silicificado em sua base, enquanto que os jacupiranguitos desenvolveram uma cobertura de natureza esmectítica. Numa fase posterior, processos erosivos relacionados a um soerguimento da região, provocaram a remoção das coberturas de alteração até o resistente *boxwork* silicoso, no caso dos dunitos, e mais profundamente, no caso dos jacupiranguitos. Num período seguinte, sob clima mais úmido, semelhante ao atual, a alteração, desta vez de caráter laterítico, promoveu o desenvolvimento de espessos perfis. Neste período, um aporte coluvionar, a partir de litologias mais ácidas, sobre as áreas de dunito e jacupiranguito, forneceu material que misturado àquele derivado das rochas subjacentes gerou a cobertura que hoje capeia os perfis. Por analogia com a evolução supergênica de outros maciços ultramáficos brasileiros, o ciclo erosivo acima citado pode ser correlacionado ao ciclo Velhas, do Terciário Superior, o que coloca um limite máximo para a idade do manto de alteração em Jacupiranga.

INTRODUCTION

The Jacupiranga alkaline complex consists of an association of ultramafic, alkaline and carbonatitic rocks intruded at the boundary between Proterozoic granodiorites and Archean basement. Dunites and jacupirangites are the predominant rocks, covering an area of about 70% of the complex. Both are ultramafic units, but chemical and mineralogical differences in their compositions have an important influence on their weathering alteration and give characteristic features to the thick lateritic blanket derived from them.

This paper is concerned with the structural, mineralogical and chemical characterization of the different horizons of the alteration profiles developed on dunites and jacupirangites and with the elaboration of a genetic model for the lateritic cover as a whole.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The Jacupiranga complex is located about 200 km SW of the city of São Paulo and covers an area of 65 km². It corresponds to an undulated eroded area where the elevations range from 40 to 330 m above sea level. The climate is humid and warm, with average monthly temperatures between 15 and 25°C and average annual rainfall of about 1500 mm.

The complex belongs to a group of alkaline intrusions of Cretaceous age which occurs at the margins of the Paraná basin. K-Ar dating yielded 130 ±5 Ma (Amaral, 1978). It is an elliptical body of 10 and 6 km of extension in the NNW-SSE and ENE-WSW directions respectively. According to Germann *et al.* (1988) the northern part of the massif consists of serpentinized dunitic rocks surrounded by a zone of dunitic assimilation with peralkalic dykes. The jacupirangites are the most important rock type dominating the southern half of the massif. As a magmatic differentation product of the jacupirangite magma, a crescent-shaped ijolite body occurs in the western part of the jacupirangite area. The carbonatite (sövite) is in the central part of the jacupirangite area, representing the final intrusive phase. A fenitization halo can be found along the western margin of the massif. The geologic map of the massif is shown in Figure 1.

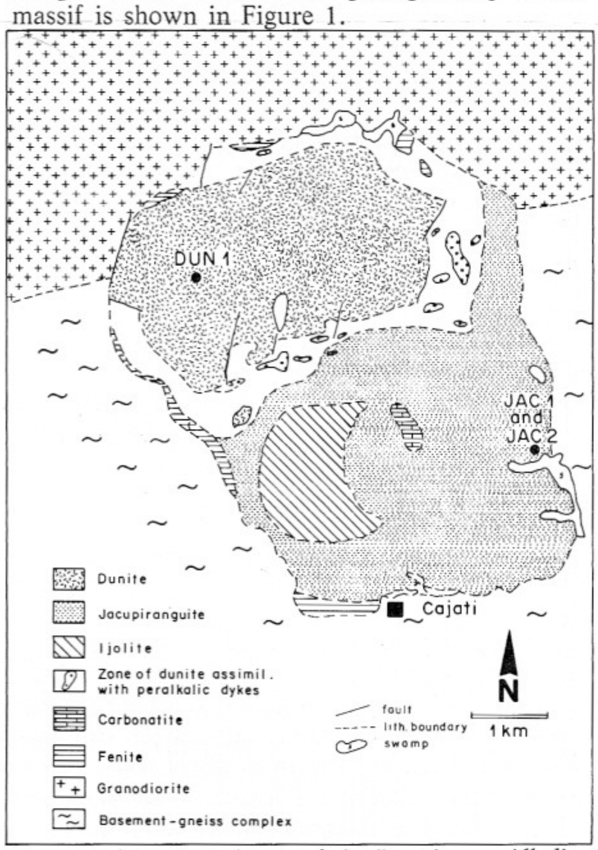

Figure 1 — Geological map of the Jacupiranga Alkaline Complex (after Germann *et al.*, 1988).

The jacupirangites and dunites have developed a thick lateritic cover in hill top positions and on flat ridges and plateaux. The laterite thickness can exceed 40 m. The dunite areas present a thick Si-boxwork layer creating a stable, erosion resistant, plateau of high elevation (up to 190 m) and wide drainage patterns. The jacupirangites areas are likewise covered by thick laterites, forming a more segmented morphology with a denser drainage pattern at a lower topographic level (15-50 m). The ijolite body forms a high ridge (300 m) made of fresh rock. The lateritic cover above the carbonatite, enriched in apatite, has been totally mined out.

WEATHERING OF DUNITES

The weathering profile overlying dunites has been investigated in the western part of the massif. The drill hole DUN 1 (Fig. 1) went down to 39 m, without reaching fresh rock, which has been sampled in 3 outcrops. In the dunite the relicts of olivine (40%) are surrounded by a network of serpentine with magnetite grains between the fibers. Chromite and ilmenite are the main accessory minerals. The bulk density of the fresh rock is 2.8.

The weathering profile consists from bottom to top of three zones: a) saprolite up to 26 m: greenish yellow-brown material with intercalations of less altered kaolinized syenites; b) Si-boxwork: brownish laterite filling up a quartz boxwork that reproduces the original structures of the rock, about 13 m thick; c) laterite: yellow to purple argillaceous laterite, without any original structure, 13 m thick.

At the bottom of the saprolite zone serpentine is present but olivine has already been hydrolized, being replaced by smectite and a ferruginous poorly crystallized product. In the cracks of the altered rock, quartz and garnierite occur as neoformed phases. Towards the top of this zone, smectite and serpentine alter and the original structures tend to disappear. In this level, black asbolane concretions are common. The density ranges from 2.5 to 1.5 in this zone.

The Si-boxwork zone is very heterogeneous with a composition ranging between a quartz pole (density about 2) and a goethitic one (density of 1). The lateritic zone is homogeneous, consisting of fine grained, poorly crystallized kaolinite and aluminous goethite. Quartz is abundant throughout this zone.

The general trends concerning the mineralogical evolution of these dunites during weathering have already been described by Oliveira & Trescases (1985).

Geochemical data for the major and trace elements in each zone are presented in Figures 2 and 3. Average contents are listed in Table 1.

The inhomogeneity of the weathering profile and its subdivision in three zones can clearly be seen from the major elements distribution within the profile (Fig. 2). Mg and Ca are almost totally depleted from the saprolite zone upwards. Al, Fe, Cr, Ti, V, P and Zr are enriched towards the upper levels and show a homogeneous behavior in the laterite zone. Si shows high values throughout the profile due to Si-precipitation as secondary quartz. Co and Ni are enriched in the lower

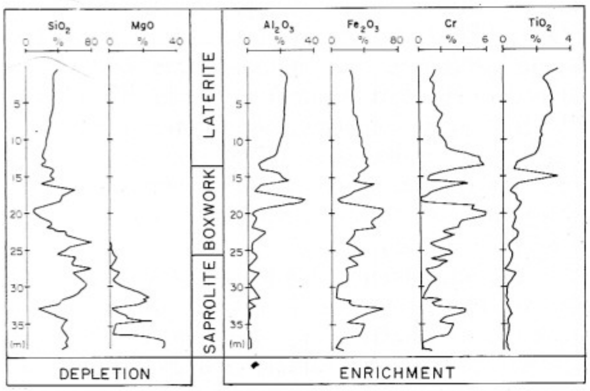

Figure 2 — Major elements distribution within the profile DUN-1.

Table 1 — Average values for the elements in the alteration profile overlying dunite (DUN-1).

	Laterite (n = 27)	Si-boxwork (n = 24)	Saprolite (n = 22)	Fresh rock (n = 3)
	Major elements in weight %			
SiO_2	29.4	37.1	48.6	38.7
TiO_2	2.4	0.9	0.3	0.1
Al_2O_3	20.2	11.1	2.4	0.3
Fe_2O_3	30.6	35.1	22.5	12.6
CaO	0.06	0.02	0.05	0.23
MgO	0.19	0.68	13.2	37.4
MnO	0.19	0.45	0.43	0.20
P_2O_5	0.23	0.11	0.04	0.01
	Trace elements in ppm			
Zr	340	110	51	n.d.
Nb	58	34	15	n.d.
Ce	235	223	101	85
V	454	317	82	34
Cr	22115	25272	15397	7440
Ba	355	720	410	n.d.
Zn	174	217	296	85
Cu	69	100	57	68
Ni	1027	3996	9053	4730
Co	49	288	401	186

n, number of samples; n.d., not determined levels. Mn and Ce have similar behavior, being probably together in the asbolane concretions.

The chemical evolution from fresh rock to saprolite is typical of lateritic weathering. The Si-boxwork zone is characterized by an absolute accumulation of silica, demonstrated by isovolumetric calculations (Oliveira & Trescases, 1985). The laterize zone, homogeneous and enriched in elements untypical of dunites (Al, Ti, Zr, V, P), must be the result of allochtonous contribution.

WEATHERING OF JACUPIRANGITES

Two profiles overlying jacupiranguites have been sampled (Fig. 1). Drill hole JAC-2 (40 m depth) was sunk on the flat top of a hill, while JAC-1 (30 m depth) was sampled along a channel trench on a slope position, 25 m bellow JAC-2. Along JAC-1 the following horizons are macroscopically distinguishable from bottom to top: a) saprolite (30-16 m): greenish to yellow saprolitic material with intercalation of white nepheline veins; b) laterite (16-0 m): purple argillaceous laterite without any original structure. In the profile JAC-2 the laterite consistence along the whole profile is very homogeneous and corresponds to the laterite zone of the profile JAC-1. The fresh rock has been sampled in outcrops and consists of titanoaugite (60-90%), Ti-magnetite and perovskite, with olivine, nepheline and phlogopite as the main accessory minerals. It's density is around 3.0.

The micromorphological aspects concerning the weathering evolution of the jacupirangites have been described by Oliveira & Delvigne (1988) and can be summarized as follows: a) pyroxenes alter into smectites in the saprolite zone (density between 1.1 and 2.4) and then to goethite and kaolinite in the laterite zone (average density 1.4); b) magnetite may be partially oxidized into hematite; c) perovskite is found only in the fresh and slightly altered rock, being totally transformed into anatase, which concentration increases towards the top of the profile; d) phlogopite (vermiculite) and nepheline alter partially into kaolinite.

Thus, the mineralogical composition of the saprolite is dominated by 2:1 phylosilicates whereas the laterite zone is composed essentially by 1:1 phylosilicates and goethite. In its upper levels, detritic quartz grains occur in minor quantities.

Table 2 presents the average contents for major and trace elements in each zone of JAC-1. Major element distribution along JAC-1 and JAC-2 is shown in Figure 4.

Ca and Mg are depleted in the saprolite zone, being totally leached in the laterite. The depletion of silica is less intense. Al, Fe and Ti behave in the opposite manner, being enriched in the laterite. Among the trace elements 2 groups can be distinguished: a) V, Cr and Zr are gradually enriched from the fresh rock to the laterite; b) Ba, Zn, Cu, Ni, Co, Ce and Mn are enriched in the early stages of the alteration process, but are depleted onwards. The upper levels of the laterite cover (laterite 2 in JAC-2) present a homogeneous distribution in the contents of Al, Fe, Ti and Si, being in this aspect similar to the lateritic cover above dunites.

The jacupirangites show a normal lateritic evolution from the fresh rock to the laterite 1 zone. However, in the upper levels of the profile, present in JAC-2 and eroded away from JAC-1, a mechanical reworking of the laterite by colluvial transport seems to have happened.

Table 2 — Average values for the elements in the alteration profile overlying jacupirangite (JAC-2).

	Laterite 2 (n = 26)	Laterite 1 (n = 46)	Saprolite (n = 8)	Fresh rock (n = 13)
	Major elements in weight %			
SiO_2	30.9	15.1	22.2	41.7
TiO_2	6.9	9.4	7.8	4.0
Al_2O_3	21.3	15.7	16.7	8.9
Fe_2O_3	28.0	48.6	41.0	18.2
CaO	0.05	0.03	0.19	13.74
MgO			0.47	9.25
K_2O	0.12	0.19	0.07	1.24
MnO	0.19	0.98	1.07	0.18
P_2O_5	0.38	0.62	0.75	0.40
	Trace elements in ppm			
Zr	370	321	271	109
Nb	67	45	8	n.d.
Ce	396	465	701	42
V	1163	2373	1678	460
Cr	1021	882	945	274
Ba	512	1771	2939	1005
Zn	74	154	358	71
Cu	219	914	1289	248
Ni	79	176	421	199
Co	31	233	557	71

DISCUSSION

Taking into account the characteristic features of the lateritic cover above dunites and jacupirangites and the similarities with the supergene evolution of other ultramafic massifs in Brazil (Melfi *et al.*, 1980), a genetic model for the weathering history of Jacupiranga is proposed.

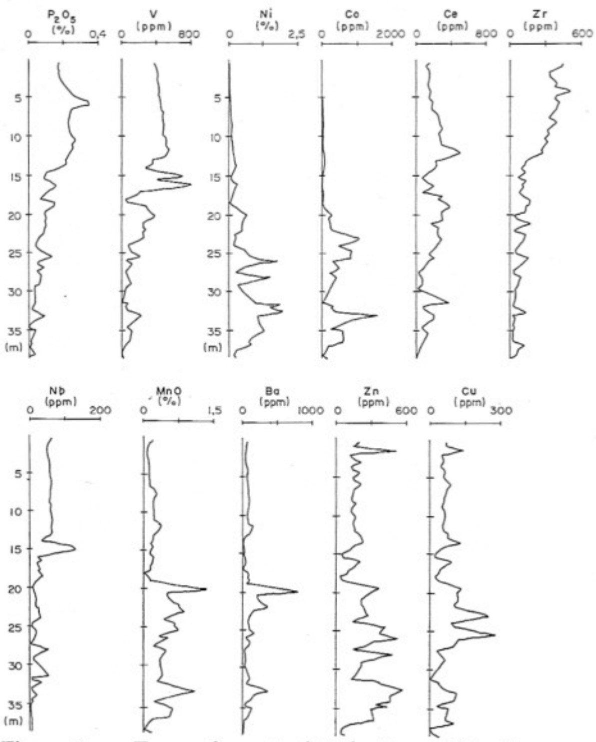

Figure 3 — Trace elements distribution within the profile DUN-1.

The alkaline complex of Jacupiranga has been submitted to a polycyclic evolution comprising 3 phases:

- An initial phase of weathering occurred during Early Tertiary under a more arid climate. Dunites developed a silicified layer at the bottom of the profiles, due to the strong retention of silica in drier conditions. Jacupirangites altered to a smectitic material which did not evolve to a goethite plus kaolinite horizon.
- Tectonic uplift and subsequent erosion during Late Tertiary led to the removal of the alteration blanket down to the Si-boxwork layer in the case of the dunites and to deeper levels in the case of jacupirangites. This hypothesis can explain why dunites are found in higher topographic levels than jacupirangites.
- During a following period of humid tropical climate, lateritization transformed the fresh and the silicified rocks into the products found today in the alteration profiles. Colluvial detritus of Si-Al-rich composition covered the in situ weathered materials and mixed up with them, forming the partially allochtonous blanket.

The lateritic weathering which altered the lithological types of the Jacupiranga complex had some metallogenetic consequences. In the dunite area, concentrations of Ni led to the formation of an ore deposit with 2.10^6 ton averaging 1.5% Ni (Schobbenhaus *et al.*, 1984). Although without economic interest, concentrations of Co and Cr up to 0.16 and 5.9% respectively can be found. In the jacupirangite area, Ti may be concentrated up to 4 times its original contents, reaching values of about 10% TiO_2. Finally, the lateritic cover developed above carbonatites contained up to 23% of apatite residually concentrated (Melcher, 1954).

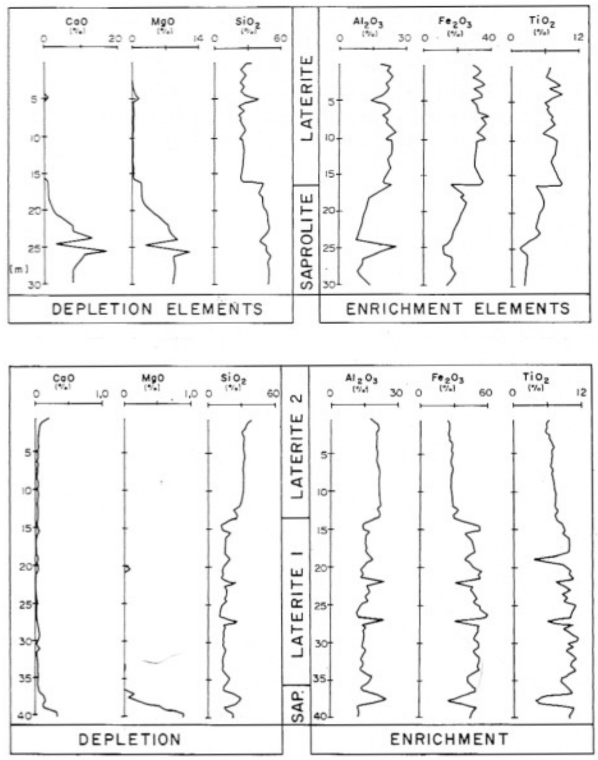

Figure 4 — Major elements distribution within the profiles JAC-I and JAC-2.

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