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1. THE JACUPIRANGA ALKALINE COMPLEX

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Introduction

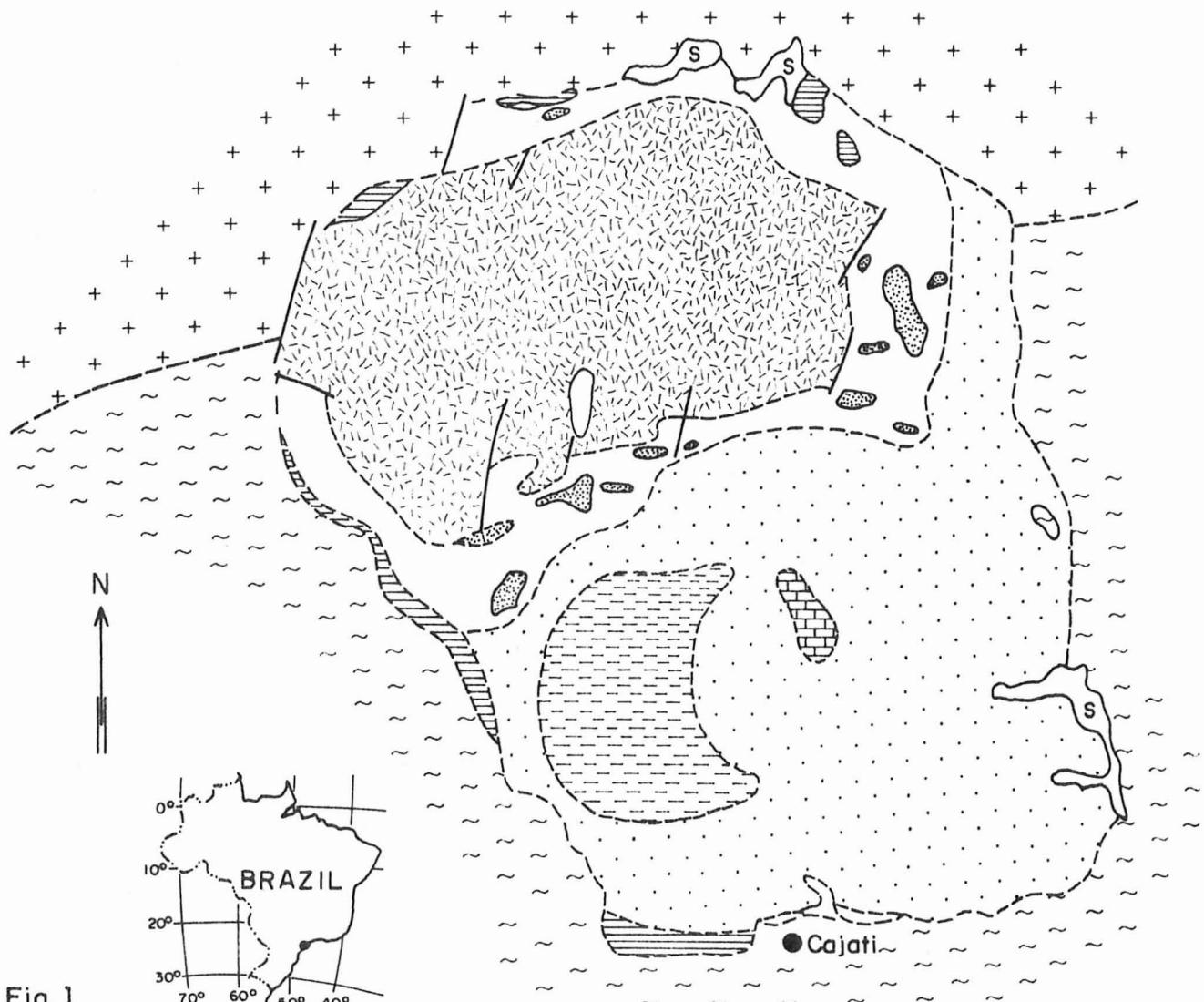
The complex is located about 200 km southwest of the city of São Paulo (Fig. 1) and covers an area of about 65 km^2 . It is intrusive at the contact of tightly folded mica schists of the Açuñui Group and a syntectonic granodiorite belt, both of Late Precambrian age.

First discovered by Bauer (1877) as an iron ore deposit, the JAC became world-famous after work by Melcher (1954, 1966), who was the first to suggest a magmatic origin for the carbonatites which intrude the jacupirangites in the central part of the complex. This area has been mined for apatite by Serrana S/A de Mineração for several decades.

According to K/Ar determinations from Amaral et al. (1967), and especially Amaral (1978), the main phase of the JAC intrusion has an age of $130 \pm 3 \text{ Ma}$.

Germann et al. (in press) present a geological map of the whole complex (Fig. 1) which essentially maintains the main divisions and outcrop areas proposed by Melcher (1966). Peridotites (dunites), pyroxenites, jacupirangites and ijolites are main rocks, with a carbonatitic plug in the central part of the southern half, chiefly made up of jacupirangites. Peridotites (dunites according to Germann et al., in press) are dominant in the northern part of the complex and are essentially composed of fine-grained olivine (Fo_{90}), partially altered to serpentine. In the areas close to the dunitic body, and also in the southern part of the complex, a mineralogical gradation to ijolitic terms (with sodic pyroxenes) may be noticed.

Typical jacupirangite is essentially composed of clinopyroxene (Ti-augite) and Ti-magnetite, with biotite, apatite, nepheline, perowskite and calcite in minor amounts. In many places, this rock exhibits a foliated structure.



Gabbroic dykes, in the western part of the complex, as well as essexitic and theralitic dyke swarms, in the eastern part of the transition zone between dunites and jacupirangites, are reported by Germann et al. (in press), who also state that syenitic dykes, which intersect the cited dyke rocks, show a gradual transition to alkali granites. Ijolitic, monchiquitic and tinguaitic dykes are also referred by Melcher (1966).

According to this last author, the basic complex was probably emplaced in two separate intrusive stages: first, the peridotitic-dunitic body, in the northern part of the structure, being enveloped by pyroxenites; and then, an almost circular plug of jacupirangite, with local differentiation to ijolite, in the southern region. The core of carbonatites then intruded the central part of this last silicate intrusion.

A complex zone of fenitization occurs along the contacts with the country rocks. At the contact with granodiorites, fenitization proceeded with a gradual decrease in quartz content, substitution of biotite by sodic clinopyroxene, and feldspar recrystallization around the margins of older feldspar grains. Where metasomatism was stronger, the quartz disappears, and the feldspar is completely recrystallized to soda-orthoclase or anorthoclase, also with the formation of nepheline and minor calcite. The leucocratic alkaline rocks (syenites), found both to the west and east of the contact between the two major intrusions, may represent mostly rheomorphic mobilization from fenites. They are essentially composed of alkali feldspar (sodic plagioclase or anorthoclase), with minor amounts of nepheline, aegirine-augite, biotite, titanite and apatite. The distinction between true nepheline syenites and fenites is sometimes difficult, suggesting that a gradation occurs from country rock to intrusive nepheline syenites.

The Jacupiranga carbonatites

The carbonatitic body at Jacupiranga is oval (1000 x 400 m) and crops out in a hill called "Morro da Mina", which had an initial height of 225 m at the start of mining activities, which first removed the residual apatite ore formed by

weathering of the carbonatite. Today, the fresh surface of the carbonatite can be seen everywhere on the open-pit walls: it clearly intrudes the jacupirangites, with a steep contact and outward dips (Fig. 2).

Melcher (1966) found two independent plugs, the northern and southern bodies. Gaspar & Wyllie (1983) identified five distinct intrusions; three of them, C1 (sövite), C2 (dolomitic sövite) and C3 (sövite), form the southern intrusions, while C4 (sövite) and C5 (rauhaugeite) correspond to the northern body. The intrusion sequence is C1 the oldest and C5 the youngest. Hirano et al. (1987) considered C3 and C1 as belonging to the same intrusive episode, since they present the same mineralogical characteristics. Swarms of beforitic dykes occur in some areas, but in other places the dolomitic composition is attributed to metasomatic dolomitization of primary sövites.

The main mineralogical and petrographical features of the carbonatite intrusions identified by Gaspar & Wyllie (1983) are summarized in Table 1. Hirano et al. (1987) grouped the mineralogical varieties into four classes: calcite carbonatite (CC); magnetite-rich calcite carbonatite (CCmt); apatite-rich calcite carbonatite (CCap); and dolomite carbonatite (DC); main features are summarized in Table 2.

The southern plug is mainly composed of CC, with CCmt bands, as well as xenoliths and bands of CCap in the marginal portions, the whole mass displaying a crescent-shaped structure. DC form a swarm of small dykes in the northeastern portion of the southern body. Jacupirangite xenoliths with reaction bands are frequent close to the contacts with silicate rocks. In the southern part of this body, CC intrudes the jacupirangite as dyke swarms with nearly straight boundaries, whereas plastic deformation can be noticed in the host rock, in the northern margin (Hirano et al., 1987). CC and CCmt exhibit mineral banding due to alignment of magnetite concentrations, interpreted as flow structures by Melcher (1966).

The northern body is a pipe-like composite plug, mainly composed of CC with a DC core. CCmt bands, inside CC, present a distinct concentric pattern with

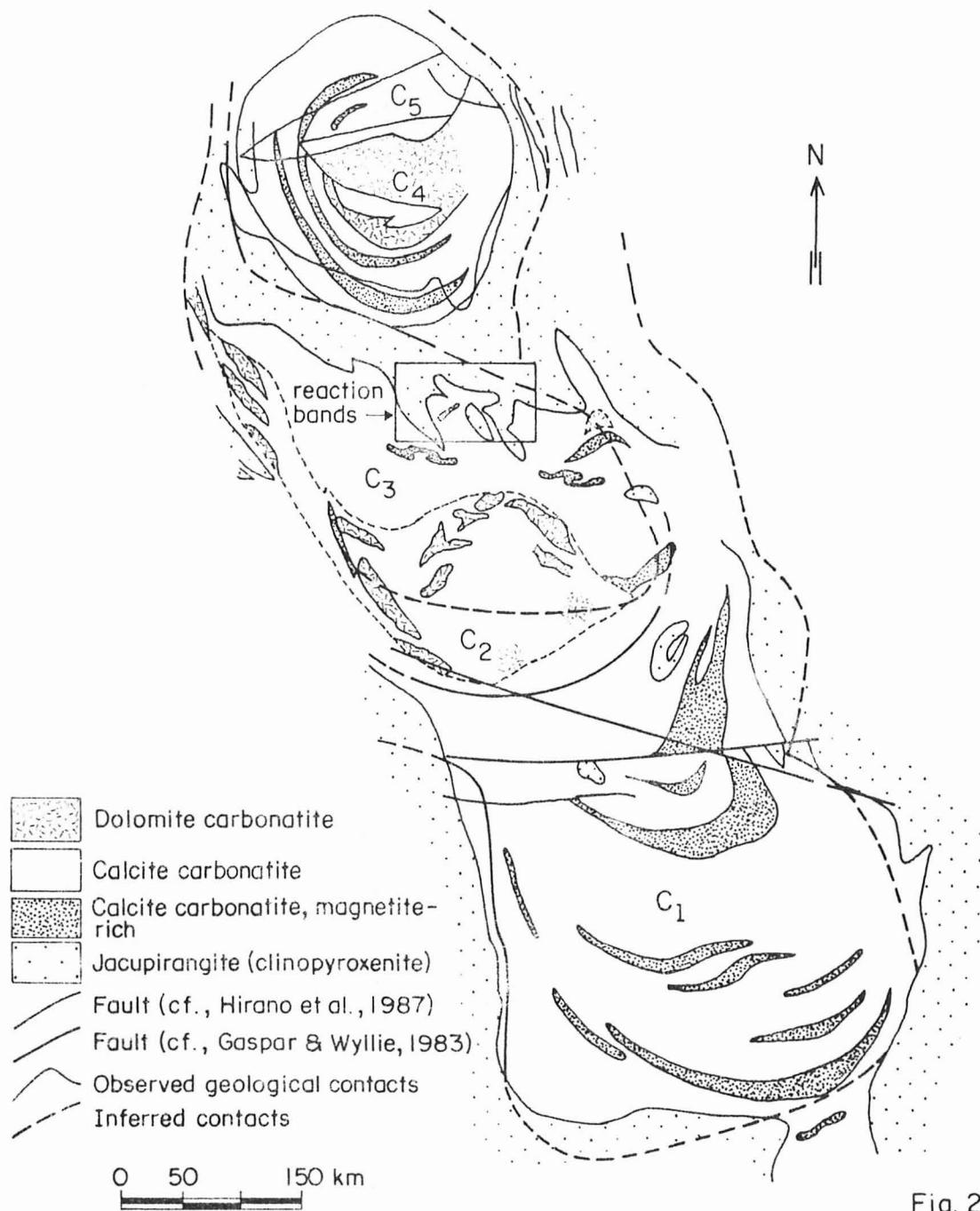


Fig. 2

Table 1 - Petrography of carbonatites and jacupirangite (after Gaspar & Wyllie 1983)

| Rock type* | | Main mineralogy** | Grain size | Other features | |
|--|----------------|--|---|---|---|
| | C ₁ | Sovite | Calcite, apatite, magnetite, olivine, phlogopite, dolomite, sulfides. | Coarse | Coarsely banded |
| Southern Intrusions | C ₂ | Dolomitic sovite | Calcite, dolomite, apatite, magnetite, phlogopite, sulfides. | Fine to medium | Finely banded |
| | C ₃ | Sovite | Calcite, apatite, magnetite, phlogopite, dolomite, olivine, sulfides. | Medium to coarse | Non-carbonate minerals fewer than in other sovites. Banding less evident. |
| Northern Intrusions | C ₄ | Sovite | Calcite, apatite, magnetite, olivine, phlogopite, dolomite, sulfides. | Medium | |
| | C ₅ | Rauhaugite | Dolomite, apatite, phlogopite, magnetite, sulfides, calcite. | Medium to coarse | Very few silicates, oxides and sulfides |
| Dikes*** | B ₄ | Beforsite | Dolomite, phlogopite, magnetite, calcite | Fine | Intruded in the C ₄ sovite |
| | B ₅ | Beforsite | Dolomite, calcite, apatite, magnetite, phlogopite, sulfides. | Medium to fine | Offshoot of the C ₅ rauhaugite in the C ₄ sovite |
| Rocks from the contact between carbonatite intrusions C ₂ and C ₃ | S | Sovite | Calcite, dolomite, apatite, phlogopite, magnetite, sulfides. | Medium to coarse | Diffuse banding |
| | B | Beforsite | Dolomite, calcite, apatite, magnetite, sulfides | Medium | Diffuse banding |
| Reaction zone between the intrusions (C ₁ , C ₃) and C ₅) and the jacupirangite | Reaction rock | Phlogopite, alkali amphibole, calcite, magnetite, apatite, sulfides, ilmenite, clinohumite | Fine to coarse | Silicate rich bands alternate with carbonate rich bands (magnetite occurs in the silicate bands only) | |
| Host rock | JAC | Jacupirangite | Titanoaugite, titanomagnetite | Medium | |

* Other rock types cited in the text: alvikite (calcite, apatite, dolomite, phlogopite) and ijolite (clinopyroxene, nepheline).

** The minerals are cited in an estimated decreasing order of abundance

*** The characteristics cited for these two dikes refer specifically to them and not to the dikes in general that occur in the carbonatite bodies.

vertical dip. The mineralogy of the northern CC and CC_{mt} is essentially the same as that of the southern body, except for the lack of olivine-bearing CC and CC_{Cap}.

Distribution maps for P₂O₅, total Fe₂O₃ and MgO were drawn by Melcher (1966), based on chemical analysis of more than 400 carbonatite samples from the surface (Fig. 3). Although the topography has been changing during the last 20 years, a good correspondence can be seen among these maps and the geologic map presented by Hirano et al. (1987) for the Jacupiranga carbonatites (Fig. 3), a fact that is interpreted by these authors as evidence of the high-angle chemical structure of the carbonatite plugs. The distribution pattern of P₂O₅ is governed by the high concentration of two apatite-rich types: fine-grained apatite in DC of the northern and southern plugs, and coarse-grained apatite in CC_{Cap} in the marginal zone of the southern plug.

Table 2 - Classification and main features of Jacupiranga carbonatites.

| Rock name | Occurrence | Main carbonate mineral | Other major and accessory minerals (decreasing order of abundance) |
|--|---|------------------------|---|
| Calcite carbonatite (CC) | Major constituent of the both, southern and northern plugs. Some CC intrude into other CC as sheets and dikes. | | Apatite, magnetite, dolomite; accessory phlogopite (with more than 10% BaO, Gaspar and Wyllie, 1982), corroded olivine (Fog3, Mitchell, 1978), anhedral piirrotite, chalcopyrite and valleriite (Boctor and Svisero, 1978). Clinohumite as olivine reaction borders. |
| Magnetite-rich calcite carbonatite (CCmt) | CCmt occurs as rhythmic bands in CC of the both plugs. | calcite | Magnetite (3 to 15 mm, frequently zoned), dolomite, phlogopite, apatite, and minor olivine and sulphides. |
| Apatite-rich calcite carbonatite (CCap) | CCap occurs as xenoliths and bands in CC, especially in the marginal zones of the southern carbonatite plug. | | Apatite (3 mm, euhedral to subhedral, more than 40% modal content), olivine (anhedral, includes apatite), magnetite, dolomite and minor phlogopite and sulphides. CCap may represent primitive carbonatitic magmas, and are mineralogically correspondent to phoscorites. |
| Fine to medium grained dolomite carbonatite (DCfg) | DCfg intruds in the center of the carbonatite plugs. | both | Apatite (acicular and columnar, 10 - 30% modal content; minor amounts of magnetite (anhedral to subhedral), phlogopite and anhedral calcite (2-8%), sulphides and sometimes olivine with phlogopitic borders. |
| coarse grained dolomite carbonatite (DCCg) | DCcg occurs mainly the center of the northern plug as rhythmic bands with DCfg. Some large crystals of dolomite develope from the wall of DCfg. | DCcg | |

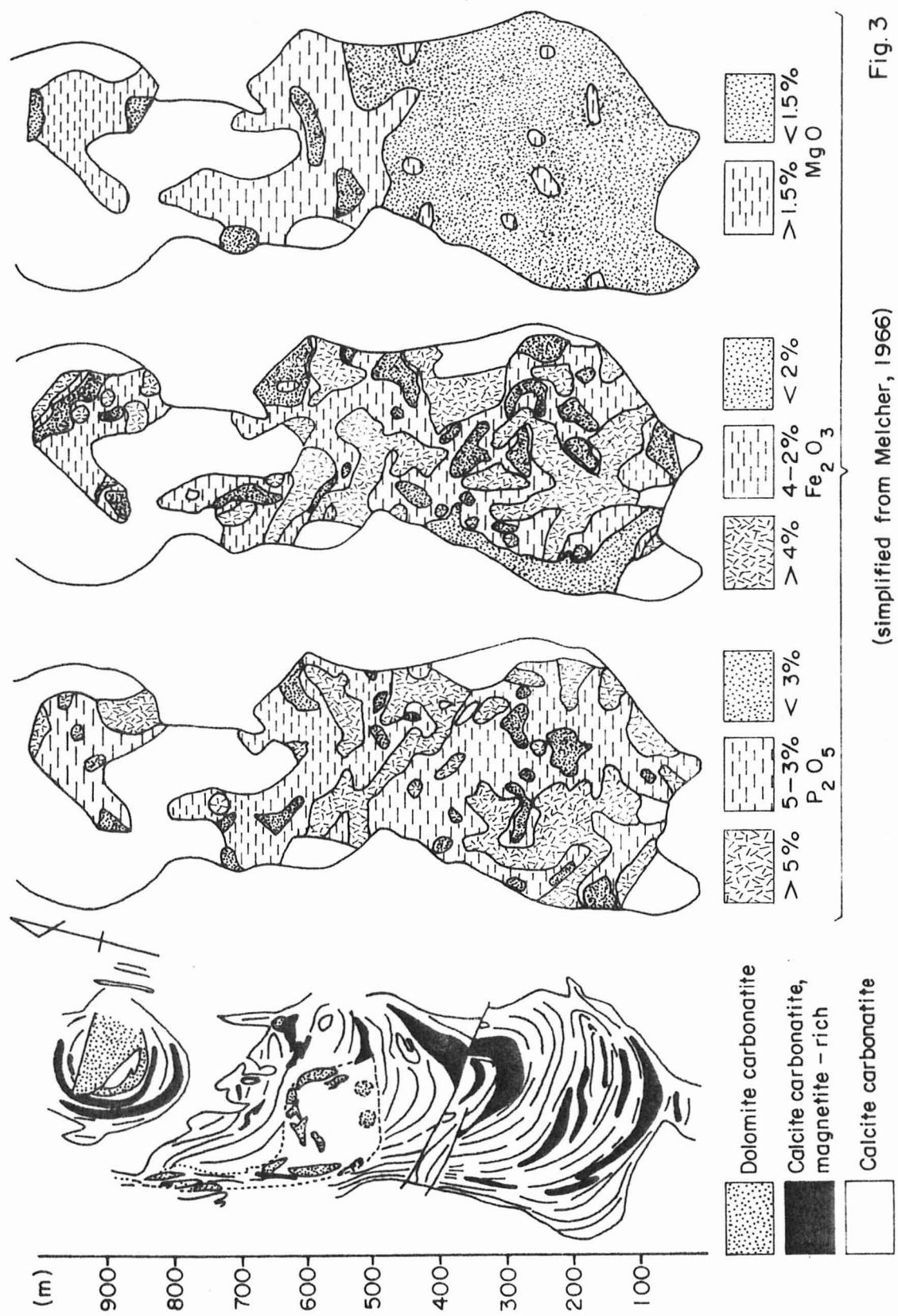
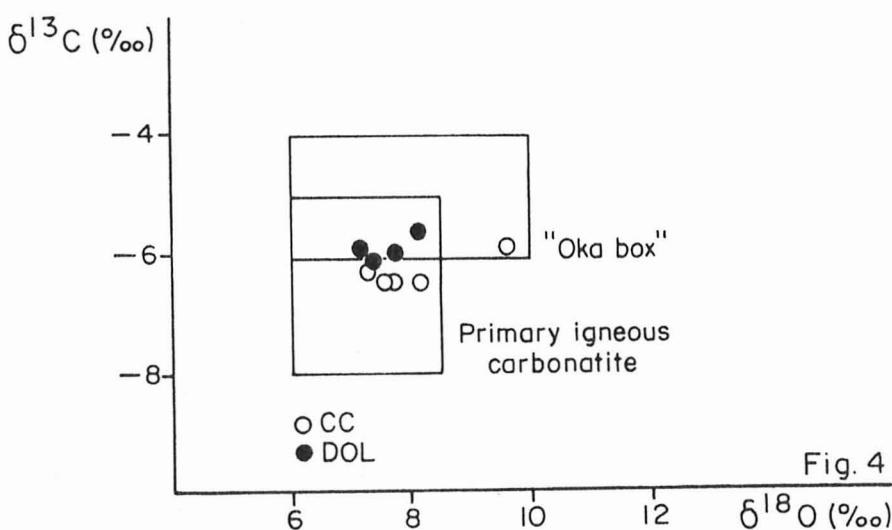


Fig. 3

(simplified from Melcher, 1966)

Roden et al. (1985) revealed recently that the southern carbonatites, including DC, are isotopically quite homogeneous, whereas the northern carbonatites have slightly more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. These data may suggest that the southern carbonatite magma has been less contaminated with the radiogenic continental materials, compared with the northern one.

Morikiyo et al. (1987) present some data on carbon and oxygen isotope compositions of carbonates from the Jacupiranga carbonatites. The $\delta^{13}\text{C}$ values are uniform from -6.4 to -5.6 per mil, and the average value is -6.07 per mil. Except for one sample, the $\delta^{18}\text{C}$ values of the same carbonates are between 7.1 and 8.1 per mil, and the average value is 7.6 per mil. The $\delta^{13}\text{C}$ values of dolomites are about 0.5 per mil higher than those of calcites, a difference which is much smaller than the previously reported results. The isotopic data for Jacupiranga in the $\delta^{13}\text{C}$ vs $\delta^{18}\text{O}$ diagram (Fig. 4) are considered as representative of primary igneous carbonatite values well inside the "primary igneous carbonatite" field (Taylor et al., 1967) and very close to the "Oka box" defined by Conway & Taylor (1969). The anomalous $\delta^{18}\text{O}$ value was interpreted as indicative that this calcite was precipitated from the magmatic fluids at a later stage.



The reaction zones

According to Morbidelli et al. (in press), jacupirangite blocks, up to 50 m across and included in the carbonatites, are enveloped by almost concentric shells whose width varies from a few cm up to 1 m. Not rarely, some portions of the outermost part of these shells show plastic deformation due to intrusions of carbonatitic veins.

Starting from jacupirangite to carbonatite, the normal sequence of the shell is as follows: A (amphibolic), P (phlogopitic) and O (olivinic).

Shell A (amphibolic)

This shell, which is in contact with the fresh black jacupirangite, is commonly deep green in colour, fine-grained and 1-5 cm thick, exceptionally reaching 20 cm; starting a few cm from the sharp contact with the jacupirangite (transition zone), millimetric white carbonate bands are interposed at subcentimetric intervals.

Transition from the jacupirangite to shell A is marked by an abrupt change in mineralogical composition, but the jacupirangite texture is almost completely preserved. Clinopyroxene crystals are pseudomorphically substituted by amphiboles (Mg-arfvedsonite, pargasite, Mg-hastingsite, besides richterite, the dominant phase) and subordinate phlogopite aggregates, of later formation with respect to the amphiboles, show more than one type of occurrence; the phlogopite crystals, which are commonly zoned and with reverse pleochroism, exhibit a differential growth from the jacupirangite zone to the outer part of this shell.

Magnetite is the only important mineral from the jacupirangite remaining in this shell, but farther away from the transition zone it loses its identity. Diffuse ilmenite grains and elongate clusters of titanite are also described.

The carbonate bands in this zone are quite regular, with anhedral calcite crystals including needle-shaped richterite and laths of phlogopite. Apatite from the carbonatitic magma is also commonly associated with the carbonates.

Shell P (phlogopitic)

This shell, wine in colour and ranging in width from centimetric to 1 m ca.,

shows a similar configuration to the previous one, but the white veins are not so regular and sometimes they lose their planar identity and assume the form of white spots or lines with oblique orientation relative to the borders of the shell.

The most striking mineralogical difference with respect to shell A is the dominance of phlogopite over amphibole. Phlogopite, which here also has reverse pleochroism and is usually zoned, exhibits grain size similar to those developed in the outer part of that shell. Ilmenite grains, associated with this mineral, are smaller and in greater number than in the amphibole aggregates from shell A.

The magnetite crystals in shell P are partially or completely transformed so that no big crystals occur; their grain size, however, is more developed than that of ilmenite grains; titanite is virtually absent in this shell.

Amphiboles become essentially restricted to large needle-shaped crystals, with rhombic section, diffuse along the borders of the protoclinopyroxene crystals, or associated with calcite; in this shell, only richterite is present.

Apatite minerals are well developed in the carbonate levels.

Shell O (olivinic)

This is the outermost shell; it is several centimeters up to decimeters wide and distinguishable from the preceding one by its darker, almost black colour, with no reddish-violet tint. The external shape of this shell is not as regular as the jacupirangite-shell A contact, since it is frequently deformed by the intrusion of one or more carbonatitic veins.

As already noted, the relative thickness of these shells is quite variable, but shell P is by far the most developed. Shell O may sometimes be absent, especially when no carbonatite vein is found between two xenoliths.

In this outer shell, as expected, the influence of carbonatite-derived transformation processes is still more evident than in the preceding ones, especially because it was usually also strongly pervaded by the carbonatite magma.

This shell is characterized by the presence of abundant olivine, mostly

rounded and with central clouds of thin inclusions of an opaque mineral that is very difficult to determine, even by microprobe analyses, but should be related to the finely dispersed ilmenites of shell P. Some larger olivine crystals are of a second generation, and besides these two mineral phases some relict olivine can also be found. These relict olivine crystals may be easily distinguished by their larger size, irregular shape and intense fracturing, as well as by the absence of the cloudy inclusions described above. These olivines are strongly affected by serpentinization processes.

Clinohumite, forming large crystals, sometimes titaniferous, with typical golden yellow to light yellow pleochroism, sometimes substitute both kinds of olivine.

Phlogopites are also of two generations: the older one, which can be included in some larger olivine grains, is fine-grained and anhedral, forming clusters in close association with opaque minerals; the second generation forms relatively large poikilitic crystals which, in turn, include also the second generation olivine and opaque minerals. The colour, pleochroism and zoning of the first generation of phlogopites, in the internal zones of this shell, are similar to those typical of shell P. In the external zone of shell O, where the carbonatitic influence is more evident, all phlogopites become less coloured, rarely zoned, with cores exhibiting mild yellow to green colour and almost colourless rims.

Opaque minerals - magnetites and ilmenites - of large size (0.5-1 mm) and irregular shape also occur in this shell.

As already stressed, the carbonatitic fluids were very pervasive here. Carbonates constitute isolated laths or well defined veins and, in this case, are frequently accompanied by apatite, which includes very rare needles of amphibole at the contact of the carbonates with the silicate bands.

Morbidelli et al. (in press) carried out detailed study of these reaction bands in order to define their most distinctive mineralogical and petrographical features, bulk chemical composition (major, minor, trace elements and REE

distribution) and chemistry of the more significant minerals.

Whilst the general structural aspects inherited from the jacupirangite protolith are still visible in shell A, shell O appears like a much more evolved level, as a consequence of the direct contact with the carbonatitic mass, which pervaded all this zone and sometimes seems to have disrupted and folded the preceding silicate (especially phlogopitic) aggregates.

The relations among the various quantitatively most important silicate minerals (amphiboles, olivines and phlogopites) suggest that the carbonatitic fluids responsible for the jacupirangite transformation initially caused a change of the Ti-augite in calcic, calcic-sodic and sodic amphiboles; successively, with the growing influence of potassium, and in a still aqueous environment, began the formation of phlogopite.

This last phase, probably owing to a relative alumina deficiency, crystallized as tetraferriphlogopite concomitantly with the formation of well crystallized richterite grains, in this oxidizing environment.

Petrographic evidence also indicates that the olivine formed soon after the amphibole crystallization was inhibited by the scarcity of sodium in the system, and that phlogopite crystals developed even after the olivine segregation. The formation of this phlogopite was probably carried out in lower fO_2 conditions, as indicated by its pleochroism and by chemical analyses of larger crystals in shell O.

The presence in shell O of olivine belonging to three generations is suggestive that the magmatic material responsible for the formation of this level had different characteristics from that one which caused the formation of shell A.

The chemical and physical data summarized by Morbidelli et al. (in press) indicate that the jacupirangite transformations developed in several stages, with a complex paragenesis. They also show that the protolith mineralogical association suffered the action of both volatile fluids and carbonatitic melts, characterizing metasomatic as well as carbonatization phenomena, which are

evidenced by the presence of calcite veins (shells A and P) and mostly by the calcite impregnation (shell O).

The volatile fluids generated new metasomatic aggregates containing remarkably greater quantities of major and trace elements (Na, K, Rb) than are found in such jacupirangite or in the carbonatitic rocks from the whole complex.

The REE contents of the various shells resulting from these fenitization processes are intermediate between those of jacupirangite and carbonatite, pointing out that the penetrative effect of these processes was modest and inversely proportional to the distance from the carbonatitic rocks.

In the Jacupiranga complex the fenitization processes affected the country rocks over a great areal extent, but cannot be related with confidence to carbonatitic fluids, like the processes which generated these reaction bands. The study of Morbidelli et al. (in press) elucidates an aspect that is somewhat confusing in the literature: the original characteristics of carbonatitic magmas, and especially their contents in alkalies, can be suggested by the transformations that carbonatite derived fluids are able to provoke in ultramafic country rocks like the jacupirangites.

According to the chemical balance performed by the same authors, it was possible to conclude that the carbonatitic magma, probably due to its extreme paucity of silica and alumina, was not capable to maintain all the alkalies present in the crystallizing melt during its solidification process.

If on one hand, Morbidelli et al. (in press) agree with Gittins et al. (1975) and with others which stressed the importance of the alkali activity, and especially Na and K, in these fenitizing fluids, it must be kept in mind that a relatively low total weight of these elements would be enough to cause the effects verified in the Jacupiranga reaction bands.

Acknowledgments

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