PETROGENESIS OF THE MONZONITIC-MONZODIORITIC PIRACAIA MASSIF, STATE OF SÃO PAULO, SOUTHERN BRAZIL: FIELD AND PETROGRAPHIC ASPECTS

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ABSTRACT The Piracaia Massif, located within a migmatized sequence of ortho- and paragneisses, is petrographically and structurally very complex. Detailed mapping has identified about 30 petrographic varieties (facies). Composition varies from diorites to quartz alkali feldspar syenites, with predominant monzodiorites and monzonites. The overall intrusive sequence is from more mafic to more felsic units. Main primary minerals are plagioclase, biotite, augite and alkali feldspar, with hypersthene restricted to some monzonites and quartz appearing in more differentiated rocks. Most rocks show, at least in part, tectonic foliation (correlated with the regional F_{n+2} phase of deformation) and post-magmatic recrystallization. Early facies were frequently permeated by quartz monzonite and quartz syenite veins, defining the migmatite "look" of many outcrops. Some monzodiorites and monzonites show segregation structures such millimeter to centimeter as sized ocelli and styctolithic veins. The fractionation of the earliest rock types (diorites to leuco-monzonites) was partly controlled by extraction of plagioclase, biotite, and augite from a predominantly liquid mush of monzodioritic composition. More felsic varieties apparently were formed by segregation, starting with ocellar structures and giving rise, by increasing collection of material, to larger magmatic masses. Recrystallization within the massif started as a segregation-related "syn-deformational" plutonic event, with an increase in a (H_2O); igneous mafic minerals were chemically re-equilibrated, and granoblastic textures were locally formed. Later metamorphism at diminishing temperatures generated brown biotite and hornblende (mainly from pyroxenes) which, in turn, were replaced by lower-grade assemblages with greenish biotite and epidote.

RESUMO O Maciço de Piracaia, localizado em uma área composta por orto- e paragnaisses migmatizados, é bastante complexo petrográfica e estruturalmente. O mapeamento de detalhe revelou a presença de cerca de 30 variedades petrográficas (fácies). As composições variam entre dioritos e álcali feldspato-quartzo sienitos, com monzodioritos e monzonitos como tipos dominantes. A seqüência de intrusões é, de um modo geral, das unidades mais máficas para as mais félsicas. Os principais minerais primários são: plagioclásio, biotita, augita e feldspato alcalino, com o hiperstênio restrito a alguns monzonitos e o quartzo aparecendo nas rochas mais diferenciadas. A maioria das rochas mostra, ao menos em parte, foliação tectônica (correlacionada à fase F_{n+2} de deformação regional) e recristalização pós-magmática. Os fácies antigos do maciço são freqüentemente permeados por veios quartzo-monzoníticos a quartzo-sieníticos, definindo um aspecto migmatítico em muitos afloramentos. Alguns monzodioritos e monzonitos mostram estruturas de segregação, como ocelos (de centimétricos a milimétricos) e veios estictolíticos. O fracionamento dos litotipos mais antigos (dioritos a leuco-monzonitos) foi parcialmente controlado pela extração de plagioclásio, biotita e augita de um magma dominantemente líquido de composição monzodiorítica. As variedades mais félsicas parecem ter-se formado por segregação, que se iniciou como estruturas ocelares e gerou, por coleta mais avançada de material, massas magmáticas maiores. A recristalização no interior do maciço teve início como um evento "sin-deformacional" relacionado à segregação. Com um aumento na atividade de H_2O, minerais máficos ígneos foram reequilibrados quimicamente, e localmente se formaram texturas granoblásticas. Metamorfismo posterior a temperaturas decrescentes gerou biotita marrom e hornblenda (principalmente a partir dos piroxênios), que, por sua vez, foram substituídas por associações de mais baixo grau com biotita esverdeada e epídoto.

INTRODUCTION About 200 main granitoid occurrences are known to exist within the Precambrian basement of São Paulo State. The Piracaia Massif, located 80 km NE of the city of São Paulo, is unique among them, on account of its mostly intermediate composition (with predominant monzodiorites and monzonites) and its structural complexity. The massif was first described by Cavalcante & Kaefer (1974). Campos Neto & Artur (1983), who studied it with more detail, identified 7 main rock associations, but recognizing further heterogeneities at mesoscopic scales.

Additional field work by one of us (V.A. Janasi) showed that about 30 different facies had to be defined, in order to describe the large petrographic and textural variations that do occur in the massif; these are due, to a large extent, to the complex history of the massif, where previously solidified igneous rocks underwent partial (in part also complete) recrystallization under the influence of metamorphic overprints (Janasi 1986). The described facies were then grouped, for mapping purposes (on a 1:25,000 scale), into several mappable facies associations, much along the lines already used in the detailed mapping of alkaline and other granitoid massifs in southern Brazil (Ulbrich 1984, Vlach 1985). The observed field

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relationships guided subsequent laboratory work and the interpretation of data.

Textures, petrography, and metamorphic reaction sequences, as described in the following pages, were studied by conventional optical microscopy. The chemistry of the main minerals (biotites, feldspars, pyroxenes, amphiboles) was determined with a manual ARL microprobe (for procedures and applied corrections, see Janasi 1986).

In this paper, emphasis is placed on the descriptive aspects and the metamorphic history. A forthcoming paper (Janasi & Ulbrich in prep.) will deal with chemical aspects of the igneous evolution.

REGIONAL GEOLOGY The Guaxupé Median Massif, within which the Piracaia Massif is located, is composed of pre-Brasiliano rocks, in part reworked during the Brasiliano cycle (Wernick 1978). Recent studies consider that the Piracaia Massif intruded an allochthonous block, emplaced by nappe tectonics of early Brasiliano age (Campos Neto et al. 1984).

Two main litostratigraphic units are described in the region. One is the Piracaia Metamorphic Complex (PMC), of uncertain age, with peraluminous, hornblende-biotite, and calc-silicate gneisses of supracrustal origin, while the other is the unit of Socorro orthogneisses, of Upper Proterozoic age, intrusive into the PMC and in part showing transitions to undeformed hornblende-biotite granitoid rocks (Fig. 1).

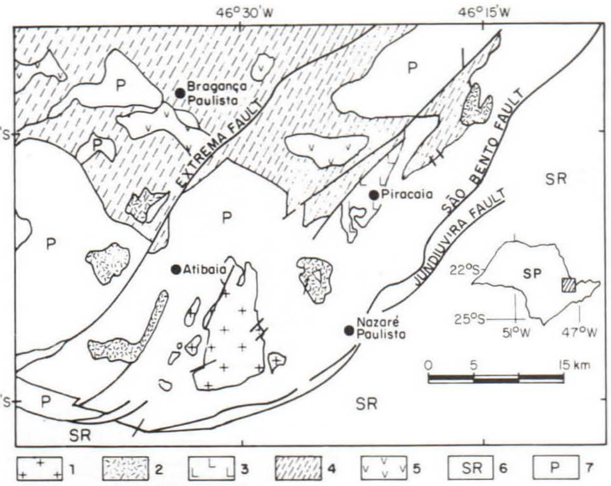

Figure 1 – Simplified geologic map of Piracaia region (based on unpublished compilation from M.C. Campos Neto and A.C.B.C. Vasconcellos). **1.** *Atibaia Massif;* **2.** *Nazaré and Quatro Cantos Suites;* **3.** *Piracaia Massif;* **4.** *Socorro augen-gneisses;* **5.** *Socorro even-grained gneisses;* **6.** *São Roque Group; and* **7.** *Piracaia Metamorphic Complex*

Within the PMC, small mappable granitoid areas are observed (muscovite-biotite and garnet-biotite granites of the Quatro Cantos and Nazaré Paulista suites, respectively; cf. Campos Neto *et al.* 1983).

Several deformational phases are recognized in these rocks. The S_{n+1} transposition foliation in the PMC is affected both by the mesoscopic F_{n+2} folds, showing subvertical ENE axial planes, and by the regional F_{n+3} megafolding (Campos Neto *et al.* 1983, Morales *et al.* 1985). S_{n+1} is the primary tectonic foliation in the Socorro orthogneisses.

The principal metamorphic event in the PMC is roughly coeval with the F_{n+1} phase. In the Piracaia area, high-grade metamorphism in these rocks (with the pair sillimanite/K-feldspar in peraluminous lithotypes) was accompanied by intense migmatization (leucosomatic veins are either coeval or slightly later than S_{n+1}). The nebulitic granitoids of the Quatro Cantos and Nazaré Paulista suites were emplaced apparently during the F_{n+2} phase (Campos Neto *et al.* 1983).

GEOLOGY AND PETROGRAPHY OF THE PIRACAIA MASSIF The Piracaia Massif has an ellipsoidal form (14.5 x 3.5 km) with a N35E trend (Fig. 2). Igneous rocks within the massif occupy a total area of about 28 km^2. Their contacts with the country rocks are always intrusive; in parts, they have been tectonized, principally along the E and W borders.

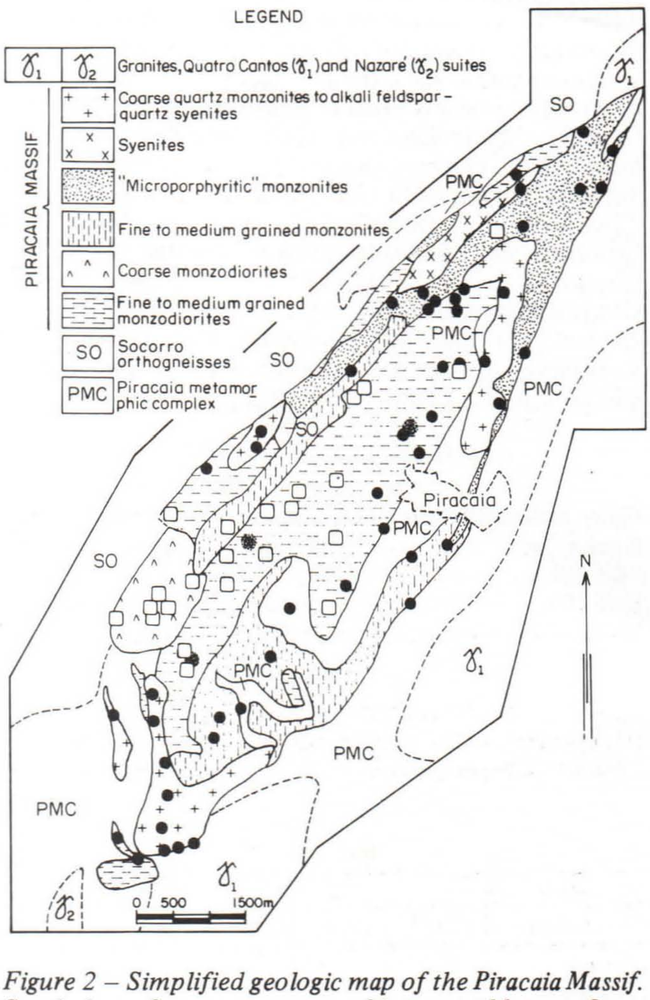

Figure 2 – Simplified geologic map of the Piracaia Massif. Symbols refer to metamorphic assemblages. Open squares: *hornblende + brown biotite stable;* filled circles: *epidote + greenish biotite stable*

Detailed faciological mapping identified 29 primary and secondary facies, which were grouped into 17 mapping units (Janasi 1986). Secondary processes (such as deformation, metamorphism, and segregation), overprinting primary igneous rocks, were active in most areas of the massif and are in part responsible for the large number of identified facies.

All colected samples show, macroscopically or at least under the microscope, incipient to strong post-magmatic recrystallization. Within the adopted nomenclature, care was taken to define as "metamorphic equivalents" of the primary igneous rocks all the types showing well-developed metamorphic structures and textures, and presenting low-temperature re-equilibration (with stable pair epidote and green biotite; cf. Fig. 2). In the following descriptions, each facies type is defined by its primary mineralogy and texture; descriptions of the recrystallized facies are added.

Representative modal analysis of the main units of the massif are presented in table 1. Trends defined by these modal analysis (Fig. 3) show an almost continuous variation from diorites to quartz alkali-feldspar syenites. Whenever possible, strongly recrystallized rocks were discarded for modal purposes, on account of mineral changes. Primary igneous equivalents of the most differentiated rocks were not found; in this case, the metamorphic mineralogy was modally counted, and some corrections were then applied, to estimate the primary igneous proportions (mainly to discount albite exsolved from primary perthite, and secondary quartz formed by breakdown reactions involving mafic minerals). The observed modal trend (Fig. 3) is akin to the granitoid "alkaline" and "sub-alkaline" series of Lameyre & Bowden (1982), but without an intermediate modal gap (Bonin & Giret 1983). Observed proportions of outcropping rocks in the Piracaia Massif are as follows: diorites, less than 1% ; monzodiorites, about 45% ; monzonites, 30% ; syenites, 4% ; quartz monzonites, 15% ; quartz syenites to alkali-feldspar granites, less than 5%.

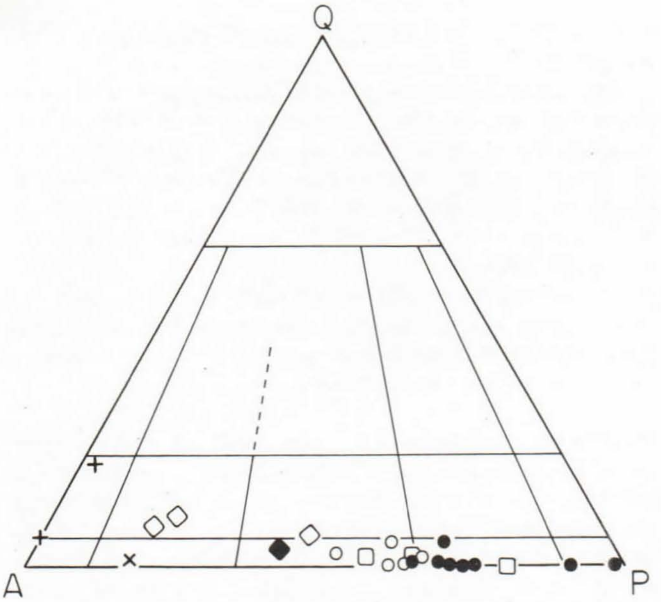

Figure 3 – Modal analysis of rocks from the Piracaia Massif in the QAP diagram: filled circles – *Mdf and Mdm units;* open circles – *Mfc;* open squares – *Mdr;* X – *Scm;* filled diamond – *Qs darker quartz monzonites;* open diamonds – *Qs felsic quartz monzonites and quartz syenites;* crosses – *Qs more differentiated facies*

Description of the units

Fine- and medium-grained monzodiorites (Mdf, Mdm) Rocks belonging to these units make up about 40% of the massif, cropping out mainly in its core area (Fig. 2). Most of these rocks are metamorphosed and show gneissic structures; preserved primary minerals and textures are found mainly in the central-western portion of the massif. Also found, besides the dominant medium- and fine-grained rock types, are a fine-grained porphyritic facies with tabular plagioclase, and a darker very fine, mostly even-grained facies.

The fine and medium-grained monzodiorites (Mdf, Mdm) are mostly equigranular dark grey rocks, typically heterogeneous even at an outcrop scale. The Mdm facies apparently grades regionally into the predominant Mdf facies, which occupies the core area of the main mapped occurrence (Fig. 2). Mdf and Mdm show some plagioclase as larger strongly zoned tabular phenocrysts (1-2 mm in length in the Mdf rocks) (core, An_{45-52}; rim, An_{26-31}); mostly, however, it is a groundmass mineral (An_{26-31}).

Table 1 – Modal analysis of representative samples for the Piracaia Massif: tr = trace amounts; (1) includes 28,5% of phenocrysts, with the relative proportions: plagioclase, 64; biotite, 31; Ca-pyroxene, 5; (2) includes 2,1% of hypersthene; (3) 60% of plagioclase as albite (An_{0-5}); (4) 50% of plagioclase as albite (An_{0-5})

Unit	Mdf			Mdm	Mdr		Mfc			Mp	Scm	Qs	
Sample	170a(1)	171/1	75	185	259	256	179b	358a	179a	40	26b	43a	270a
Quartz	–	–	–	–	0.2	0.8	1.3	tr.	0.4	2.1	0.7	6.8	9.7
Plagioclase	50.2	54.0	48.0	44.5	52.0	54.6	48.7	48.8	49.8	22.3	34.9(3)	30.2	38.6(4)
Alkali feldspar	11.7	0.5	21.1	24.5	12.3	29.9	25.3	28.6	33.1	47.7	48.1	46.7	44.2
Biotite	28.6	31.3	18.7	22.5	20.3	8.4	15.8	12.8	8.6	15.0	8.0	11.0	4.3
Ca-pyroxene	4.7	0.3	2.9	1.7	2.6	1.5	2.5	4.6	3.5(2)	–	–	–	–
Amphibole	0.6	6.8	4.8	1.7	5.0	1.0	1.8	0.9	1.3	6.0	6.6	1.8	–
Ore	2.2	4.3	2.1	2.6	4.2	1.8	3.0	2.9	2.6	1.0	0.1	0.7	0.7
Apatite	1.4	0.9	tr.	2.0	2.5	1.7	0.8	0.9	0.4	0.6	0.5	0.6	0.2
Sphene	0.4	1.5	1.1	0.2	0.9	tr.	–	–	–	1.1	0.7	0.7	tr.
Others	0.2	0.4	1.3	0.3	0.1	0.3	0.5	0.5	0.2	4.2	0.5	1.5	2.3
Color Index	38.1	45.5	30.9	31.0	35.5	14.7	24.7	22.6	16.7	27.9	16.3	16.3	7.5

Alkali feldspar is perthitic and interstitial. Brown biotite and greenish to colorless, generally poikilitic augite, are the main primary mafic minerals; accessories are apatite, magnetite, ilmenite, and subordinate zircon and allanite.

The plagioclase-rich porphyritic fine-grained rock is much rarer and was observed in a few outcrops in the W margin of the main Mdf-Mdm occurrence (Fig. 2). Plagioclase phenocrysts show sometimes biotite and magnetite inclusions, and frequently form synneusis textures. The composition of these rocks is mainly monzodioritic, but locally there are dioritic rocks with little groundmass.

The very fine-grained types, usually equigranular, are found as enclaves; a single larger outcrop area was found in the central-western part of the massif. These rocks are modally heterogeneous, but monzodiorites predominate. One described sample (PI-170a) presents phenocrysts of plagioclase (with calcic cores, An_{55-60}), of brown biotite (as large flakes, up to 3 x 0.5 mm, with irregular borders and no inclusions) and of an extremely poikilitic augite (up to 50% of inclusions of biotite, ore, and plagioclase) in a "granoblastic" groundmass with plagioclases in the range An_{32-34}. Augite, sometimes having inverted pigeonite exsolution lamellae, is frequently observed as aggregates of two or more phenocrysts; in other cases, phenocryst-like aggregates are found, constituted by a polymineralic mass of small crystals, with clinopyroxene as predominant mineral.

Post-magmatic recrystallization is present in all these rocks, and all sorts of gradations to fully metamorphic equivalents are observed. The principal mineralogical features in the less modified samples are the formation of greenish hornblende from Ca-pyroxene, the growth of sphene on ilmenite crystals and within biotite, and the appearance of brown biotite around magnetite and at the expense of clinopyroxene and feldspar.

Metamorphic equivalents The recrystallized varieties are by far predominant. Textures are metamorphic. Renmants of former plagioclase phenocrysts are sometimes observed, with their cores strongly altered into aggregates of epidote and green biotite. Main minerals are oligoclase (An_{18-22}), cross-twinned microcline*, irregular crystals of greenish biotite, and greenish-bluish hornblende (sometimes showing lighter, more actinolitic patches, or relicts of Ca-pyroxenes in its interior). Some secondary quartz is also observed, derived from metamorphic reactions. Biotite in these rocks can derive from an originally brown biotite (it shows then sphene inclusions) or from reactions which involve hornblende (in which case it can have wormlike quartz inclusions) (cf also section on metamorphic reactions).

Coarse purple-grey monzodiorites (Mdr) These rocks are coarser, mainly massive and more homogeneous than the Mdf and Mdm varieties; color is also different, due to the presence of purple-greyish feldspar. The Mdr rocks constitute about 5% of the massif and are concentrated at its SW portion (Fig. 2). Two facies are recognized: one is darker, of dioritic to monzodioritic composition, and the other is lighter, subordinate, and mainly of monzonitic composition (color indices 30 and 15, respectively).

The main textural features of these rocks are the large (4-5 x 1 mm) tabular plagioclase megacrysts, usualy grouped in synneusis textures, in turn surrounded by biotite flakes. Smaller plagioclase crystals may form granoblastic textures. Augite forms isolated crystals, and alkali feldspar is interstitial.

Plagioclase megacrysts are strongly zoned (from An_{50-58} in the core to An_{25-28} at the rim in one analyzed light-colored sample); the granoblastic plagioclase of the matrix has An_{25-28}. Alkali feldspar, rare or absent in the diorites, is finely perthitic and xenomorphic, reaching 4 mm in some monzonites. Brown biotite appears as aggregates of flakes, surrounding the larger plagioclases; most acessories (apatite, magnetite, and ilmenite) are associated with, and in part enclosed by, the biotites. Augite, with some inclusions (biotite, apatite, and ore), is subidiomorphic-prismatic and shows sometimes pigeonite exsolution lamellae oriented parallel to (001).

Most Mdr rocks were affected by some degree of metamorphic recrystallization (*e.g.*, ilmenite lamellae within biotites, formed by Fe-Ti release; augites partially transformed into hornblendes, sometimes with actinolitic cores etc.), but entirely "metamorphic" equivalents were not recognized.

Grey medium- to fine-grained monzonites (Mfc) Rocks belonging to this unit cover about 22% of the total outcrop area; two areas were mapped where this unit predominates, in the W and SE portions of the massif (Fig. 2). Constituent rocks are heterogeneous; six facies were recognized. Two facies occur only in dikes and veins (one is grey-colored, the other is whitish). The dominant less-recrystallized variety is a medium- to fine-grained grey facies. Less abundant are other two facies: a fine-grained greyish type identified in only one outcrop, and a medium-grained greenish-grey rock. Most abundant, though, are the metamorphosed types, with gneissic structures, which were here grouped into a single facies.

The dominant less recrystallized medium- to fine-grained facies is homogeneous, somewhat inequigranular, with plagioclase predominant over microcline, and a color index of about 25. Plagioclase in the groundmass is oligoclase (An_{25-29}), but the rare larger crystals show calcic cores (An_{47-49}). Microcline is perthitic and shows inclusions of all other minerals; the estimated original composition is in the range $Or_{54}Ab_{38}An_{8}$-$Or_{68}Ab_{28}An_{4}$. Mafic minerals are brown biotite and augite, together with apatite, magnetite, ilmenite, and rare zircon and allanite.

The fine-grained grey facies is equigranular, with a similar mineralogy as described above. Plagioclase, predominant, is oligoclase (An_{23-26}); augite, almost without biotite inclusions, shows large pigeonite lamellae. Cummingtonite-bearing pseudomorphs may represent former hypersthene crystals.

The greenish-grey facies was found only in two outcrops; its color index is about 15. Megacrysts of plagioclase show faint zoning; composition is around An_{23-26}. Alkali feldspar is relatively abundant

* The name microcline refers to alkali feldspars with well-developed cross-twins.

($Or_{70}Ab_{27}An_3$ to $Or_{80}Ab_{18}An_2$). Mafic minerals are brown biotite, augite, and prismatic to equidimensional hypersthene (with biotite, ore, and zircon inclusions).

The other two facies, appearing as veins and dikes, are somewaht lighter than the previous types. Alkali feldspar is more abundant than oligoclase. Mostly recrystallized brown biotite is the main mafic mineral in the grey facies, while in the whitish facies it is accompained by homogeneous olive-green hornblende.

Metamorphic equivalents The gneissic equivalents of the Mfc rocks, all strongly recrystallized, seem to derive mainly from the grey medium- to fine-grained facies; to the SE of the massif, however, gneissic Mfc varieties are microcline-rich and may be the metamorphic equivalents of the greenish-grey facies. Textural and mineralogical changes observed in these rocks are roughly as described for the gneissic equivalents of Mdf-Mdm units.

Metamorphic reactions are very evident in the Mfc rocks, and will be discussed in more detail in a specific section. The formation of secondary hornblende is clearly observed (as rims on Ca-pyroxenes, as patches near inclusions within the pyroxenes etc.), associated with quartz, carbonate, and occasional magnetite (in part, reaction products). Zoned, usually fibrous actinolite, is found as cores in Ca-pyroxenes, together with carbonate, quartz, and abundant magnetite; with the reaction's progress, hornblende is finally formed at the expense of this actinolite. Hyperthene is replaced by biotite (along fractures, or along its borders, where biotite may appear together with some cummingtonite). In some samples, a mass of a vividly-colored fibrous serpentine-like mineral, with an outer actinolite rim (which grades, on the outside, into green hornblende), was identified. Some quartz-rich aggregates (with brown biotite and hornblende, as well as subordinate amounts of carbonate and magnetite) may appear, and may represent a final breakdown product of a reaction sequence which started with the above-mentioned "serpentine" pseudomorphs.

"Microporphyritic" monzonites (Mp) The Mp unit is petrographically heterogeneous, and is mainly characterized by the presence of alkali-feldspar rich, light-colored, centimeter-sized ocellar patches, set in a dark-grey, fine- to medium-grained matriz. The ocellar structures, which at first sight mimick phenocrysts, are coarser-grained than the matrix and appear in varying proportions. Within them, or irregularly distributed in the matrix, milimeter-sized mafic minerals (usually hornblende) are observed.

A mappable unit of Mp was identified in the northern half os the massif (Fig. 2; 11% of total area). There, Mp rocks predominate and a gradation into locally abundant Mdf monzodiorites appears to take place, mainly by decrease in size and number of ocelli. Mp rocks are petrographically very variable, presenting a broad modal range, which goes from monzodioritic to syenitic compositions, mainly on account of the irregular distribution of the ocelli.

The matrix of the Mp rocks is usually fine-grained, dark-grey, with a metamorphic texture (foliated and granoblastic, resembling equigranular gneissic equivalents of Mdf). Brown biotite and oligoclase are dominant, sometimes with relictic textures (*e.g.*, traces of former plagioclase phenocrysts in synneusis arrangement); well-recrystallized Mp rocks, which are predominant over less-recrystallized types, show epidote and greenish biotite.

The ocelli are alkali-feldspar syenitic to syenitic in composition, and they are coarser (0.7-1 mm) than the matrix. Microcline predominates, associated with few hornblende megacrysts (which may show relict Ca-pyroxene in its core). Plagioclase is normally a subordinate, finer-grained mineral. Biotite, when observed, is mostly a breakdown product of hornblende. The contact between ocelli and matrix is always very sharp.

Medium-grained syenites (Scm) This unit (about 4% of total area) crops out as an elongated band, at the NW border of the massif (Fig. 2). Constituent rocks are medium-grained light-grey, slightly foliated syenites.

The rocks are always recrystallized, and primary mineralogy and textures are not preserved. Some of the cross-twinned microcline grains are megacrysts (up to 2 mm), showing albite as iso-oriented perthitic bands and twinned patches. Albite and microcline appear, in the matrix, as grains with irregular contacts, suggesting an origin from extreme unmixing of formerly perthitic alkali feldspars. Matrix albite (An_{2-6}) is also observed as granoblastic patches. More calcic plagioclase (An_{9-11}) only occurs as irregular relicts within larger microcline grains or as very rare isolated crystals.

Greenish-bluish hornblende (up to 0.5 mm) is the main mafic mineral; it appears as evenly distributed grains, in part showing passage to epidote and biotite with small quartz inclusions. Greenish biotite also occurs as isolated flakes; rarely it shows brownish cores. Allanite prisms (up to 2 mm) are conspicuous, with inclusions of ore and brown biotite; also observed were zircon, apatite, magnetite, and ilmenite with sphene rims.

COARSE QUARTZ MONZONITES TO QUARTZ ALKALI FELDSPAR SYENITES (Qs) Rocks of this unit cover about 5 km^2 (18% of total area) and were mapped in two main occurrences: one to the SE with a "V" form and another as an elongated band, to the NE of the massif. Several other minor occurrences were also observed; two of these are large enough to be mapped (Fig. 2).

This unit is petrographically very variable. The main features of the constituting facies are the coarse grain size, the presence of quartz and of larger amounts of alkali feldspar, and the lighter color. All rocks within this unit show at least some tectonic foliation; locally (mainly in the occurrence to the NE), the rocks are actually augen-gneisses. It is thus very difficult to define more precisely both primary mineralogy and textures of these rocks.

The more mafic varieties (color index about 20) are (quartz) monzonites which occur as border facies in the larger mapped occurrences of Qs and also form the two smaller outcrop areas. More abundant are the light-colored leuco-quartz monzonites and leuco-quartz syenites (color index apr. 10) that predominate in the two larger occurrences and also constitute most of the veins which invade rather frequently the earlier more mafic units. Even more differentiated types (quartz alkali-feldspar syenites and alkali-feldspar granites) were observed only as veins and small intrusive bodies in the northern half of the massif, where they usually intrude Mp rocks.

The texture of the Qs rocks is hypidiomorphic with a deformational overprint: larger feldspar crystals are set in a seriated, somewhat granoblastic matrix, the proportion of which increases with deformation. The mafic minerals, especially in the lighter rocks, are mostly present as polymineralic aggregates.

Among the larger crystals, cross-twinned xenomorphic perthitic microcline is predominant: it may include, in part or totally, some matrix grains. Less frequent are megacrysts of a more idiomorphic alkali feldspar, with few inclusions and Carlsbad twins. Albite is found, within the microcline, both as fine and coarse perthitic blebs and as larger iso-oriented patches. Also present are inclusions of somewhat altered sodic oligoclase, biotite, hornblende, sphene, quartz, and magnetite. Larger plagioclase megacrysts are usually absent in the lighter Qs rocks; they are however common features in the more mafic varieties, where compositions are around An_{18-23}. In some light-colored samples, they form grains with oligoclase cores (up to An_{12}) and albite rims.

Greenish biotite is the main mafic mineral. It is xenomorphic and frequently grows into nearby feldspar and hornblende crystals. In the less deformed rocks, hornblende is observed as larger single crystals, while in the more deformed ones it is replaced by biotite-hornblende aggregates in which the amphibole appears as relictic iso-oriented patches.

Zircon and allanite are, as accessories, much more abundant in the Qs varieties than in other less differentiated rocks of the massif. Allanite, in particular, is frequently observed as large (up to 2 x 1.5 mm) strongly zoned prisms. Sphene appears as a reaction product of both ilmenite and biotite. Granular epidote results from breakdown of calcic plagioclase and hornblende. Apatite and magnetite are found sparsely.

A special rock type is a whitish coarse-grained quartz-alkali feldspar syenite, mainly constituted by mesoperthites (with inclusions of smaller augite prisms) and some interstitial quartz. The mesoperthites appears as large (up to 1 cm) composite microline-albite grains.

Structural geology Many units of the Piracaia Massif have a definite migmatite "look"; given by the appearance of several late Qs (quartz monzonites to quartz alkali-feldspar syenites) veins and sheets within earlier monzonitic and monzodioritic varieties. These veins are probably near the areas where mappable occurrences of the late facies are found, and they tipically do not present mafic selvages against the invaded more mafic rocks.

Other features are clearly segregation structures. Foremost among them are the centimeter-sized ocelli, with a syenitic to alkali-feldspar syenitic composition. In the N half of the massif, they are so abundant as to form the mappable unit of the "microporphyritic" Mp monzonites (Photo 1). Some veins of styctolithic aspect are locally associated with the ocelli. They are sometimes discontinuous and show irregular to difuse contacts with the country rocks (Photo 2), and are considered representatives of a more advanced stage of segregation than the ocelli.

The Piracaia Massif presents xenoliths of the Socorro orthogneisses (showing their S_{n+1} foliation) in some of its border facies, and its emplacement is thus later than F_{n+1}. Deformation, sometimes very intense, is observed in most

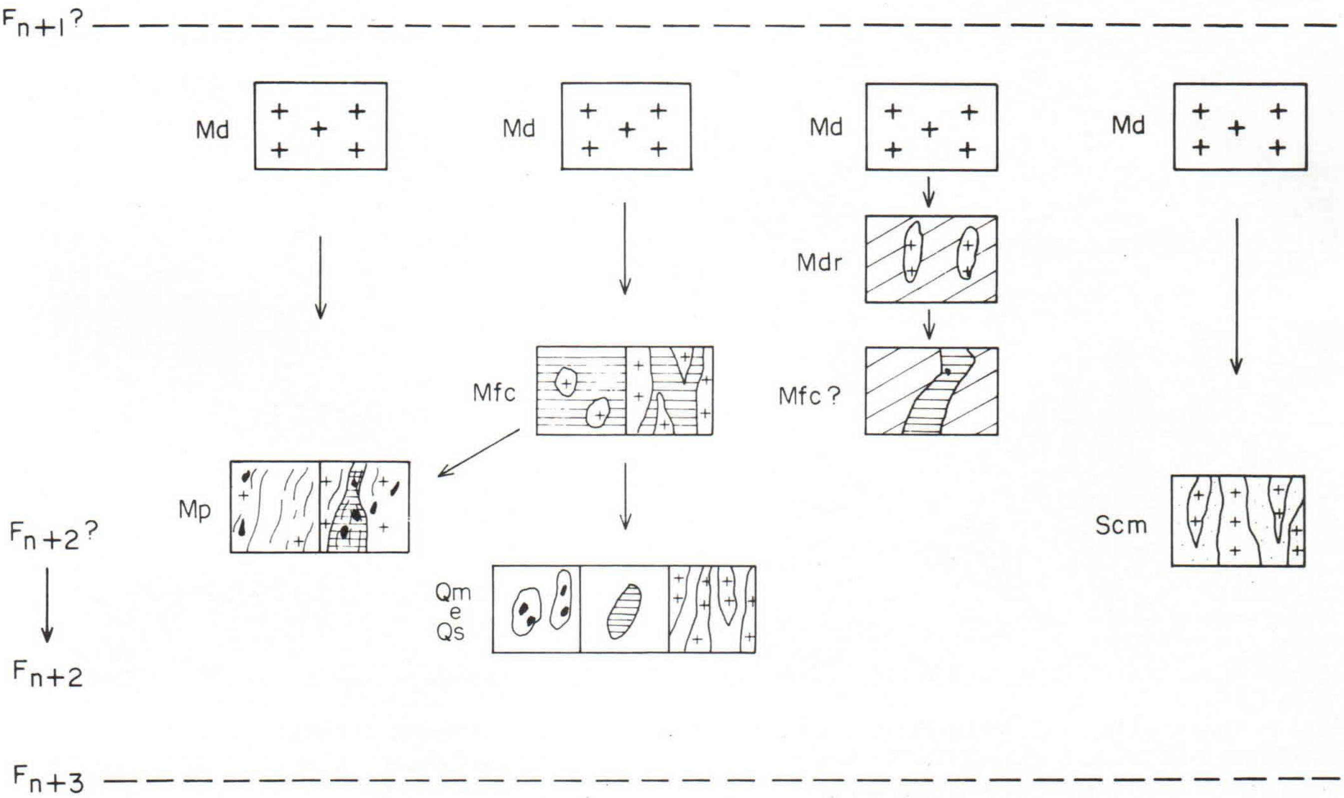

Figure 4 – Sequence of events in the Piracaia Massif. Md corresponds to both Mdf and Mdm units; Qm/Qs correspond to Qs unit. Other abbreviations are as utilized in text

rocks of the massif; ensuing foliation is oriented mainly NE-SW, parallel to the length of the massif, and is attributed to the F_{n+2} phase. The beginning of segregation (ocelli formation etc.) probably occurred at this time and continued from there on (some styctolithic veins clearly cut the foliation within the massif). The last stages of magmatic evolution of the massif seem to be, thus, related to the F_{n+2} phase, at a time when the massif was still crystallizing and behaved as a ductile, rather than a cold, mass.

Age relationships A schematic summary of the age relationships in the Piracaia Massif, based on geological observation, is shown in figure 4.

Earliest facies are the fine to medium-grained monzodiorites (Mdf, Mdm). It is not known which of the recognized varieties is earlier; they may be more or less coeval, as pointed out by some observed gradational contacts. Contacts with basement rocks are either parallel or tectonic.

The coarse Mdr monzodiorites are later than the rocks of the PMC, although direct observations were not available (the Mdr outcrop pattern cuts, on the map, both banding and foliation of PMC gneisses). In one case, intrusion into Socorro orthogneisses was observed. Rounded enclaves of very fine-grained, dark monzodiorites are common in Mdr rocks. Darker Mdr facies is earlier than the lighter one, in turn followed by light monzonitic veins (some with pegmatite cores).

The Mfc monzonites present xenoliths of both Socorro orthogneisses and PMC migmatized rocks. the Mfc fine-grained grey facies is intruded by the medium- to fine-grained one; lighter colored facies are only observed as late veins intruding monzodiorites. Occasionally, enclaves of Mdf are also present within the earlier Mfc facies.

Ocellar features and other types of segregations, shown by rocks of the Mdf, Mdm, and Mfc units (including the whole Mp mapped unit) are apparently contemporaneous with the S_{n+2} tectonic foliation.

The Scm syenites invade Mdf and Mdm types, and show also Socorro augen-gneisses as xenoliths.

More evolved rock types (Qs quartz monzonites to quartz alkali-feldspar syenites) are definitely late facies.

Plate 1: Photographies: **1** – *Monzodioritic rock with abundant segregation structures: syenitic ocelli, with associated hornblende megacrysts, grading into vein structures. Diameter of scale is appr. 6 cm;* **2** – *Syenitic veins with styctolithic structure in Mdf monzodiorite;* **3** – *Angular xenoliths of ocelli-bearing monzodiorites in grey quartz monzonite. Xenoliths have a feldspathic border surrounded by a lighter-colored quartz monzonite matrix, probably due to assimilation;* **4** – *Light Qs quartz monzonites later than drak-grey Qs quartz monzonites, both showing ellipsoidal Mdf monzodioritic enclaves*

They invade Socorro and PMC rocks, and most of the other units of the massif, particularly Mdf, Mdm, and Mp types (Photo 3). Relationships with Mdr and Scm are not known. Within this late Qs unit, darker facies are earlier than more felsic ones (Photo 4).

Observations on the late Qs facies suggest a rather large mechanical contrast between the corresponding magmas and the country rocks: gneissic xenoliths are frequently very angular, and locally oriented textures and structures are very marked, indicating forceful injection. On the other hand, rounded enclaves of monzodiorites and monzonites are observed within late facies (Qs and Scm), usually elongated parallel to mutual contacts (Photo 4), suggesting invasion of late magmas into rather plastic previous units, under a forceful intrusion regime (cf Marre 1982).

Migmatization of the metamorphic country rocks was repeated several times. Some migmatite veins are late phenomena; very locally, monzodioritic rocks are cut, along the southern border of the massif, by some of these late veins.

IGNEOUS PETROLOGY **Primary magmatic mineralogy** Most of the units mapped in the Piracaia Massif show at least some sign of metamorphic recrystallization. Main primary magmatic minerals are plagioclase, alkali feldspar, brown biotite, and a Ca-pyroxene (generally augite). Hypersthene is found in a few monzonites, while quartz, which occurs in minor amounts in some intermediate rocks, may be plentiful in the more differentiated varieties.

Mafic minerals The absence of primary hornblende and the presence of pyroxene and abundant biotite suggest magmatic crystallization under conditions of low to intermediate water activities (cf Maaløe & Wyllie 1975, Naney 1983). At the same time, the appearance of biotite as an early crystallizing phase points to high K^+ activity in the magmas. The restriction of hypersthene to monzonitic compositions seems to be a common feature in the "alkaline" granitoid series of Lameyre & Bowden (cf Bonin & Giret 1983).

Microprobe analysis of brown biotite (some selected analysis appear in table 2) show a decreasing *mg* index (Mg/Mg + Fe total) with differentiation (varying from 55 in the less differentiated monzodiorites to 43 in alkali feldspar-rich monzonites), which is the normal tendency in igneous suites. Primary biotites may have reached even lower *mg* values in more differentiated rocks (down to 25 in Scm syenites), as suggested by the compositions of the analysed greenish biotites (recrystallization of brown to greenish biotites seems to have little effect on *mg* indices).

Clinopyroxenes (Tab. 2) are Ca-rich, mostly exsolved varieties (in part with rather broad pigeonite lamellae), and an estimate of their primary composition is difficult to obtain. Analysis of optically homogeneous clinopyroxenes shows a trend of decreasing *mg* from monzodiorites (*mg* = 68) to alkali feldspar-rich monzonites (*mg* = 56), accompanying the trend of both biotite and rock chemistry.

Table 2 – Representative microprobe analysis of some biotites and clinopyroxenes from the Piracaia Massif: n.a. = not analysed; (1) **Ca, Mg, Fe** = *Ca, Mg, Fe* converted into 100%; Fe* = Fe total as* Fe^{2+}

BIOTITES						CLINOPYROXENES				
Unit	**Mdf**	**Mfc**			**Scm**	**Unit**	**Mdf**	**Mfc**		
Sample	**170a/3**	**358a/4**	**175/1**	**175/3**	**26b/6**	**Sample**	**170a/10**	**358a/8**	**179a/F**	**179a/G**
SiO_2	36.84	36.62	36.67	37.27	35.71	SiO_2	51.38	50,74	51.16	52.57
Al_2O_3	13.97	12.71	13.16	13.83	14.09	Al_2O_3	3.32	1.78	1.50	1.16
TiO_2	4.21	5.01	4.13	4.04	2.27	TiO_2	0.25	0.25	0.27	0.18
FeO_T	18.75	20.17	22.54	21.63	29.33	FeO_T	11.03	12.13	16.43	12.39
MnO	0.16	0.21	0.26	0.23	0.65	MnO	0.64	0.64	0.72	0.58
MgO	12.21	10.77	9.51	9.50	5.27	MgO	12.30	11.33	11.57	11.46
CaO	0.00	0.22	0.10	0.22	0.03	CaO	20.53	22.07	17.93	21.67
Na_2O	0.09	0.11	0.08	0.11	0.04	Na_2O	0.55	0.52	0.60	0.53
K_2O	9.47	9.44	9,50	9,14	9.76	–	–	–	–	–
BaO	1.34	0.55	0.15	0.24	n.a.	–	–	–	–	–
Total	**97.04**	**95.81**	**96.10**	**96.21**	**96.82**	**Total**	**99.99**	**99.46**	**100.19**	**100.56**
Si	5.575	5.637	5.666	5.703	5.660	Si	1.931	1.942	1.958	1.982
Al	2.425	2.305	2.334	2.297	2.340	Al	0.069	0.058	0.042	0.018
Al	0.066	0.000	0.064	0.197	0.280	Al	0.078	0.032	0.026	0.034
Ti	0.479	0.508	0.480	0.464	0.271	Ti	0.007	0.007	0.008	0.005
Fe	2.373	2.597	2.913	2.768	3.825	Fe*	0.347	0.388	0.526	0.391
Mn	0.020	0.027	0.034	0.030	0.086	Mn	0.020	0.021	0.023	0.019
Mg	2.755	2.472	2.190	2.167	1.312	Mg	0.689	0.646	0.660	0.644
Ca	0.000	0.036	0.017	0.036	0.005	Ca	0.827	0.905	0.735	0.876
Na	0.025	0.033	0.023	0.032	0.013	Na	0.040	0.039	0.045	0.039
K	1.828	1.854	1.873	1.784	1.944	**Ca**(1)	43.8	46.2	37.8	45.4
Ba	0.079	0.033	0.009	0.015	–	**Mg**	36.6	33.0	33.9	33.4
Total	**15.625**	**15.574**	**15.603**	**15.493**	**15.736**	**Fe**	19.6	20.8	28,2	21.2
mg	53.7	48.8	42.9	43.9	25.5	*mg*	66.5	62.5	55.6	62.2

Felsic minerals Plagioclase is the first feldspar to crystallize in practically all the rocks of the massif. In some monzodiorites, early plagioclase crystallization is followed by a interval where both feldspars crystallize together, and finally by a stage of plagioclase resorption (Tuttle & Bowen 1958, Rahman & MacKenzie 1969) and isolated precipitation of alkali feldspar. In these rocks, plagioclase phenocrysts show irregular borders and are mantled by alkali feldspar. The plagioclase of the more differentiated, usualy quartz-bearing rocks, still an early phase, reaches more sodic compositions. These observations are compatible with those of various authors (*e.g.*, Carmichael 1965, Rahman & MacKenzie 1969), showing that alkali feldspar and plagioclase are joined by tie lines with a steeper slope in "rhyolithic" magmas.

MAGMATIC EVOLUTION Both chemical and field data suggest a two-stage model of magmatic differentiation for the rocks of the Piracaia Massif. The first stage defines the relation between diorites, monzodiorites, and monzonites, while the second stage controls the evolution of the late felsic facies.

Whole rock chemistry, as well as trace element data, indicates that diorites, monzodiorites, and most monzonites (up to alkali-feldspar-rich varieties) define a chemical trend that is compatible with simple crystal fractionation, by separation of plagioclase, biotite, augite, and some accessories, in due proportions, from a presumably monzodioritic parental magma (cf Janasi 1986, Janasi & Ulbrich in prep.). It is not known which is the actual mechanism of crystal fractionation, but at the first stage it probably involved withdrawal of liquidus phases from largely liquid mushes (compare with the segregation process proposed for stage two, below). Some textural and structural observations indicate that crystal accumulation preceded fractionation (plagioclase phenocrysts, for instance, appear frequently as synneusis glomerules, augites form polycrystalline aggregates etc.). Others may indicate different mechanisms (*e.g.*, many varieties of more primitive rocks, such as monzodiorites, differ mainly in their phenocryst-to-groundmass ratios, suggesting liquid withdrawal rather than dynamic crystal separation). None of the characteristics which are distinctive of stratiform massifs were encountered, and so the actual crystal "fractionation" mechanism in this case (as also in most granitoid massifs) may not operate by a combination of gravity settling and density currents, as proposed for crystallization in many basaltic magma chambers.

Further magmatic evolution corresponds to the second stage and would be responsible for the appearance and emplacement of the more differentiated varieties of the Qs units. Chemical data corresponding to this stage show, in variation diagrams, a slight deflection from the trend devised by the earlier rocks. The differentiation can be chemically modelled by the removal of the same mineral assemblage as in the previous stage (but with a greater amount of plagioclase, and possibly also with tne late removal of alkali feldspar; Janasi 1986). Magmas, at this stage, are envisioned as being largely crystalline mushes, with slightly different overall compositions and also different stages of solidification. Textures and structures such as ocelli, veins, and larger sheets are interpreted as being "frozen" representatives, caught at different stages, of an essentially continuous segregation process. The beginning of this process would be signalled by the appearence of the alkali feldspar syenitic ocelli, whose composition is in accordance with that expected from residual liquids derived from monzodioritic (or monzonitic) mushes (as deduced from petrography, and substantiated by phase diagramas, early precipitated plagioclase should reach a stage, in this chemical system, where resorption sets in, leaving alkali feldspar as the only feldspar to precipitate, together with some clinopyroxene). From a crystallizing mush, minor amounts of residual liquids would be plastically extracted, aided by the beginning of regional deformation, to be locally concentrated as ocelli. More effective concentration would give rise to veins and sheets; finally, the late Qs facies would represent larger volumes of collected segregations which detached themselves from their root zones and invaded as true magmatic liquids. The important modal and chemical variations seen in the crystallized segregation products probably reflect the differences both in composition of the original mush and of its degree of crystallization; needless to say, larger segregated magma volumes may themselves be subjected to further "normal" magmatic differentiation. The whole second-stage segregation process is broadly "syndeformational" and was apparently accompanied by an increase in the $a(H_2O)$ of the system (particularly along the margins of the massif, with water flowing in from the more water-rich gneisses).

The migmatization of the massif can be considered an appealing alternative hypothesis to the second-stage segregation model. The coarser grain of "leucosomes", contrasting with that of the groundmass "mesosomes", together with the presence of megacrysts of mafic minerals (styctolithic structure in the leucosomes), for instance, are reminiscent of many structures found commonly in migmatite terrains. There the veins are usually interpreted as the products of a rather low-temperature anatexis, with the mafic minerals representing drier residua of formerly more hydrated minerals (*e.g.*, Lappin & Hollister 1980). Several field and mineralogical observations, however, point against it. Granitic migmatite veins invading the Piracaia rocks are rarely seen, although the massif was emplaced into an area of strongly migmatized rocks. Xenoliths of migmatized country rocks are found within early Piracaia facies, clearly indicating that their emplacement was later than the F_{n+1} phase of deformation, which also probably signals peak metamorphic temperatures. After this event, there are no indications that the whole area was heated up to the high temperatures needed to melt the rather dry intermediate, mostly quartz-free, Piracaia protolith. On the other hand, dehydration-triggered melting should not take place, since biotite is a stable phase in the groundmass of ocelli-bearing rocks.

METAMORPHIC REACTIONS Several stages of metamorphic reactions are recognized in most rocks of the Piracaia Massif. The first stage is a high-temperature late magmatic event and is succeeded by stage two, mainly characterized by the breakdown of pyroxenes, and finally by stage three of lowest temperatures.

The high-temperature metamorphic event accompanies the formation of ocelli (stage one, Fig. 5). As seen earlier, this event largelly coincides with the late magmatic history

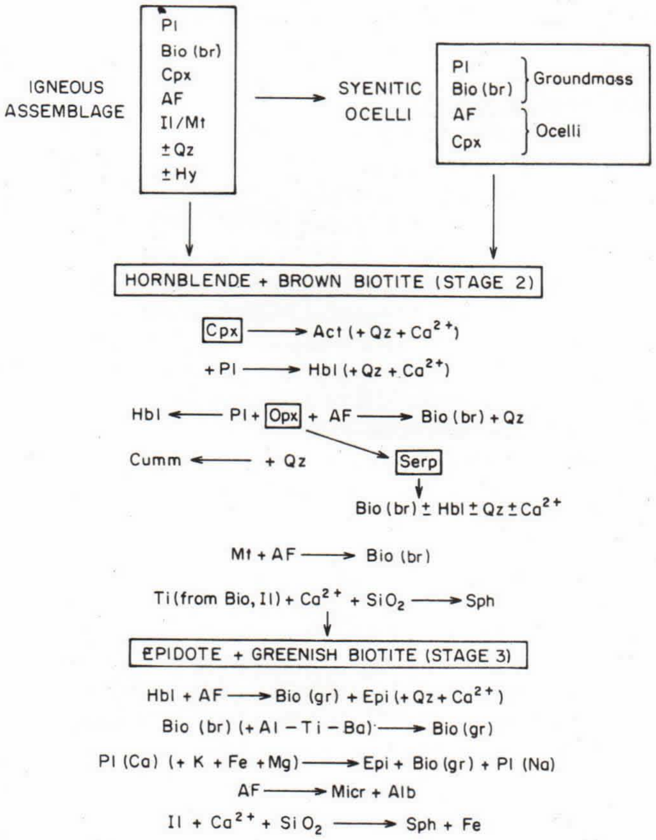

Figure 5 – Main post-magmatic "metamorphic stages" observed in the Piracaia Massif: Act – *actinolite;* AF – *alkali feldspar;* Alb – *albite;* Bio(br) *brown biotite;* Bio(gr) – *greenish biotite;* Cpx – *clinopyroxene;* Cumm – *cummingtonite;* Epi – *epidote;* Hbl – *hornblende;* Hy – *hypersthene;* Il – *ilmenite;* Micr – *microcline;* Mt – *magnetite;* Opx – *orthopyroxene;* Pl – *plagioclase;* Qz – *quartz;* Serp – *serpentine-like mineral;* Sph – *sphene*

of the massif, with the extraction of residual liquids and concomitant formation of metamorphic mosaic textures in the solidified portions of the mushes. The effects of this stage are also evident in the unusual zoning pattern observed in the mafic minerals. Megacrysts of "magmatic" brown biotites show centers with lower *mg* values than their borders and the biotites in the groundmass (Table 2) which, at the same time, may have lower Ti and Ba and higher Aℓ values. The *mg* increase could be ascribed to increasing f_{O_2} (Wones & Eugster 1965, Czamanske & Wones 1973) in the course of the rock crystallization, to which however there is no independent evidence (on the contrary, groundmass biotite is seen growing around magnetite). The global chemical changes are thus attributed to increasing $a(H_2O)$ during the recrystallization process, under temperatures lower than those of the primary crystallization of the biotites. Pyroxene crystals are also re-equilibrated (inverted pigeonite lamellae are, for instance, evident); in some cases, cores of the larger crystals show more salitic compositions (*i.e.*, indicating lower temperatures) and higher *mg* than their borders and the small crystals.

Stage two (Figs. 2 and 5) is mainly characterized by the breakdown of primary pyroxenes and the appearence of hornblende and another generation of brown biotite as main mafic minerals. Metamorphic reactions are complex and may present some intermediate products (*e.g.*, actinolite or cummingtonite) before leading to the final stable assemblage. Written reactions are in part simplified from Beach (1980).

Ca-pyroxene conversion into hornblende is sometimes direct with intervening plagioclase

$Cpx^* + Plag + H^+ \rightarrow Hb + Ca^{2+} + SiO_2 + H_2O$ (1)

or it may involve the formation of actinolite as an intermediate phase

$Cpx + H^+ \rightarrow Act + Ca^{2+} + SiO_2 + H_2O$ (2)

which, when in contact with plagioclase, reacts to form hornblende in a similar way to the former reaction. The actinolite is usually Mg-richer than the parent Ca-pyroxene and the small grains of ore included in the amphibole may represent sinks for the Fe excess.

Hypersthene is usually altered directly into brown biotite:

$Opx + AF + H_2O + H^+ \rightarrow Bio + SiO_2 + K^+$ (3)

Some cummingtonite may form from hypersthene

$Opx + SiO_2 + H_2O \rightarrow Cumm$ (4)

which, when in contact with plagioclase, leads to hornblende formation

$Cumm + Plag + SiO_2 + Ca^{2+} \rightarrow Hb + H^+$ (5)

Some hypersthene grains pass into the cited unidentified serpentine-like mineral (cf for comparison the hypersthene "alteration products" described by Kerr 1979 and Vielzeuf 1982). The thin amphibole reaction rim around the "serpentine" must result from interaction with feldspar generates the quartz-rich aggregates that seem to represent the final breakdown products of hypersthene.

In stage three, green biotite and epidote are the main mafic minerals, formed mainly at the expense of earlier hornblende and brown biotite. Stage three reactions affect about three quarters of the massif (Fig. 2) and are more noticeable near its border, especially near contacts with the PMC gneisses.

Direct passage of brown into green biotite takes place with Ti loss and Al increase, suggesting an exchange reaction such as: 3 Ti = 4 Al^{vi}. Green biotite is richer in Mn and poorer in Ba than the brown varieties; *mg* indices remain practically the same.

Green biotite also forms by breakdown of hornblende with addition of K^+:

$Hb + K^+ + H^+ \rightarrow Bio + SiO_2 + (Mg, Fe)^{2+} + Ca^{2+} + Na^+ + H_2O$ (6)

where K-feldspar is the probable major source of K^+ (for instance, biotite flakes are seen projecting into K-feldspars). Epidote is usually associated with newly formed biotite, probably built up from such breakdown products as Ca^{2+} etc. The silica released from such reactions may turn up as quartz, in part as wormy intergrowths with biotite.

Stage three metamorphism also recrystallizes some preserved calcic cores of plagioclases, frequently conver-

* Abreviations used in the reactions: Cpx= clynopyroxene; Opx= orthopyroxene; Plag= plagioclase; Hb= hornblende; Act= actinolite; Cumm= cummingtonite; Bio= biotite; AF= alkali feldspar.

ting them into aggregates of green biotite + epidote + calcite ± clinozoisite. Otherwise, plagioclases tend to be very homogeneous in most rocks which recrystallized under stage three conditions (An_{18-22} in monzodiorites to quartz monzonites; albite or sodic oligoclase in more differentiated types). K-feldspars are very Or-rich (around Or_{92}) and exsolution textures are very marked, often leading to near complete unmixing: albite migrates to the border of its hosts and may form independent crystals. Newly formed non-perthitic microcline is also observed, either as independent grains and megacrysts or as borders around earlier perthitic alkali-feldspars.

SUMMARY AND CONCLUDING REMARKS The Piracaia Massif shows, very clearly, an earlier history of magmatic evolution, followed by several episodes of recrystallization.

The sequence of igneous rocks can be explained by simple fractionation, whereby withdrawal of plagioclase, biotite, and augite leads to a series of diorites, monzodiorites, and monzonites (stage one of magmatic evolution). This stage is followed by the formation of more differentiated rock types (quartz monzonites, quartz syenites, and quartz alkali-feldspar syenites). In this case, segregation processes would extract liquids from largely crystalline magmatic mushes; the corresponding solidified masses would appear as ocelli and veins, and eventually also as larger masses of differentiated rocks.

A high-temperature late magmatic recrystallization accompanies the segregation process, chemically re-equilibrating some of the primary igneous minerals (*e.g.*, brown igneous biotites) and annealing groundmass crystals (*e.g.*, granoblastic matrix in ocelli-bearing rocks). A stage of pyroxene breakdown follows, equilibrating hornblende and another generation of brown biotite. A last, low-temperature recrystallization follows, leading to the appearence of the pair epidote-greenish biotite. The observed sequence of post-magmatic mineral assemblages is thought to be largely autometamorphic, recording the progressive cooling of the massif in a syn-deformational environment, with water flowing in from country gneisses. Thus, only the last metamorphic event (with epidote and greenish biotite) seems to be compatible with the contemporaneous low-temperature metamorphism seen in the country rocks.

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