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Evidence of magma mixing in the Itaporanga batholith, Northeastern Brazil

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ABSTRACT. — Three very large high-K calc-alkaline batholiths (Bodoco, Serra da Lagoinha, and Itaporanga) intruded amphibolite facies metamorphics of the basement adjacent to the northern boundary of the Precambrian Cachoeirinha-Salgueiro Fold Belt, west of Pernambuco and Paraíba states, northeastern Brazil. These bodies were intruded syntectonically to the F_2 deformation with a final diapiric emplacement. In the Itaporanga batholith, the best studied of these bodies, three petrographic facies were mapped. A hybrid zone, characterized by chemical and mechanical mixing, composes most of the outer portion of the batholith, where intense interaction between granite, granodiorite and diorite melts took place, giving rise to migmatitic-like features. A commingling facies where granite to granodiorite and diorite units may be well individualized, is located towards the center of the batholith. Finally, areas of porphyritic facies are more abundant in the hybrid zone than in the commingling one.

In the hybrid zone, diorite shows sometimes pillow-like structures evidencing quenching, confirmed by the presence of fine-grained facies and acicular apatite crystals. Cuspate contacts between diorite dikes and porphyritic granodiorites portray the viscosity contrast between these coexisting melts. Obstacles to mixing were very often overcome, judging from the extensive chemical mixing in the hybrid zone. K-feldspar megacrysts in the granodiorites often show biotite-rows, evidencing possible hiatuses in the crystallization due to successive influxes of hotter magma of dioritic composition.

Preliminary major, trace element and REE data showed reasonable agreement with a mixing model where 45% of the mafic magma (diorite) added to the felsic (granite) gave rise to the observed hybrid composition.

Within the batholith, a well developed foliation dips inwards and suggests the present level of exposure as the root zone of a diapiric complex. Intense degree of interaction between the felsic and mafic magmas seem to have taken place at this zone.

The porphyritic facies was dated by a Rb-Sr isochron at 620 ± 22 Ma with an initial $^{87}/^{86}Sr$ ratio of 0.7057 ± 0.0003, probably representing the emplacement age. Hornblende and biotite yielded $^{40}Ar/^{39}Ar$ age spectra with well-defined plateau ages of c. 580 Ma and c. 540 Ma, respectively. They probably represent cooling ages and their meaning is not well understood.

Key words: Magma mixing, Commingling, Hybrid, Fold Belt, Batholith.

Introduction

Numerous granitic plutons and dikes pierce the low-grade metasedimentary rocks of the Cachoeirinha-Salgueiro Fold Belt (CSF) and adjacent areas, in the western portions of the states of Paraíba and Pernambuco, Northeastern Brazil (Fig.1).

These granitoids intruded the multiple deformed and poly-metamorphosed Precambrian low-grade metasediments of the Cachoerinha Group (BARBOSA, 1970). ALMEIDA et al. (1967) identified two groups of granitoids in the CSF: a) Synorogenic granodiorites, tonalites and calc-alkaline porphyritic granites regarded as the oldest granitoids in the area and called Conceição-type. They also recognized granitic rocks with extremely well developed porphyritic texture, characterized by abundant microcline megacrysts (up to 10 cm long), named Itaporanga-type. The Itaporanga-type granites have widespread distribution in northeastern Brazil, often being found whenever metamorphism reached amphibolite-grade

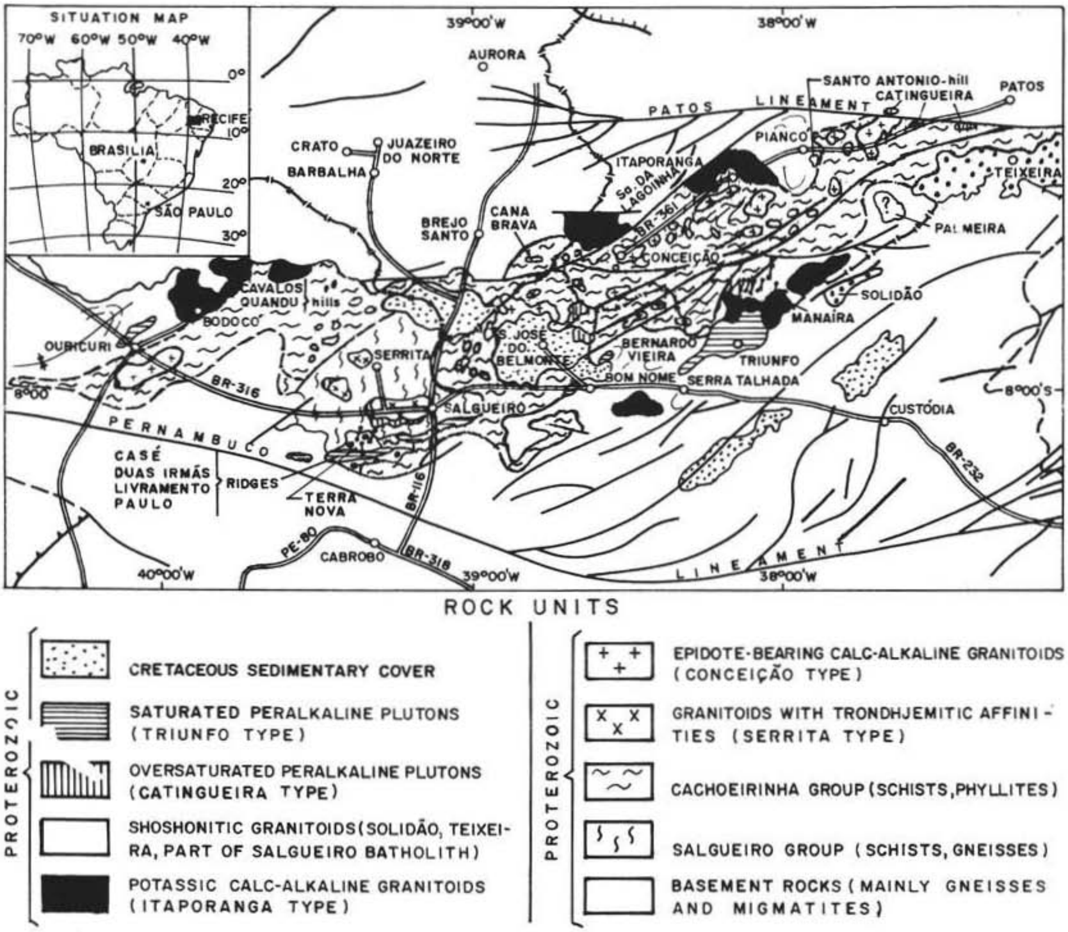

Fig. 1. — Geological sketch of the Cachoeirinha-Salgueiro Fold Belt. Four different granitic groups are shown (SIAL et al. 1987).

(ALMEIDA et al., 1967). Three batholiths of this kind (Bodoco, Itaporanga, and Serra da Lagoinha batholith) intruded intermediate- to high-grade metamorphics of the basement along the northern contact of the CSF. b) Late orogenic granitic rocks included the Itapetim- and Catingueira-types, the former composed essentially of biotite granites occurring associated with the Itaporanga-type granite, being more abundant in areas of gneissic and migmatitic rocks. The mineralogical composition of the Itapetim- and Itaporanga-types is very similar. The Catingueira-type is mainly represented by dikes of silica oversaturated alkaline rocks, with alkali-pyroxene and amphibole as common mineral phases, and well represented in a dike swarm near the town of Catingueira, Paraíba, where five dikes were emplaced parallel to the Patos-Aurora lineament, probably during the early stages of the onset of the lineament.

Although the work of ALMEIDA et al. (1967) was a marker in granite studies in northeastern Brazil, it lacked geochemical data which were only recently provided by SIAL et al. (1981a, 1981b) and SIAL (1984a, 1984b), when major and trace elements, REE, and oxygen isotope data became available.

SIAL et al. (1981a, 1981b), studying the granitic rocks of the CSF and adjacent migmatitic basement, used a geochemical classification to distinguish four major groups

(Fig. 1):

a) K calc-alkaline Group — the same as the Itaporanga-type of ALMEIDA et al. (1967) — emplaced in the basement migmatites, northern and southern borders of the CSF.
b) Calc-alkaline Group — the same as the Conceição-type of ALMEIDA et al. (1967) — emplaced in the CSF metasediments.
c) Trondhjemitic Continental Group - includes portions of the Salgueiro batholith and Serrita stocks which intruded the Salgueiro Group Schists.
d) Peralkaline Group — the same as the Catingueira-type of ALMEIDA et al. (1967) — commonly associated with fault zones or ring structures.

The peralkaline bodies were studied by SIAL (1986) and FERREIRA and SIAL (1986) and found to surround the CSF, being divided into two major groups: (a) Silica oversatured peralkaline rocks located in the northeastern extremity of the fold belt (e.g. Catingueira, Solidão, Teixeira) and (b) Silica saturated peralkaline bodies approaching the southwestern extremity of the belt (e.g. Triunfo, and Ouricuri) (Fig. 1).

The main purpose of this work is to study preliminary geochemical data, associated with field observations in order to analyze the possibility of mixture of magmas as a major petrogenetic process in the Itaporanga batholith, as a first step to further studies on these porphyritic bodies in the CSF and elsewhere, in Northeast Brazil.

General geologic features

The Cachoeirinha-Salgueiro Fold Belt (CSF), also called the Pianco-Alto Brigida System by BRITO NEVES (1975), who described it as an ENE trending belt, located in the states of Pernambuco and Paraíba, has its northern limit on the Paraíba lineament and the southern one on the Pernambuco lineament (Fig. 1), comprising an area of approximately 40,000 Km^2. The CSF is composed of green schist to amphibolite facies metamorphic rocks and several plutonic intrusions.

The Itaporanga batholith, a porphyritic diapiric igneous body, intrusive in the northern border of the CSF, between its low-grade metasedimentary rocks and the green schist- to amphibolite-grade rocks of the Seridó Group, is limited in its NW portion by a major sinistral strike-slip fault (Boqueirão dos Cochos Fault), which imposed to it a tectonic foliation, better developed near the fault zone (Fig. 2). This fault zone has approximately 700 m of outcrop width and seems to have cut the batholith when it still showed some degree of plasticity, as deduced from the predominance of ductile deformation. This horn-like batholith is surrounded by a foliation probably generated by shearing associated with ballooning during its final emplacement. This diapiric emplacement is characterized by folded border zones, where schists of the CSF show overturned folds, and also where early folded apophyses of the porphyritic rocks represent an early phase of the intrusion before the emplacement of the main body.

The foliation (ballooning + fluxion foliation) dips inwards the batholith, suggesting that the present level of exposure may represent the root zone of the diapir.

The Cachoerinha Group schists show two major foliations characterized by fine grained (F_1) and coarse grained biotite (F_2), the latter assumed to be syntectonic to the Brasiliano (= Pan-African) cycle. The Itaporanga batholith shows xenoliths with F_2 foliation parallel to the granite foliation, suggesting its emplacement as syn- to late-tectonic to the Brasiliano cycle.

Field evidence for magma mixing

Mixing of magmas has been proposed as a major petrogenetic process in the origin of hybrid rock types in plutonic environments (WALKER and SKELHORN, 1966; WIEBE, 1974 and 1980; VERNON, 1983; WHALEN, 1985; WHALEN and GARIEPY, 1986) and in the volcanic associations (GROVE et al., 1982; WHALEN and CURIE, 1984; HOOPER, 1985; KOYAGUCHI, 1986). The features observed in rocks where magma mixing took place, often associated with crystal fractionation, exhaustively discussed in an increasing number of papers (VOGEL, 1982; WIEBE and

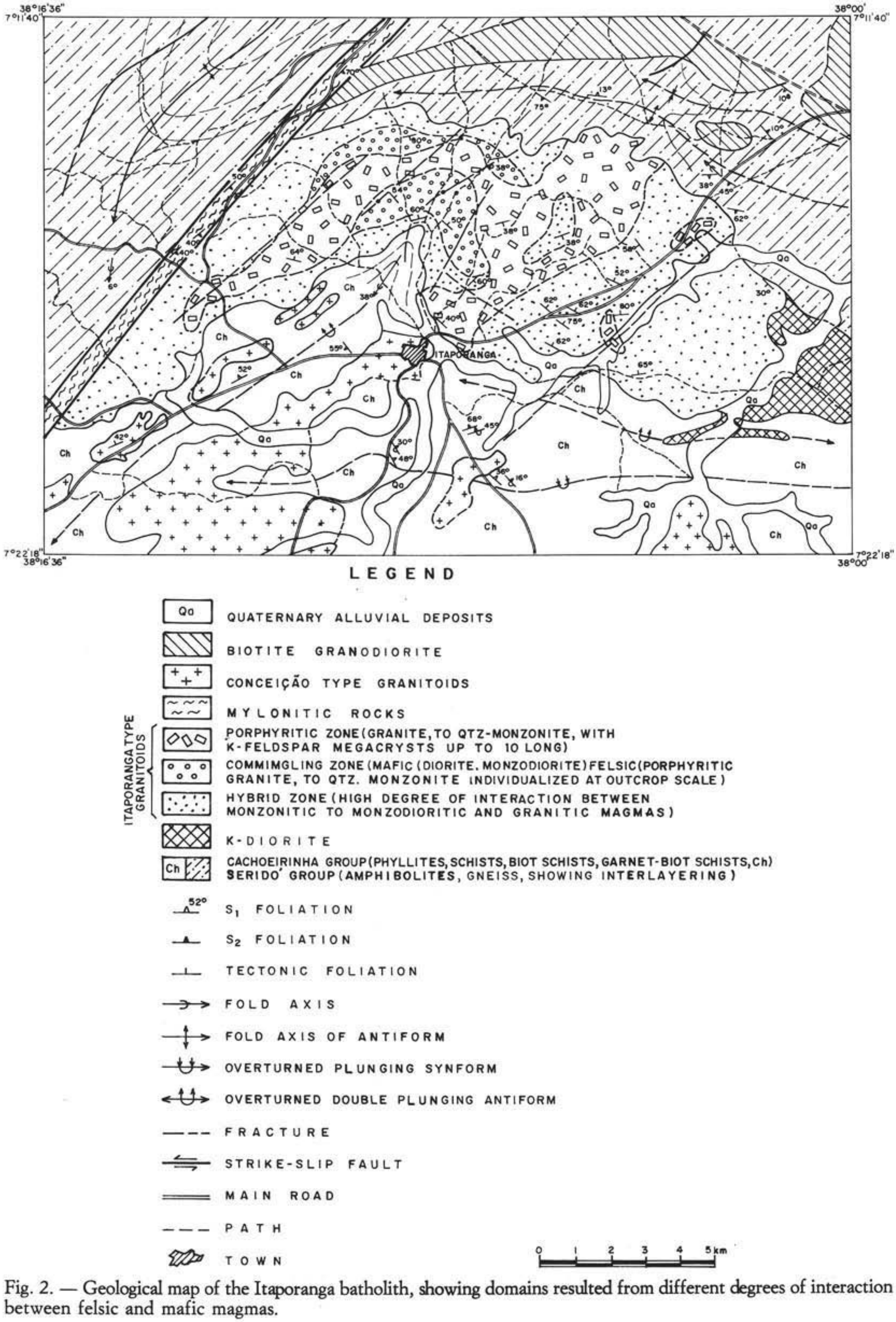

Fig. 2. — Geological map of the Itaporanga batholith, showing domains resulted from different degrees of interaction between felsic and mafic magmas.

WILD, 1983; BARNES, 1983; WHALEN, 1986), led us to think this may have been the case with the Itaporanga batholith. This batholith is composed of granite, granodiorite, quartz monzonite, monzonite, and diorite, and this compositional gradation may have resulted by interaction of granitic to granodioritic and dioritic magmas. Field evidence and preliminary chemical data will be discussed here in an attempt to analyze magma mixing as a major petrogenetic process in the Itaporanga batholith.

In order to have mixing of magmas several obstacles must be overcome. These obstacles are differences in viscosity, density, and temperature between the felsic and mafic magmas, and also the very low diffusion rates of chemical species in silicate liquids (VOGEL et al., 1984).

The Itaporanga batholith was divided into three domains, based on possible mixture of magmas. The hybrid zone, which varies in composition from granodioritic to quartz monzodioritic, the porphyritic zone composed of granite to quartz monzonite and the commingling zone where dioritic rocks are in close association with granitic, granodioritic and monzonitic ones and identified as isolated units at outcroup scale (Fig. 2).

Hybrid zone - the obstacles to mixing mentioned above seem to have been suppressed in this portion of the batholith, where a high degree of interaction between felsic and mafic magmas is often observed, giving rise to a migmatite-like structure (photo 1). In some of the outcrops mafic layers 10-50 cm wide are followed by felsic porphyritic ones, with approximately the same variation in width. K-feldspar megacrysts in the mafic layers, as well as across the boundary between mafic and felsic layers, are evidence of the degree of chemical equilibrium (diffusion + mechanically controlled) attained by these layers (photo 1). On the other hand, there are mafic layers without K-feldspar megacrysts, suggesting recurrence of the mafic magma pulses, corroborated by biotite-rows in K-feldspar megacrysts. These biotite-rows represent changes in temperature during K-feldspar growth probably caused by more than one mafic pulse.

Another common feature is the abundance of mafic enclaves, some of them with crenulated contacts (photo 2) and others, more regular, either angular or elliptical. According to DIDIER (1987) these enclaves may represent proximity and distance of mixing site, respectively.

Cuspate contacts between mafic portions and the porphyritic granodiorite (photo 2), and pillow-like structures developed by the mafic magma in contact with the cooler felsic one (photo 3), are evidence of viscosity and temperature differences between the two magmas. Although differences in viscosity and temperature are obstacles to mixing, the intense degree of interaction between mafic and felsic magmas observed throughout this zone suggests that these obstacles were overcome.

The syn- to late-emplacement of the Itaporanga batholith in relation to a major tectono-thermal event (the Brasiliano cycle) may have increased the possibility of mechanical interaction between the two magma types by favoring turbulent flow of magmas, both in a liquid state (TURNER and CAMPBELL, 1986). Mechanical mixing may also have being enhanced by a major strike-slip fault which cuts the western portion of the batholith, promoting homogeneization of the different magma types.

Porphyritic zone - these portions may represent areas that crystallized before the tectono-thermal event peak and had their identities preserved without much mixing, or pulses of felsic magma which crossed the magma chamber without much contamination by the mafic magma. The degree of interaction between diorite and granodiorite in the porphyritic zone was restricted to the presence of mafic enclaves. These enclaves are commonly ellipsoidal showing sharp contacts, representing some distance from the mixing site (DIDIER, 1987).

Commingling zone - in this portion of the mapped area mafic (diorite) portions inside the porphyritic granodiorite with sharp contacts may be observed on the outcrop scale. Some of the mafic portions show growth of K-feldspar megacrysts, attesting that at least some degree of chemical equilibrium was

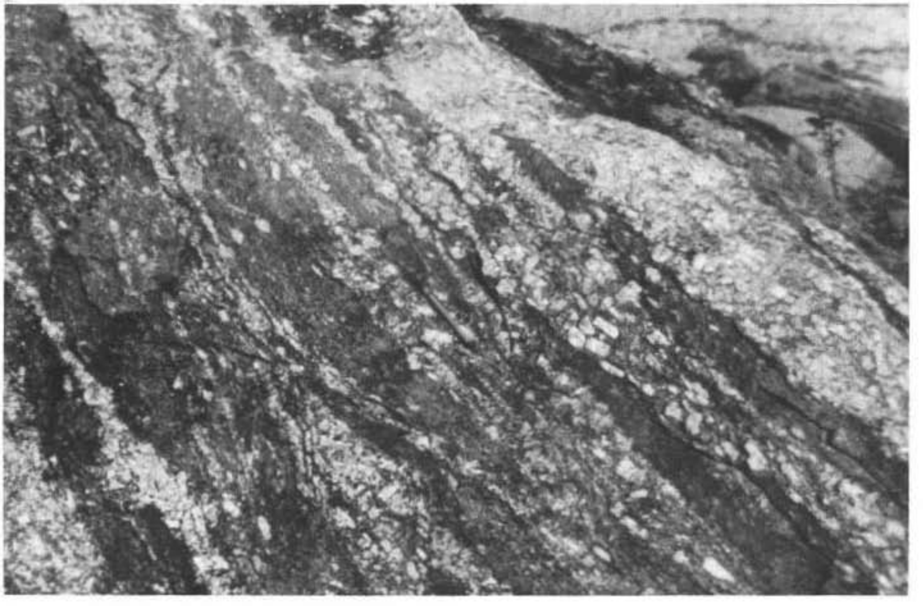

Photo 1. — Migmatite-like structure in the hybrid zone characterized by intense interaction of mafic and porphyritic felsic portions. a) K-feldspar megacrysts in mafic layers, attesting that some degree of chemical equilibrium between mafic and felsic layers was attained.

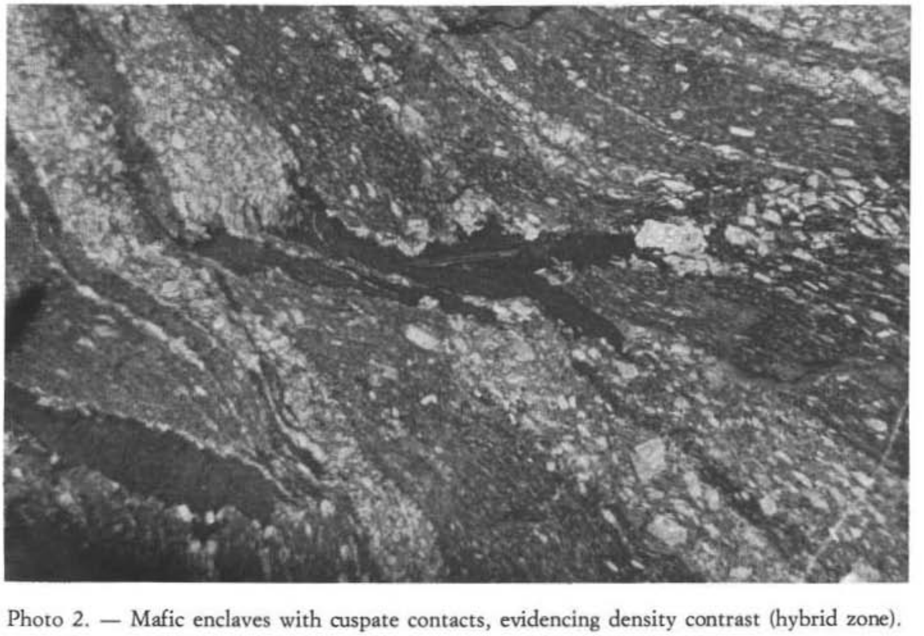

Photo 2. — Mafic enclaves with cuspate contacts, evidencing density contrast (hybrid zone).

attained (photo 4).

Petrography

Porphyritic zone - the rocks that compose this portion of the batholith vary from quartz monzonite, to quartz monzodiorite, granodiorite, to granite, the latter being more common and attesting to a less intense or

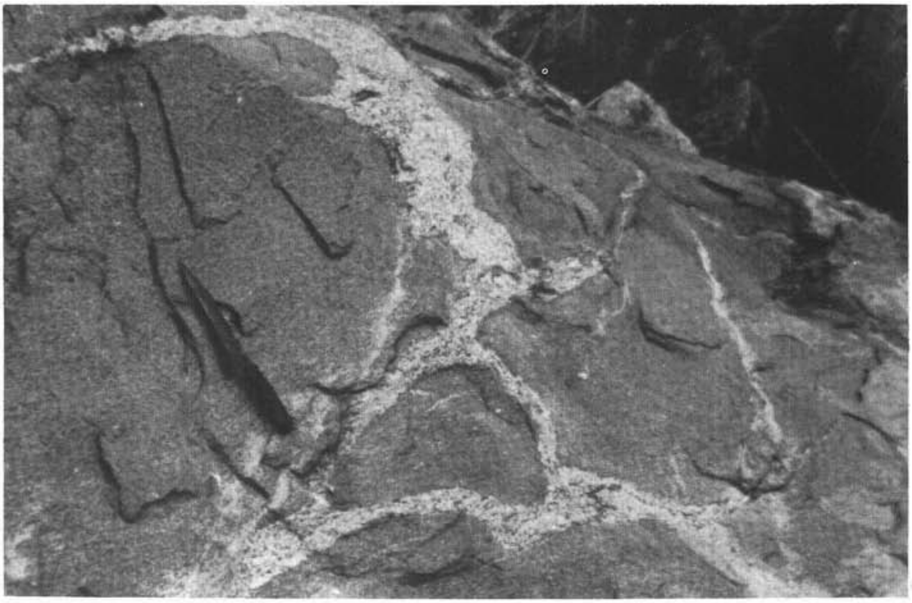

Photo 3. — Pillow-like structure developed by the hotter mafic magma, in contact with cooler felsic one.

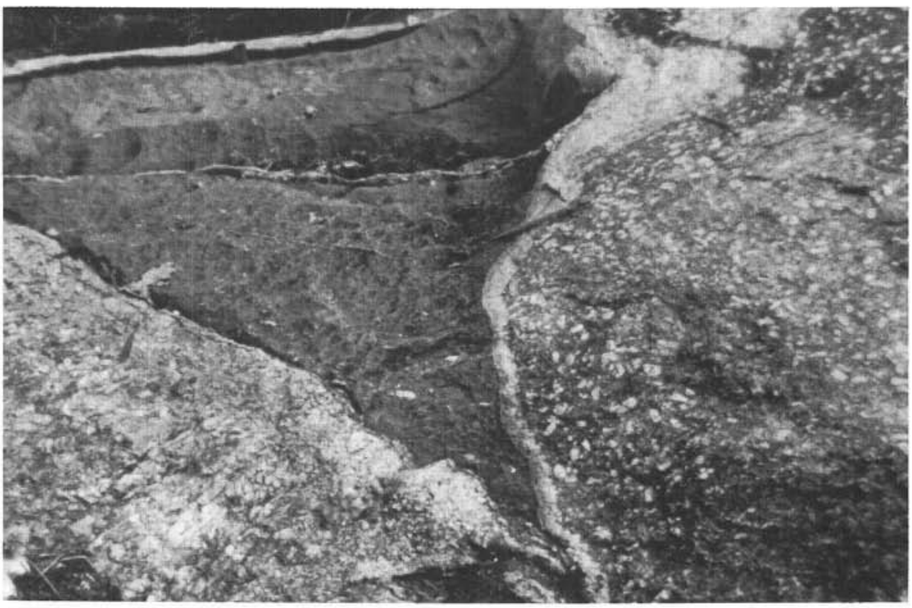

Photo 4. — Mafic portion isolated and in sharp contact with felsic portion (commingling zone).

almost absent degree of mixing Quartz, plagioclase (An 10-30), microcline, biotite, ± hornblende are the major mineral phases; sphene, allanite, apatite and zircon are common accessory phases, and calcite, sericite and chlorite represent products of late hydrothermal alteration.

The evidence for mixing in this zone is mainly represented by mantled plagioclase inclusions in the microcline megacrysts. These

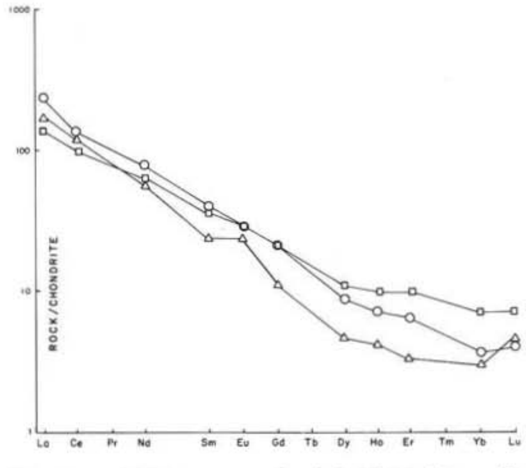

Fig. 3. — REE patterns for hybrid (circle), mafic (square), and felsic (triangle) portions of the Itaporanga batholith.

plagioclase crystals may represent a syn-mixing growth. The discontinuity of the plagioclase mantle characterizes reaction with the matrix, probably caused by disequilibrium during mixing.

The tectonic foliation imposed on the batholith is observed on the microscopic scale by deformed plagioclase crystals showing mismatches of polysynthetic twins, K-feldspar megacrysts with deformed cross hatched twins, mortar texture, kinkbands in biotite, and quartz showing subgrain formation and ribbon texture.

Hybrid and Commingling zones - the lithologic types occurring in these zones are diorite, quartz monzodiorite, quartz monzonite, and granodiorite, showing mineralogy similar to that observed in the porphyritic zone.

In the hybrid zone a striking feature to attest mixing of magmas is the occurrence of migmatite-like structures composed of alternation of mafic (dioritic) with porphyritic bands, and also a complete gradation between these two.

In the commingling zone where mafic and felsic magmas interacted, acicular hollowed apatite with L/W = 40 is observed evidencing the contrasting temperatures, reinforced by zoned plagioclase with subcircular cores and mantled plagioclase inclusions in the K-feldspar. Diffusion-controlled growth of K-feldspar in the mafic portions suggests that the two end-members eventually reached equilibrium.

Geochemistry

Fifteen samples were analysed for major and selected trace elements by X-ray fluorescence techniques. Table 1 shows chemical analyses for different zones in the batholith. REE were analysed by induced coupled plasma, at the Geosol laboratory, Minas Gerais, for three samples from the same outcrop, representing respectively mafic, hybrid, and felsic members (Fig. 3).

The REE show small variations in the three samples analyzed, with the hybrid sample enriched in LREE in relation to mafic and felsic samples, and placed intermediate to mafic and felsic ones for the HREE (Fig. 3). The three samples analyzed show LREE enrichment related to HREE and flat negative slopes, with the exception of the porphyritic sample (felsic end-member) which showed a small, negligible positive Eu anomaly. SIAL (1984) observed the same behavior for the HREE in other K-rich porphyritic calc-alkaline plutons in the CSF.

Major element variation diagrams (Harker diagrams) show near linear trends (Fig. 4) with the field identified as hybrid composition (quartz monzodiorite to quartz monzonite) plotting in an intermediate position to the mafic (quartz diorite to diorite) and felsic (quartz monzodiorite to granite) compositions, whereas the trace elements variation diagrams (Fig. 5) often show scatter suggesting that petrogenetic evolution was more complex than simple two end-member mixing.

Geochronology

The porphyritic facies of the Itaporanga batholith was dated by a five point Rb-Sr isochron, with an emplacement age of 620 ± 22 Ma, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7057 ± 0.0003 (Brasiliano = Pan-African cycle). Hornblende and biotite yieldeld $^{40}Ar/^{39}Ar$ age spectra with well-defined plateau ages of c. 580 and 540 Ma respectively. They probably represent cooling

TABLE 1
Whole rock major and trace element analyses of the Itaporanga Granite

	A) Porphyritic facies						b) Hybrid facies						c) Mafic facies		
ELEM.	1-P	2-P	10-P	91-P	101-P	153-P	1-H	2-H	10-H	161-H	145-H	169-H	1-M	145-M	161-M
SIO2	63.5	61.9	61.0	63.2	62.3	66.7	60.6	58.5	55.3	60.9	58.4	59.0	53.6	52.0	56.7
TIO2	0.52	0.82	0.84	.0.64	0.96	0.51	1.2	1.2	1.3	0.99	1.2	0.96	1.4	2.1	1.4
AL2O3	16.0	15.7	16.8	15.9	15.5	14.7	14.9	15.6	16.7	16.7	15.2	14.4	14.8	17.2	16.30
FE2O3	0.53	1.0	0.70	0.85	1.7	0.94	0.52	1.6	1.9	0.87	1.4	2.0	1.1	1.6	2.4
FEO	2.22	4.29	4.14	3.55	3.84	2.66	5.47	5.92	6.21	4.44	5.03	5.03	7.10	7.25	6.51
MNO	0.03	0.10	0.07	0.06	0.08	0.06	0.09	0.14	0.12	0.09	0.10	0.13	0.12	0.12	0.13
MGO	1.7	1.5	1.7	1.2	2.0	1.0	2.6	2.3	1.9	2.1	3.0	2.0	5.4	2.6	1.9
CAO	2.7	2.8	2.8	2.2	2.9	1.9	4.2	3.6	4.3	3.4	3.8	5.0	6.6	5.3	5.2
NA2O	5.3	4.8	4.8	4.8	4.8	4.4	3.9	4.9	4.9	4.3	4.3	3.7	4.2	5.2	4.3
K2O	5.8	5.8	5.5	5.9	3.8	5.6	4.6	4.8	5.2	4.4	5.8	5.9	3.9	4.3	3.3
H2O+	0.59	0.54	0.69	0.65	0.89	0.66	0.49	0.75	0.84	0.84	0.63	0.54	0.73	0.72	0.86
H2O-	0.10	0.14	0.08	0.09	0.08	0.04	0.05	0.09	0.05	0.01	0.09	0.09	0.09	0.04	0.20
CO2	0.40	0.25	0.50	0.40	0.42	0.39	0.52	0.25	0.52	0.25	0.50	0.61	0.40	0.42	0.24
P2O5	0.21	0.32	0.33	0.23	0.37	0.22	0.45	0.38	0.59	0.34	0.45	0.43	0.39	0.80	0.49
TOTAL	99.60	99.96	99.95	99.67	99.64	99.78	99.59	100.03	99.83	99.63	99.90	99.79	99.83	99.65	99.49

TRACE ELEMENT ANALYSES

	a) Porphyritic facies								b) Hybrid facies						c) Mafic facies		
ELEM	1-P	2-P	10-P	91-P	101-P	153-P	163-P	167-P	1H	2H	10H	161H	145H	169H	1M	145M	161M
Rb	110	170	160	160	130	160	140	120	120	160	150	160	120	140	130	110	99
Sr	840	490	600	380	530	400	540	400	700	440	660	720	640	550	660	650	630
Ba	1420	1140	1400	1510	910	1200	1400	890	1800	1050	1480	2400	1960	1270	920	1710	1980
Th	<15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ta	<15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zr	340	380	360	470	410	340	175	200	180	400	390	550	500	280	240	590	320
Nb	<20	20	21	32	28	<20	20	20	20	32	34	20	34	34	<20	42	26
Hf	<100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Y	<10	16	10	26	30	<10	14	13	<10	18	28	22	22	<10	22	26	20

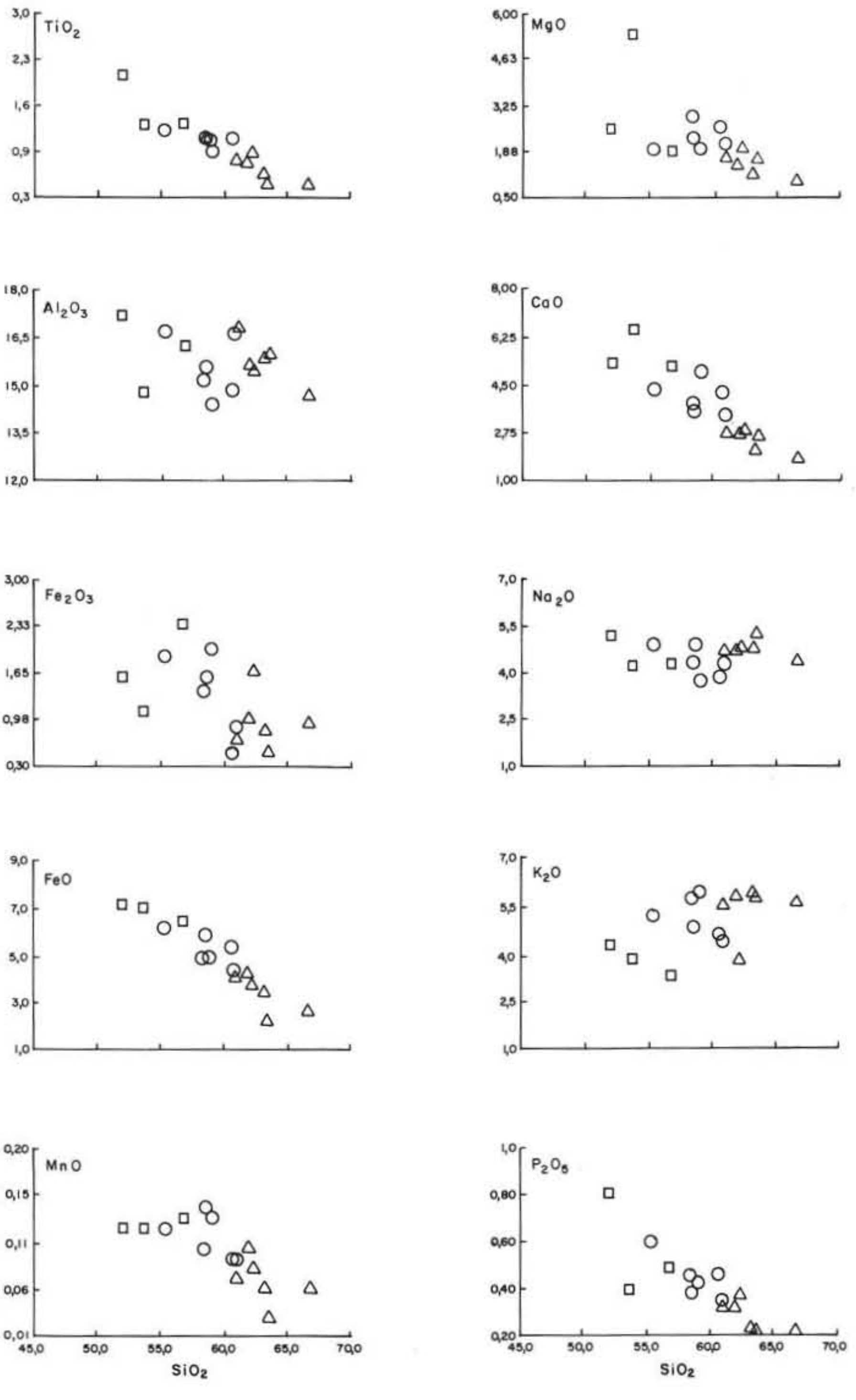

Fig. 4. — Major element variation diagrams. Symbols as in Fig. 3.

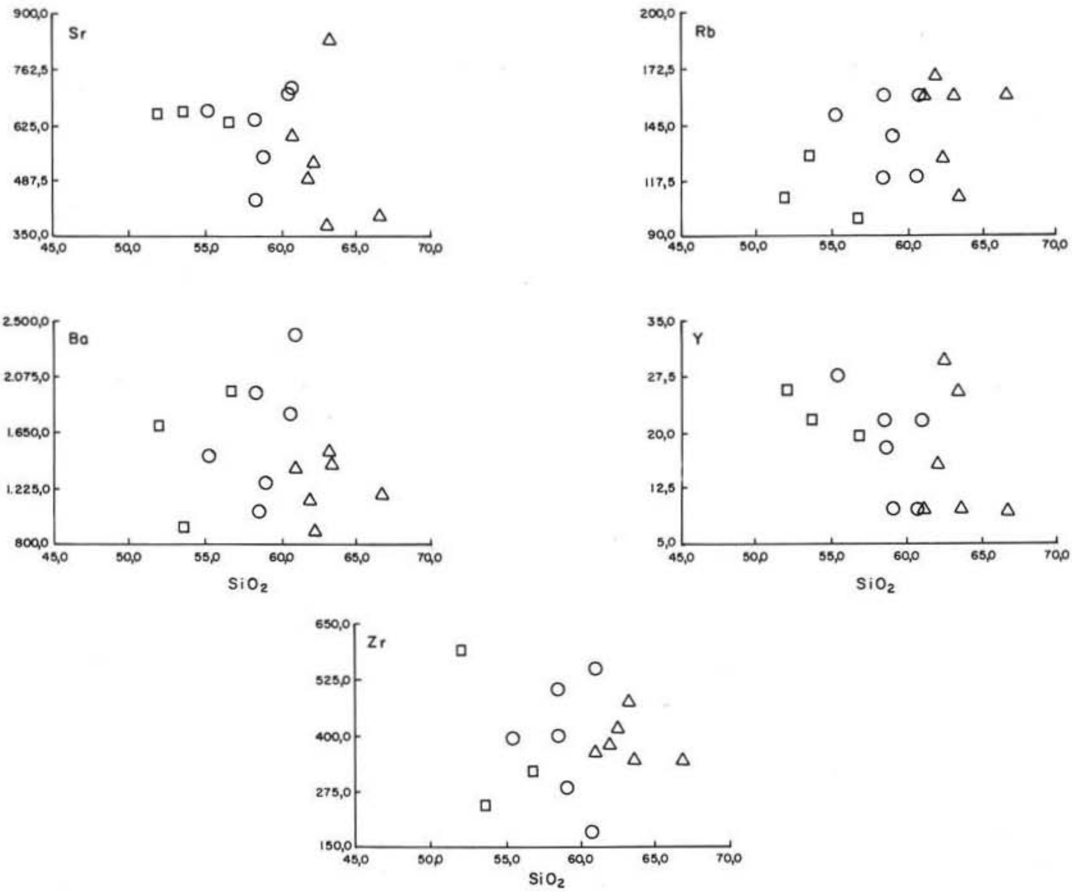

Fig. 5. — Trace element variation diagrams. Symbols as in Fig. 3.

ages, and suggest a slow cooling compatible with a relatively deep level of emplacement.

Discussion

Field observations suggested magma mixing to explain the complex chemical, and mechanical interactions between coexisting magma types.

The intense interaction among the lithologic types was tested using major chemistry and the XLFRAC program of STORMER and NICHOLLS (1978), where the felsic (granodioritic) magma was used as initial magma and 45% of the mafic (dioritic) magma was added to obtaining the hybrid component. The hybrid composition obtained was very close to the chemical composition of the hybrid member, with the sum of square of residuals = 1.0. This value shows good agreement with the data obtained through variation diagrams (Fig. 4), where addition of 55 to 65 percent of felsic to mafic magma was observed to generate the hybrid compositions.

The HREE patterns (Fig. 3) also show that the hybrid component has an intermediate composition between felsic and mafic magmas. This behavior is not observed for the LREE patterns suggesting that a simple two end-member magma mixing was not the only process involved in the evolution of the Itaporanga batholith and that mixing of magmas may have occurred in association with other processes such as crystal fractionation. The absence of the Eu anomaly is explained by the balance between feldspar and hornblende. The relative enrichment in LREE compared to HREE may have been caused by the mineral association apatite, sphene and allanite, frequently observed in the lithologic types which compose the batholith.

Microscopic observations showed hollowed acicular apatite, which suggests contrasting temperatures between the mafic and felsic magmas and a rapid cooling of the hotter magma when in contact with the cooler one. Mantled plagioclase inclusions in the K-feldspar megacrysts throughout the batholith, associated with biotite-rows in those megacrysts, indicate that changes in temperature were probably caused by successive pulses of mafic magma. The extensive shearing observed throughout the batholith may have an important role in the mechanical interaction, contributing to the formation of abundant hybrid composition.

The chemical equilibrium attained, demonstrated by growth of K-feldspar megacrysts in the mafic portions, attests that an interaction between the two magmas of contrasting compositions occurred when they were in a liquid + crystal state (crystal-liquid mush), enhanced by a major shearing event.

The inward dipping tectonic foliation within the batholith, associated with cuspate contacts between mafic enclaves and dikes and their host porphyritic rocks observed in the hybrid zone attest, respectively, to a lower level of exposure of the diapiric intrusion and to the proximity of the mixing site (DIDIER, 1987).

Summary and conclusions

The porphyritic, K-rich calc-alkaline Itaporanga batholith shows strong field evidence for coexistence and mingling of magmas of contrasting compositions. Frozen-in magma mixing testimonies are observed throughout the batholith as pillow-like structures, cuspate contacts between mafic dikes and the porphyritic granodiorite, inclusions of biotite-rows in K-feldspar megacrysts attesting to at least two growth stages, and migmatite-like structures developed as the result of close interaction between felsic and mafic magmas.

The obstacles to mixing pointed out by VOGEL (1984), such as differences in viscosity, density, temperatures and the low diffusion rates of chemical species in silicate melts, seem to have been overcome, since complete gradation between porphyritic granodioritic and fine grained mafic dioritic rock is observed throughout the batholith.

The present level of exposure, representing the root zone of a diapiric intrusion associated with emplacement during a tectono-thermal event (Brasiliano = Pan-African Cycle), and a widespread shearing event characterized by a major sinistral strike-slip fault, which cut the batholith when it had still a high proportion of liquid provide us with uncommon degree of interaction between magmas of contrasting physical properties.

The agreement between a chemical balance model and major elements mixing diagrams, associated with HREE patterns consistent with a mixing model, suggests magma mixing as an important petrogenetic process, probably occurring together with crystal fractionation during the evolution of the Itaporanga batholith.

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