

THE SÃO VICENTE-CAICÓ MASSIF, NORTHEAST BRAZIL: EXAMPLE OF AN EARLY PROTEROZOIC GNEISSIC-MIGMATITIC SUITE WITH FEATURES OF MODERN CALC-ALKALINE I (CORDILLERAN)-TYPE MAGMATISM

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RESUMO Dados geológicos, petrográficos, mineralógicos, geoquímicos e isotópicos do Maciço gnáissico/migmatítico paleoproterozóico São Vicente-Caicó, região do Seridó, Província Borborema, Estado do Rio Grande do Norte, NE do Brasil, são apresentados e discutidos. A Suite São Vicente-Caicó inclui rochas grábróicas e granitóides polimetamórficas e polideformadas predominantemente do fácies anfibolito. Os autores concluem que as rochas pre-metamórficas são representadas por uma associação magmática derivada do manto superior/crosta inferior muito semelhantes as suites Mesozóico/Terciárias calcio-alcálicas do tipo I (Cordilherano), normal a alto-K que evoluíram por processos de MASH e ACF.

Palavras-chave: Província Borborema, Maciço São Vicente-Caicó, petrografia, geoquímica, granitóides calcio-alcálicos

ABSTRACT Geological, petrographic, mineralogical, geochemical and isotopic data from the Early Proterozoic gneiss/migmatitic São Vicente-Caicó Massif in the Seridó Area of the Borborema Province, State of Rio Grande do Norte, north-eastern Brazil, are presented and discussed. The São Vicente-Caicó Suite includes polymetamorphic and polydeformed rocks of gabbroic to granitic compositions belonging dominantly to the amphibolite facies. It is concluded that the pre-metamorphic rocks are represented by an upper mantle/Archaean lower crust-derived magmatic suite quite similar to Mesozoic/Tertiary normal- to high-K calc-alkaline I (Cordilleran)-type suites which evolved by MASH and ACF processes.

Keywords: Borborema Province, São Vicente Caicó Massif, Petrography, Geochemistry, Calc-Alkaline Granitoid Suite

INTRODUCTION Archaean/Early Proterozoic rocks built up some large areas in Northeast Brazil of which the Borborema Province (Almeida *et al.* 1977), bounded at south, northeast and northwest by the São Francisco Craton, the São Luiz Craton and the Parnaíba Basin respectively, is an outstanding example (Figs. 1A and B).

The Borborema Province (BP) has a complex yet not fully understood geological evolution and by this underwent several more or less contrasting interpretations. For example, Neves (1975) considers the BP as an Archaean basement reworked and remobilized during the Meso- to Neoproterozoic and Van Schmus *et al.* (1993, 1994a, b) defines the BP as an old paleocontinent built up by large crustal blocks of different model ages.

In the Seridó region, State of Rio Grande do Norte, the BP comprises 4 major geological units:

1- An ancient medium- to high-grade polymetamorphic basement including ortho- and parametamorphic basic to acid gneisses, migmatites and granulites.

2- Orthogneissic-migmatitic complexes with rocks of gabbroic, dioritic, tonalitic, granodioritic and (rare) granitic compositions cutting the ancient basement.

3- A Proterozoic approximately north-south trending schist belt (Seridó Group) comprising dominantly low- to medium-grade clastic psammitic-pelitic metasediments beside some mafic-ultramafic rocks (amphibolites, hornblendites), marbles and calc-silicate gneisses.

4- Plenty Late Precambrian (Brasiliano) megaporphyritic, porphyritic, uneven- and even-grained granitoid plutons associated with fine- to medium-grained aplitic dikes and several generations of pegmatites cutting older host rocks.

The aim of this paper is to present a petrographic and geochemical characterisation of the São Vicente-Caicó Massif between the homonymous cities in the State of Rio Grande do Norte in an area of about 1500 km² (Figure 2) and which belongs to the second group of the supra-mentioned geological units. Among the plenty contributions dealing either with different aspects of the here considered area or the main topics of this paper, those of Ebert (1970), RADAM Project (1981), Jardim de Sd (1992), Jardim de Sa *et al.* (1982, 1990), Hackspacher *et al.* (1990, 1992, 1994, 1997), Dantas (1992), Dantas *et al.* (1991, 1992), Magini (1994), Petta (1995), and Petta *et al.* (1992, 1994, 1996a, b, c, 1997) are stressed.

THE SÃO VICENTE-CAICÓ MASSIF General Features

The São Vicente-Caicó Massif (SVC) is located in the central part of the Seridó region in the state of Rio Grande do Norte and represents one of the oldest units of the Borborema Province. It has a regionally NE-SW trending ellipsoidal dome-shape and in the considered area a surface of about 1500 km². It comprises light to dark grey biotite hornblende gneisses, locally migmatitic, of gabbroic, dioritic, tonalitic, granodioritic, monzogranitic and rare granitic composition which,

together, define the São Vicente-Caicó Suite (SVCS). The Seridó Group to the east and the ancient metamorphic basement to the west border the SVC. Remnants of this basement in the SVC are represented by metaleucogranites, amphibolites, hornblendites, banded gneisses with alternating layers of amphibolites and metaleucogranites beside some parametamorphic schists, gneisses and migmatites. These rocks were assembled by Petta (1995) and Petta *et al.* (1996a, b, c) in the basal sequence of the SVC and considered as cut by the SVCS.

Even after its polymetamorphic and polyphasic tectonic deformation it is still possible to recognise the former polydiapiric architecture of the SVC, its regional zoned structure with a centre-directed increasing felsic composition and the dominance of biotite-hornblende tonalitic and granodioritic gneisses among the SVCS (Figure 2). Dikes of meta-aplites and amphibolites/hornblendites which widths and frequency change rapidly from place to place cut the plutons amalgamated in the SVC.

Enclaves Typical for the SVCS is the richness of the gneisses in ellipsoidal to irregular-shaped enclaves either more basic or more felsic than their host-rocks and which frequency decreases with the increasing felsic composition of the latter. The contacts between the enclaves and their host-rocks are either sharp with or without contact rims or gradual, partly assimilated, however completely absorbed "ghost enclaves" are rare. In the porphyroid gneisses the enclaves contain variable amounts of partially or completely engulfed and more or less deformed feldspar megacrysts of the host-rock and in those with amphibolitic to hornblenditic compositions also quartz xenocrysts occur.

In the less deformed gneisses it is still possible to recognise two groups of enclaves. The first comprises enclaves with either more basic or more acid composition than those of their host-rocks. They are fine- to medium-grained, some with still preserved typical magmatic textures, in general with finer grain-sizes than those of the host-rocks. Their shapes are rounded, ovoid, or dominantly irregular, grossly triangular or polygonal, with or without contact rims. The contacts vary from dominantly sharp to locally gradational, with more or less clear signs of partial assimilation and xenocrysts are in general rare. This group of enclaves represents synintrusive dikes in the plutons more or less disrupted and dispersed during or after their emplacement by the plastic flow of the more or less crystallised host-rocks. The diking process starts very early in the evolution of the diapirs and ended only after their complete consolidation by the emplacement of crosscutting acid (meta-aplitic) to basic (amphibolitic) dikes. This explains the variation of the main aspects of the enclaves of this group by several factors such as their composition, degree of cooling prior to their disruption and the time of their emplacement in relation to the cooling and ascent movements of the host-rock. Early dikes are more disrupted,

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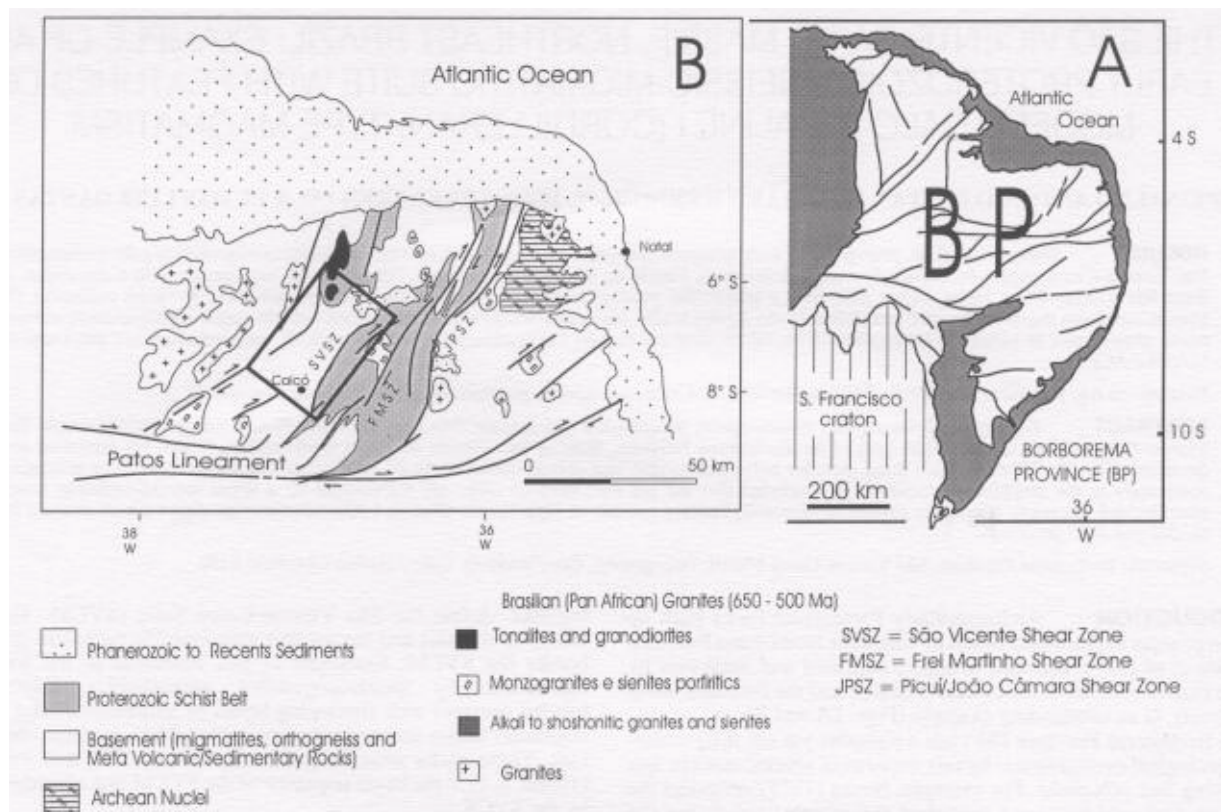


Figure 1 - Location of the Borborema Province in NE Brazil (A), its overall highly simplified geological structure in the studied area (B).

dispersed, deformed, assimilated and xenocryst bearing than younger ones which shapes are more irregular, polygonal, with sharp contacts, finer texture and poor in xenocrysts, reflecting the quenching of the synintrusive dikes prior their disruption. In this enclaves, the preserved magmatic features are rather common as are the presence of augite, mantled or not by hornblende, in basic rocks, feldspar tile texture, normal zoning in K-feldspar, hornblende and plagioclase, magmatic mineral intergrowth, corroded phenocrysts, etc. Quenching is recognised by the presence of acicular minerals and hornblende skeletons. Disrupted but not dispersed dikes results in more or less aligned "boudins" or irregular-shaped enclaves. Dikes in which disruption was not completed show pinch and swell structures. In other cases the dikes are deformed by flow folding and show some partially enclosed xenocrysts of the host-rock at their contacts, which vary, from place to place, between sharp and more or less transitional.

The second group comprises larger and more frequent enclaves with about equal grain-sizes and an always some more basic composition than their host-rocks. This means that the host-rock suite formed by (meta) granites, monzogranites, granodiorites, tonalites, diorites and gabbros comprises mainly enclaves of monzogranitic, granodioritic, tonalitic, dioritic, gabbroic and melagabbroic compositions (the last represented by mela-amphibolites and hornblendites), respectively. Typical is the rounded to flattened elliptical shape, sharp to transitional contacts, normally without contact rims, and a variable amount of xenocryst represented mainly by deformed feldspar megacrysts from the megaporphyritic host-granitoid but in some cases also small flecks of finer grained groundmass material from the host-rocks occur in the enclaves. The richness in xenocrysts reflects a long side by side flow of enclaves and host-rocks allowing a partial mechanical mixing (= mingling) of both. By this the longer axis of the elliptical shaped enclaves became parallel to the flow structure of the host-rocks expressed by the iso-orientation of the euhedral to subhedral K-feldspar megacrysts laths and biotite flakes and by a magmatic banding done by alternating layers enriched and depleted in megacrysts.

The enclaves of this group are rather common, occurring in almost any outcrops, even the smaller ones. However, there are places anomalously rich or poor in enclaves but the reason of this feature was not clearly elucidated by the field works as due to local stronger magmatic flow, convection currents, neighbourhood of pluton contacts, deeper

level of exposure, etc. A common feature is that places enriched in enclaves are also enriched in megacrysts.

Deformations The São Vicente-Caicó Massif (SVCVM) presents a regional foliation S_n developed during the main thrust faulting related strain phase D_n which coincide with the development of the progressive regional metamorphism M_n . In the SVCVM the foliation ranges from pervasive near and within larger thrust zones to weak in areas between them where the former magmatic features of the SVCS are almost completely preserved. The S_n foliation is dragged by a superimposed shear-event D_{n+1} , which produced the irregular outlines of the SVCVM by a complex network of NE-SW trending dextral transcurrent shear zones up to thousand of kilometres long and several ones wide, related to a NW directed collision during the Brasiliano Cycle (Hackspacher *et al.* 1997). They represent expressive linear zones of crustal mobility with typical deep level plastic deformation.

Within this shear zones the original S_n foliated rocks of the SVCVM underwent a profound change by intense deformation and transposition associated with intrafolial folding, strata multiplication, interference structures and the development of fine banded extremely foliated streaky gneisses with rapidly changing grain-size from layer to layer. By this strong deformation the frequent enclaves loose their original clear identity being transformed in nebulitic flatted darker lenses or layers with transitional, diffuse, contacts suggesting at the first glance magmatic mingling and mixing with the adjacent lighter gneisses which represent the deformed former host-rocks of the enclaves. Also by the tectonic repetition of the extremely flatted lighter and darker rocks lenses and strata a banded structure with centimetric to metric thick layer is developed and which can be misinterpreted as banded bimodal magmatic sequences suggesting a pre-deformational isochronous emplacement of more acid and basic magmas. However, in many cases, the colour-change in the banded structure do not correspond to a compositional change but reflects only the rapid grain-size change in adjacent tectonically more or less intensively deformed rocks. The mean composition of this banded streaky gneisses is between the former dark (gabbroic to tonalitic) enclaves and their lighter (granodioritic to granitic) host-rocks (Petta 1995).

However this tectonically generates pseudo-magmatic features, with wide regional distribution due to the frequency of the strike-slip deformation zones, disappear immediately as soon as at the contacts of the shear zones outcrops of weakly foliated S_n rocks occur.

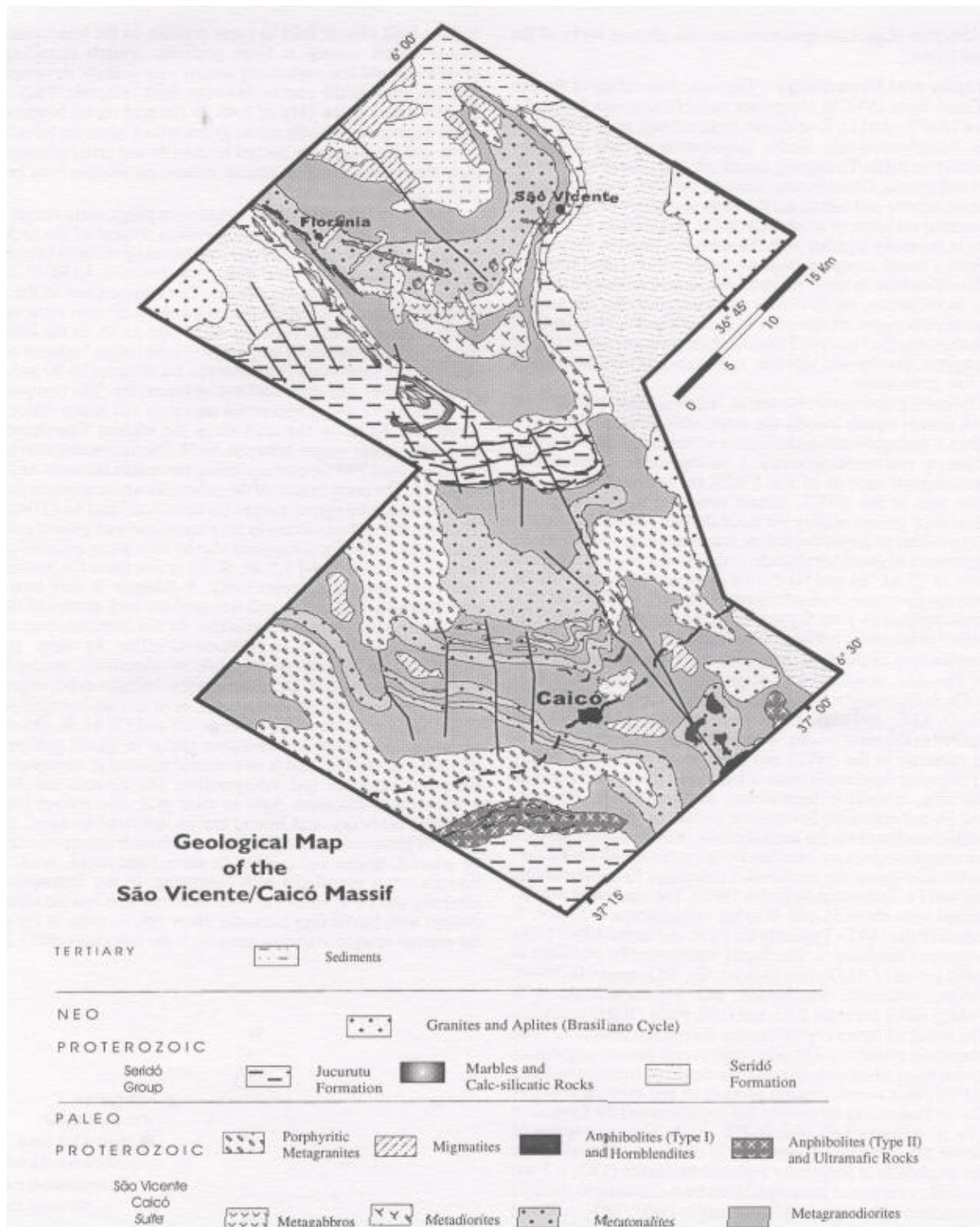


Figure 2 - Geological map of part of São Vicente/Caicó Massifs, State of Rio Grande do Norte, NE Brazil. (After Hackspacher et al 1994, modified by Petta 1995/97).

Metamorphism and Age The locally migmatitic gneisses of the São Vicente-Caicó Massif belong to the upper greenschist and amphibolite facies. The age of the high pressure M_n metamorphism is related to the Transamazonian cycle (Early Proterozoic) as determined by a $(Rb/Sr)_{WR}$ isochron (2.15-2.2 Ga; $^{87}Sr/^{86}Sr$ IR between 0.7012 and 0.7030, Dantas 1992, Dantas et al. 1992), $(U/Pb)_c$ concordia values of 2.15 Ga (Dantas 1992) and Sm/Nd model ages of 2.65 Ga (Dantas 1992, Dantas et al. 1992). The isotopic data were interpreted either as a result of the Transamazonian cratonization and/or reworking of a primordial Archaean crust (Hackspacher et al. 1990). The small negative $\epsilon_{Nd(t)}$ values were considered as expressing a depleted mantle-derived origin and the short crustal residence-time of the rocks (At

between the age of the protolith and the crystallisation age of its derived magmatic rocks) as indicating a small time-interval between the magmatic and the following tectonic and metamorphic processes considered by Petta (1995) and Petta et al. (1994, 1996a, b, c), as occurred under syntectonic conditions

The main Transamazonian M_n metamorphism is regionally overprinted by the low-pressure-high temperature M_{n+1} regional Brasiliano metamorphism which produced by partial crustal melting nebulitic migmatites associated with the intrusion of Brasiliano granitoids in the SVCM. Later on, still during the Late Precambrian, the whole SVCM was reactivated under lower metamorphic conditions producing

quartz-microcline-oligoclase-epidote-muscovite-chlorite rocks of the greenschist facies.

Petrography and Mineralogy The basic mineralogy of the São Vicente-Caicó Suite (SVCS) comprises variable amounts of quartz, plagioclase (An75 - An12), K-feldspars (microcline), amphibole (actinolite to Fe-tschermakite), biotite (lepidomelane) and pyroxene (salite/Fe-salite to augite/Fe-augite), beside allanite, chromite, magnetite, zircon and apatite. Green biotite, chlorite, epidote, sericite/muscovite, ilmenite, sphene and calcite are the main secondary minerals. The large volumetric variation of amphibole, mica, plagioclase, K-feldspar and quartz in the rocks together with the wide An-range in the plagioclase defines a broad compositional spectrum which range from ultramafic hornblendites to (rare) leucocratic granites forming a suite in which the metadiorites, metatonalites and metagranodiorites are the most frequent rock-types. Modal composition of the SVCS in the QAP diagram is shown in the Figure 3. The suite comprises rocks with (meta) megaporphyritic, porphyritic, uneven- and even-grained textures and coarse to fine grain-sizes.

In the following description the terms "basic", "intermediate" and "acid" rock groups equals loosely the association of hornblendites + amphibolites + metagabbros; metadiorites + metatonalites and metagranodiorites + metamonzogranites + metagranites, respectively. Some mineralogical aspects of the SVCS are outlined below: **Pyroxenes** are rare in the SVCS, almost restricted to the basic and intermediate rock groups mainly the amphibolites. Normally the pyroxene occurs either as preserved relicts in amphiboles or transformed in nide-aggregates of small hornblende grains. In the first case they are CaO- (mean of 23 wt. %) and Na₂O-rich (mean of 0.5 wt. %). In the second case the pyroxene is transformed in silica-rich (42-52 wt. %), and alumina-depleted (4-8 wt. %) actinolite and actinolitic hornblende with Mg/(Fe²⁺+Mg) ratios between 0.45 and 0.55.

The composition of the pyroxenes plot at the boundaries between the salite, Fe-salite, augite and Fe-augite fields in the Mg₂Si₂O₆ - Fe₂Si₂O₆ - Ca₂Si₂O₆ triangle. In zoned crystals the nucleus are enriched in FeO, Na₂O, Al₂O₃ and MgO and depleted in SiO₂, MnO, TiO₂ and CaO compared to the outer border. **Amphiboles** are the most outstanding mafic minerals in the SVCS and their compositions are highly variable. Following the classification of Leake (1978), in the basic rock group actinolite, actinolitic hornblende, Mg-hornblende, Fe-hornblende and Fe-tschermakitic hornblende occurs in the metagabbros and actinolitic hornblende in the amphibolites; in the intermediate rock group their compositions vary between Fe-hornblende and Fe-Tschermakite. In the acid group the amphiboles comprises Fe-tschermakitic hornblende and Fe-Tschermakite (Petta 1995). The amount of amphibole decreases from about 35-vol. % in the metagabbros to 25-vol. % in the tonalites (Petta 1995). Typically the basic and intermediate rocks show two types of amphiboles. The first is represented by prismatic to xenomorphic grains of Al₂O₃-rich (5-9-wt. %), SiO₂-poor (48-50-wt. %) actinolite, actinolitic hornblende and Mg-hornblende with Mg/(Fe²⁺+Mg) ratios between 0.65 and 0.80. Petta (1995) considers them as the result of direct crystallization during the middle to final stage of magmatic evolution. The other type occurs as nide-aggregates of small grains more silica-rich and alumina-depleted and is considered by Petta (1995) as a transformation product of pre-existing clinopyroxenes. In the basic rocks (mainly in the amphibolites) the formation of Al₂O₃ (> 10 wt.) and TiO₂-rich (> 0.5 wt. %) nide-aggregates of amphiboles at the expenses of pyroxene is observed whereas in the acid rocks, amphibole is frequently replaced by biotite (TiO₂ < 1 wt. %). The overall evolution of the amphiboles from the basic to the acid rocks is characterized by a gradual increasing in FeO*, TiO₂, Al^{IV} and (Na+K)_A. Contrasting with pyroxenes and amphiboles no Mg/Fe zonation is observed in the **biotites** which are represented uniformly in all three considered rock groups by lepidomelane in the (Al^{VI}+Fe³⁺+Ti)-Mg-[2(Fe²⁺+Mn)] diagram. In the Mg-(Al^{VI}+Fe³⁺+Ti)-(Fe²⁺+Mn) diagram the data plot at the boundary between Mg-biotite and Fe-biotite. Both classifications reflect the compositional field for biotite in terms of its end-member diagram where it is situated about half-way between siderophyllite and eastonite and between annite and phlogopite and with the dominance of annite and phlogopite over siderophyllite and eastonite. Finally, in the Al^{IV} x Mg diagram, all data plot in the mica field for calc-alkaline rocks. Biotite is the best mineral for the characterization of the various rock-types of the SVCS, as there is a regular shift from higher to lower Al^{IV} contents with increasing silica and at the same time in each rock-type increasing Al^{VI}-contents reflects its evolution from darker to lighter samples. In the basic rocks biotite is rather rare and mostly developed by the breakdown of amphibole, a fact which may explain its local high MgO-contents (up to 12 wt. %)

and the high x Mg of 0.51 in some crystals. In the intermediate rocks, biotite occurs mainly as large poikilitic crystals engulfing mainly plagioclase and less commonly amphiboles with the development of a reaction zone at the contact between both minerals. They are more Fe-rich with a mean x Mg of 0.48. In the acid rocks, biotite occurs in small aggregates of millimetric grains which trace the foliation of the rocks and are frequently altered to chlorite and sericite/muscovite, but their x Mg values are quiet similar to those for biotites from basic rocks (Petta 1995).

The overall compositional variation in **plagioclase** ranges between An75 and An12 and vary with the silica content of the rocks. In the basic ones the zoned megacrysts have cores up to An75 (amphibolites) or An60 (metagabbros) and outer rims between An50-40 (amphibolites) and An35-30 (metagabbros). The composition of the subautomorphic grains in the groundmass (without or with only very weak zonal structure) varies between An55 and An35. In the intermediate group the composition of megacrysts cores ranges between maximum of An50 and An45 and in the outer rim between An35-20 and An30-20 in metadiorites and metatonalites, respectively. The compositions of the subautomorphic grains in the matrix of this group varies between An40 and An22. In the acid rocks the highest Ca-contents of the megacryst-cores ranges between An38 (metagranodiorites) and An34 (metagranites) and the corresponding outer rims between An25-18 and An22-12. The composition of the subautomorphic grains in the foliated groundmass in this group ranges between An25 and An12 (Petta 1995). The decreasing An-contents in the plagioclase with growing silica-contents in the rocks is accompanied also by increasing amounts of Or with mean values of 0.5 and 1.5 wt. % for grains from the groundmass of basic and acid rocks, respectively. **K-feldspar** is very rare or completely absent in the basic and intermediate rock groups of the SVCS, but is the most important feldspar in the metamonzogranites and metagranites where it is represented either by large microcline megacrysts or as xenomorphic late microperthitic microcline commonly with mirmekitic and micrographic textures either in the groundmass of megaporphyritic/porphyritic or in uneven-evengrained rocks. Their Na₂O contents varies between 0.5 and 1.0 wt. %. **Quartz** occurs mainly as interstitial xenomorphic grains in quartz gabbros, quartz diorites and tonalites and is an essential mineral in metagranodiorites, metamonzogranites and metagranites. The crystals are dominantly xenomorphic, colorless, light to dark gray and always translucent. Sectorial extinction and healed cracks indicated by small inclusions trails are common features. **Accessory minerals** are represented mainly by allanite, zircon and apatite. In some basic rocks, small chromite crystals occur associated with magnetite. In the intermediate rocks ilmenite and Fe-Ti oxides are the most common opaque mineral. If in contact with biotite they normally show sphene rims. In the acid rock the normal opaque oxide paragenesis is the pair magnetite + ilmenite.

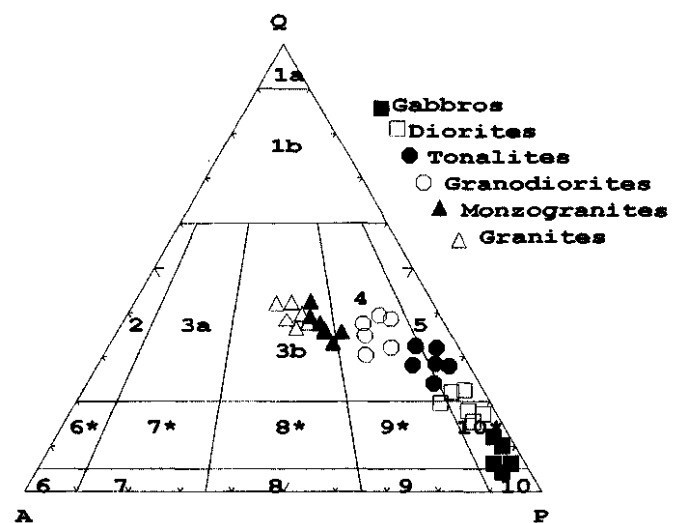


Figure 3 - Modal compositions for rocks from São Vicente/Caicó Suite, State of Rio Grande do Norte, NE Brazil, and their pre-metamorphic magmatic classification in the QAP diagram of Le Maitre 1989.

Geochemistry The major and most of the trace elements were determined at the Université Catholique de Louvain (Belgium) by combination of XRF, AAS and classical wet methods. The precision of the major elements SiO_2 , Al_2O_3 , Fe_2O_3^* , MgO , CaO , Na_2O , K_2O , TiO_2 , FeO , P_2O_5 and for the trace elements is better than $\pm 8\%$, $\pm 5\%$ and $\pm 4\%$, respectively. The REE, Hf and Ta were determined at the Université de Liège (Belgium) with a precision better than $\pm 3\%$. Selected analyses for (meta) gabbros, diorites, tonalites, granodiorites and granites are shown in Table 1.

As the rocks are metamorphosed and deformed the sampling was made preferentially in less tectonised outcrops and analyses of the same rock type but with different degrees of deformation were compared by the Grant method to detect the influence of fluid flow and associated metasomatic changes during the metamorphism. The results show that the metamorphism acted as a closed system in various sites of the SVCM (Petta 1995, Petta *et al.* 1997). Marker diagrams for major and minor elements are represented in Figure 4.

The SVCS is chemically expanded; SiO_2 ranges between 53 and 76 wt. % and shows an overall negative about linear correlation with TiO_2 , Fe_2O_3 , MgO , CaO and P_2O_5 . The Al_2O_3 trend is typically curved as in chemically expanded saturated to oversaturated magmatic suites due to the "dilution" of feldspars in an increasing amount of quartz produced during the progressive magmatic crystallization. The summit of the curve lies near 63-65 wt. % SiO_2 with about 17 wt. % Al_2O_3 . The Na_2O curve has an about similar behavior with a summit of about 4.5 wt. % also near 63-65 wt. % SiO_2 . The ascending branch of the curves reflects the increasing Na-contents in the plagioclase-rich rocks with increasing differentiation and the descending one the crystallization of larger amounts of quartz and K-feldspars in the silica-rich granitoid rocks, a fact confirmed by the $\text{SiO}_2 \times \text{K}_2\text{O}$ diagram which shows a K_2O -increasing in rocks with more than 70 wt. % SiO_2 .

Figures 5A and B show the equivalent magmatic classification of the SVCS gneissic suite in the multicationic P x Q (after Debon & Le Fort 1983) and R1 x R2 (after de La Roche 1978) diagrams and a good fit between modal and chemical classification. In the AFM diagram (Figure 5C, after Irvine & Baragar 1971) the SVCS lies about on the boundary between the calc-alkaline and tholeiitic fields, a typical feature for high-K calc-alkaline suites as it is the case of the SVCS in which only the metagabbros plot in the normal K-field (Figure 5E) after Le Maitre *et al.* (1989). In the molecular Shand diagram the SVCS plots dominantly in the metaluminous field (or completely if the a metaluminous/peraluminous A/CNK boundary-value of 1.1 is chosen (like by Chappell & White, 1974, for the I-type granites expressing by this value the upper stability of hornblende in increasing Al-richer residual melts during differentiation as determined by Zen 1986) and plot near the boundary line of the granitoid field (the diagonal line from Maniar & Piccoli 1989, in Figure 5D) confirming the highly evolved (about Ca-free) nature of the final products of the differentiation process. The evolutionary trend of the suite in this diagram also indicates the fractionation of amphibole (\pm pyroxene, \pm biotite) + plagioclase reflected by the simultaneously increasing and decreasing of the A/(CNK) and A/(NK) parameters respectively. Finally, in the Rb x Sr diagram in Figure 5F (after Johan *et al.* 1980), the SVCS values data plot in the field bounded by the Rb/Sr = 1 and 0.1 lines and which is typical for granitoids generated and/or evolved at deep levels (lower crust/upper mantle).

The data in Figures 4 and 5 are typical for normal-to high-K calc-alkaline suites of the I (Cordilleran)-type as stressed by Gill (1981), Brown (1982), White & Chappell (1983) and Pitcher (1985). Also typical is the gap between the (meta) gabbros and the others rocks of the suite, a feature emphasized by Regan (1985) which considered the gabbros in the Peruvian Batholith as reflecting a more tholeiitic (= low-K) magmatism preceding the emplacement of the other more typical calc-alkaline rocks of the suite with mainly dioritic to granitic compositions.

Also the position of some granites in the dioritic-granitic suite is not yet clear by at least three reasons (Dantas & Wernick, in preparation): i) - some of them show geochemical deviation from other granites clearly linked to the suite by a same overall evolutionary process which reflects the consanguinity between diorites, tonalites, granodiorites and monzogranites; ii) - the major part of the granites in the SVCM occurs mainly in its most migmatized areas and by this part of them may either belong to the SVCS or represent products of partial melting of SVCS-rocks during the later M_{n+1} regional metamorphism associated with the intrusion of plenty Brasiliano granitoids; iii) - deviations in $\epsilon_{\text{Nd}(t)}$ and $\epsilon_{\text{Sr}(t)}$ for the granite in relation to the (meta) dioritic-monzogranitic suite and which may indicate that they are the

result of partial melt of the countryrocks remnants in the SVCM during the emplacement of the huge volumes of calc-alkaline magmas. The association of small amounts of such types of granites with huge calc-alkaline batholiths is stressed since the first definition of I- and S-type granites by Chappell & White (1974).

Also the trace elements in Figure 6 are typical for expanded I-type suites as the outstanding $\text{SiO}_2 \times \text{Zr}$ diagram (Figure 6E) with increasing Zr-values up to 63-65 wt. % SiO_2 followed by decreasing values in silica-richer rocks. Also the Ba-curve (Figure 6J) is typical signaling the onset of major K-feldspar crystallization at about 63-65 wt. % SiO_2 . The simultaneously positive correlation for Cr and Nb and the negative correlation for Ni, Y, Sr and V in the metagabbros reflect the initial olivine, plagioclase and magnetite crystallization in their former magmatic equivalents. On the other side, the Th, Rb, Sr, Ba, Y, Cr, Ni, Co and V curves reflect clearly the increasing granitic character of the dioritic-granitic suite. In many of the trace element diagrams a typical double evolutionary tendency is expressed by the coexistence of two distinct trends, one representing the evolutionary line linking the mean composition of the different rock types of the SVCS and by another indicating the differentiation of each rock-type group.

DISCUSSION The Early Proterozoic gneissic-migmatitic São Vicente-Caicó Massif (SVCM) in the Serido area of the Borborema Province, State of Rio Grande do Norte, northeastern Brazil, with a metamorphic age between 2.15Ga [(Rb/Sr)_{WR}; (U/Pb)_Z] and 2.65Ga (Sm/Nd)_{MA} shows even after a polymetamorphic evolution and several episodes of tectonic deformation in its more preserved parts an astonishing similarity with Mesozoic and Tertiary calc-alkaline I-(Cordilleran)-type batholiths. This similarity includes mainly:

- 1- The large area of the SVCM (Figure 1B).
 - 2- Its polydiapiric architecture expressed by the amalgamation of numerous plutons with different sizes and composition (Figure 2).
 - 3- An overall zoned structure of the SVCM characterized by an center-directed increasing differentiation.
 - 4- The wide petrographic range of the SVCS including (quartz) metagabbros, (quartz) metadiorites, (quartz) metatonalites, metagranodiorites, metamonzogranites and rare metagranites (Figures 3 and 5A and B).
 - 5- The dominance of migmatitic gneisses with dioritic to granodioritic compositions among the SVCS (Figure 2).
 - 6- The compositional gap between the metagabbros and the suite ranging from metadiorites to metagranites. The compositional change within this suite is gradual, so that one rock-type merges into the other without compositional breaks (Figure 6).
 - 7- The normal-K nature of the gabbros and the normal-/high-K composition of the metadioritic to metagranitic rocks (Figure 5E).
 - 8- Some other features, like the pre-metamorphic mineralogy (including augite, hornblende, biotite, plagioclase, orthoclase/microcline and quartz beside allanite, magnetite, zircon and apatite), calc-alkaline serial character (Figure 5C), dominantly metaluminous Al-saturation (Figure 5D) and low (0.1 to 1) Rb/Sr relationships (Figure 5F), typical for granitoid suites generated/evolved in the lower crust/upper mantle and in concordance with the low $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio (0.7012 to 0.7030) and the small negative $\epsilon_{\text{Nd}(t)}$ -values for the SVCS.
 - 9- Marker diagrams for major, minor and trace elements with typical trends for Mesozoic-Tertiary calc-alkaline I (Cordilleran)-type magmatic suites (Figures 4 and 6).
 - 10- Simple and double microgranular enclaves ranging in composition from melagabbroic to granitic. The enclaves show several features (textures, mineralogy, modal composition, sizes, shapes, contacts, xenocrysts derived from the host-rocks, host-rock composition/enclave frequency relationships, etc.) quite similar to those in younger typical calc-alkaline I (Cordilleran)-type magmatic suites.
 - 11 - Two coexisting evolutionary tendencies occur with a first trend expressing the overall differentiation along the mean compositions of (gabbros), diorites, tonalites, granodiorites, monzogranites (and granites) and a second one, which reflects the evolution of each SVCS rock-type group (Figure 6).
- Some of these features show that the SVCM is the result of numerous magmatic pulses (the gabbro excepted) with about the same $\text{SiO}_2 \times \text{K}_2\text{O}$ (Figure 5E) and Rb/Sr (Figure 5F) relationships generated/evolved in the lower crust or upper mantle. Each pulse-ascending through the crust up to its final emplacement level starts from a stratified magma chamber tapped at different levels. The up-buckling of a more or less homogeneous layer in the magma chamber also affects the adjacent down laying more basic strata which is partially disrupted by the vacuum cleaner effect associated with the diapir detachment and

Table 1 - Chemical analyses (major trace elements) for selected rocks from the São Vicente Caicó suite, State of Rio Grande do Norte, NE Brazil.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Cr	Ni	Co	V	Cu	Zn	Rb	Ba	Sr	Nb	Hf	Zr	Y	Th	
GABBROS																										
PE-03	51,38	0,92	14,18	15,15	0,13	4,29	7,06	3,05	1,87	0,47	1,47	290	43	34	134	0	0	63	427	521	18	0	216	20	4	
PE-17	52,70	0,82	14,50	13,41	0,13	5,78	6,99	2,67	2,04	0,62	0,87	308	37	34	158	0	0	49	300	489	11	0	135	24	2	
PE-19a	51,12	0,78	12,85	16,12	0,12	6,47	6,57	2,09	1,73	0,60	1,53	224	55	28	216	53	78	59	360	671	7	0	102	31	6	
PE-19b	52,02	0,89	14,30	15,18	0,13	5,11	6,88	2,58	1,93	0,34	0,75	249	49	30	197	56	82	62	479	591	18	0	192	17	1	
PE-18d	53,89	0,99	14,56	12,36	0,14	4,82	6,51	3,34	1,75	0,23	0,56	263	42	36	139	0	0	82	522	405	15	4	142	11	7	
DIORITES																										
PE-2	58,76	0,61	14,71	9,86	0,08	2,41	4,09	3,46	3,00	0,47	1,03	200	28	15	81	0	0	103	920	571	13	78	190	29	7	
PE-4	55,69	0,73	14,35	12,71	0,11	3,33	5,75	3,22	2,25	0,28	1,74	163	19	13	51	26	61	95	1248	527	18	0	225	14	10	
PE-7	56,11	0,75	14,80	11,52	0,10	2,73	5,87	3,37	2,60	0,61	1,50	200	25	19	95	60	75	109	831	594	13	0	187	22	3	
PE-20	57,21	0,72	14,85	10,80	0,10	2,87	5,75	3,17	2,89	0,52	0,73	162	17	22	120	67	87	118	872	623	12	0	184	31	6	
PE-26	55,50	0,60	14,28	13,62	0,09	2,83	4,62	2,85	2,40	0,55	1,35	146	36	18	90	57	71	103	788	563	12	0	177	24	5	
PE-54	57,21	0,69	14,67	11,29	0,10	3,12	4,96	3,14	2,67	0,41	0,84	246	21	12	69	34	62	148	1073	382	9	0	118	25	3	
TONALITES																										
PE-12	61,64	0,86	14,80	8,70	0,06	1,58	3,19	3,71	3,49	0,29	1,32	175	20	14	95	0	0	86	1179	418	12	91	278	27	a	
PE-12a	61,94	0,73	15,24	9,19	0,06	1,87	2,90	3,58	3,38	0,28	0,69	231	14	9	53	8	31	150	1059	293	4	0	162	31	4	
PS-122	61,22	0,70	14,88	9,32	0,07	2,61	3,97	3,17	3,43	0,37	0,26	177	30	17	74	37	61	85	1209	568	7	79	202	17	13	
PS-137c	62,35	0,68	14,15	7,61	0,03	2,03	3,20	3,32	3,74	0,44	0,89	127	35	11	79	34	53	120	1500	372	17	0	206	8	5	
PS-147	63,52	0,49	14,93	6,75	0,05	2,41	4,15	3,40	3,19	0,31	0,63	136	7	10	47	8	46	83	795	713	6	0	172	11	11	
PH-24	60,34	0,78	14,68	9,90	0,06	1,87	3,75	3,05	3,04	0,45	0,52	249	15	14	78	45	72	151	1058	713	19	0	158	31	9	
GRANODIORITES																										
PE-8a	64,42	0,61	14,36	8,09	0,08	1,63	2,87	3,43	3,95	0,32	1,23	148	21	9	49	27	58	97	1116	521	15	0	214	23	9	
PE-8b	65,69	0,66	13,46	7,16	0,06	1,38	2,87	3,53	4,20	0,24	0,84	156	25	11	25	0	0	150	1467	429	11	69	244	29	19	
PE-11	69,14	0,40	13,91	5,35	0,04	0,83	2,25	3,03	4,36	0,17	0,49	194	19	7	74	13	65	104	1024	366	15	0	196	0	15	
PS 106	69,12	0,46	13,85	5,38	0,03	1,02	2,29	3,31	3,80	0,16	0,55	150	9	7	31	13	44	121	1008	322	7	55	181	16	7	
PS-106b	66,35	0,45	13,98	6,34	0,03	2,13	2,25	3,25	3,63	0,31	0,65	117	9	7	31	12	43	119	988	316	7	54	178	16	7	
MONZOGNANITES																										
PE-22	70,35	0,37	13,38	4,43	0,06	0,37	1,76	3,45	4,12	0,07	1,22	172	14	8	42	26	56	92	1111	492	20	0	231	24	16	
PE-07a	73,21	0,09	14,13	2,49	0,02	0,25	1,47	3,49	4,30	0,04	0,23	152	5	1	20	0	0	115	1226	301	6	0	133	4	20	
PE-13	72,42	0,21	13,73	3,16	0,04	0,43	1,61	3,14	4,46	0,06	0,61	101	6	4	7	4	40	201	690	147	14	0	184	36	23	
PE-10b	71,40	0,16	13,60	2,68	0,03	0,28	1,67	3,42	4,44	0,04	0,41	119	5	3	17	0	0	200	495	187	12	0	149	20	12	
IPE-121	70,35	0,35	13,63	4,12	0,04	0,65	1,82	3,49	4,56	0,12	0,45	100	20	3	12	0	0	117	1138	290	9	84	160	28	8	
GRANITES																										
PE-10c	75,43	0,18	12,48	2,05	0,02	0,18	0,77	2,48	5,41	0,07	0,89	107	14	1	27	18	16	192	390	163	12	0	120	2	18	
PE-10a	73,95	0,20	13,47	1,91	0,02	0,20	0,98	2,94	5,21	0,12	1,04	138	7	1	17	0	0	135	907	161	16	0	182	13	24	
Ph-26	75,74	0,09	13,33	1,36	0,01	0,09	0,84	3,16	5,19	0,04	0,34	126	5	1	10	8	20	128	705	323	15	0	114	6	12	
PH-44	74,76	0,17	12,64	2,23	0,04	0,33	1,05	3,20	5,18	0,05	0,29	74	4	1	12	0	0	175	989	258	10	0	86	21	11	
IPS-180	74,51	0,16	13,25	2,96	0,02	0,33	0,97	3,35	4,81	0,04	0,35	106	10	3	34	12	21	136	768	94	8	0	169	10	22	

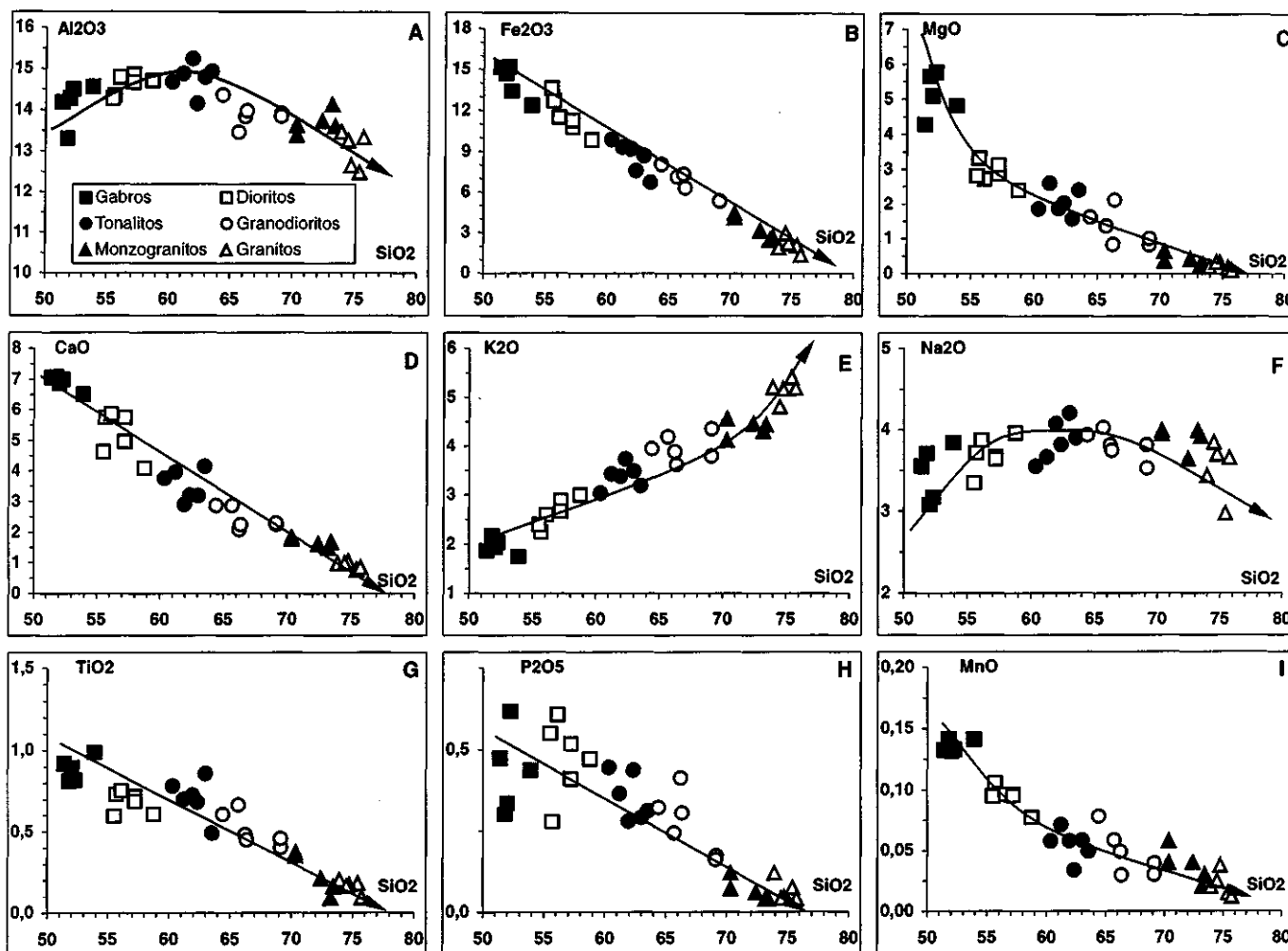


Figure 4 - Harker diagrams for major and minor elements for rocks of the São Vicente/Caicó suite, State of Rio Grande do Norte, NE Brazil. Legend as in Figure 3.

engulfed by the overlying more acidic ascending magma as enclaves. This is the case of the dominant enclaves with only little textural differences compared to those of the host-rock and a model of this process is represented by the double enclaves.

The long side by side plastic flow of the two compositional contrasted materials during their ascent allows the incorporation of xenocrysts from the host-rock by the enclaves, the iso-orientation of enclaves and flow structures, rare partial assimilation of the enclaves, textural convergence by tempering of engulfing and engulfed rocks, etc. This features differs in variable degrees from those of enclaves referred to synintrusive dikes disrupted and dispersed by the plastic flow of the host-rocks during or after their emplacement.

The compositional layering in the magma chamber is expressed by the trend connecting the mean compositions of (gabbros), diorites, tonalites, granodiorites, monzogranites and granites and the evolution of each more or less homogeneous pulse, by the evolutionary trend for each SVCS rock-type group in Figure 6. Both evolutionary trends appoint a gradual increasing in silica and incompatible elements with differentiation, but the positions of both types of vectors differ suggesting the operation of different processes during the evolution of the magma chamber and the individual magma pulses. The first process may be the sum of thermo-gravitational fractionation in an essentially liquid stage (Hildreth 1981) in the magma chamber successively recharged or not by new material generated by progressive batch melting of the source with associated magma mingling either by magma-fountaining (Huppert & Sparks 1988, Shirley 1987, Husch 1990, Campbell & Turner 1986, Sparks & Marshall 1986, Jensen *et al.* 1993, O'Hara 1977, Zorpi *et al.*, 1991), convection current (Turner 1973, Brandeis & Jaupart 1987, Marsh & Maxey 1985, Irvine *et al.* 1983, Sparks *et al.* 1984, 1985, Wilson & Larsen 1985, Frenkel 1994) or gas bubbles (Sparks 1978, Thomas *et al.* 1993) followed by new

episodes of homogenisation and new fractionation (MASH model; Arculus & Powell 1986, Hildreth & Moorbath 1988). The second process may be the sum of host rock assimilation, flow differentiation during diapir ascent (Koyaguchi & Blake 1989) and mineral fractionation during crystallization (AFC model; De Paolo 1981, Stephens & Halliday 1986, Halliday *et al.* 1980, 1984, 1989, Sparks 1986, Stephens 1992, Barnes *et al.* 1990) or the combination of magma mixing, assimilation and fractional crystallization (MAFC model; Barnes *et al.* 1990). In any case, all these models refer the involved processes mainly to deep crustal or crustal/mantle boundary levels and during part of the magma ascent route, but not to the final emplacement level of the magma where only local features of magma mingling can be observed. By this the direct extrapolation of these local features to deep-seated genetic/evolutional processes is at least questionable, as more as in the SVCS these pseudo-mingling features are mainly the products of intensive post-crystallization deformation in shear belts. All the above considered models result is the overall complex evolutionary trend observed for the SVCS which is rather similar to those for younger typical I (Cordilleran)-type upper mantle/lower crust-derived suites for which evolution such processes has been postulated.

CONCLUSIONS By this paper it is concluded that the Early Proterozoic São Vicente-Caicó Massif, State of Rio Grande do Norte, Northeastern Brazil, built up by migmatitic gneisses with gabbroic to granitic compositions has still preserved magmatic features and shows chemical trends rather similar to those for typical calc-alkaline I (Cordilleran)-type magmas generated by partial melting of lower crust or upper mantle protoliths and which evolved by MASH, AFC and MAFC processes. By this the São Vicente-Caicó Massif suite is a good example for the recurrence in space and time of magmatic series and genetic/evolutional processes and this allows the application of current geodynamic plate tectonic theory to rather old geological terrains.

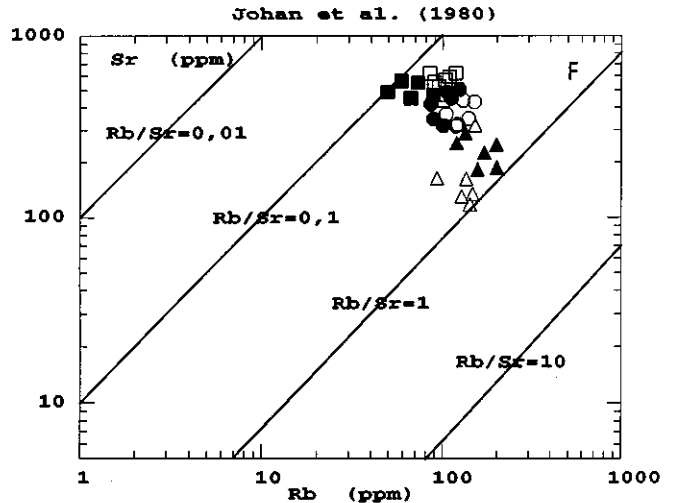
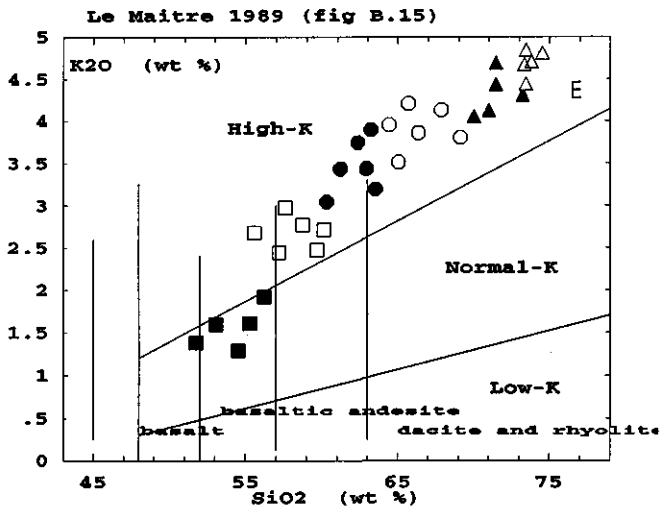
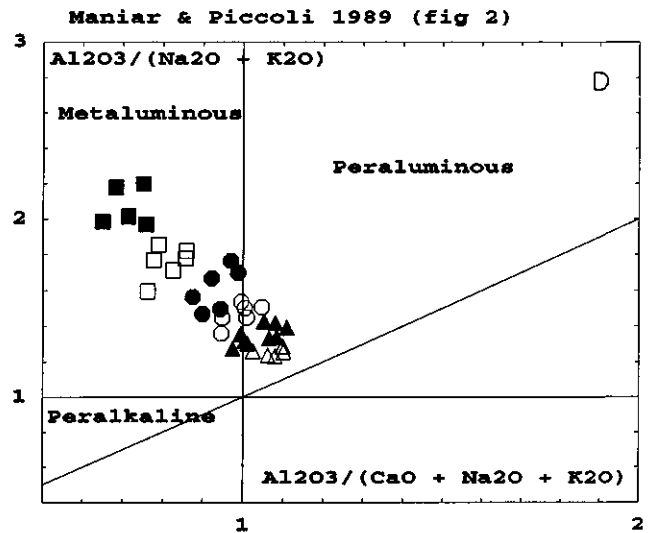
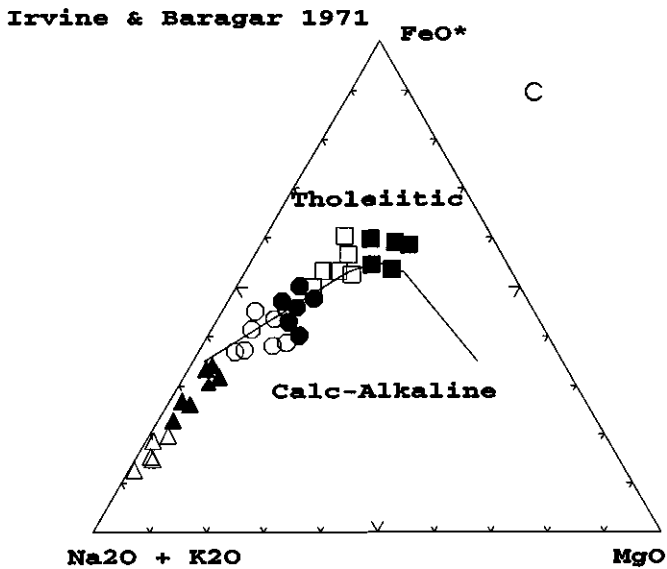
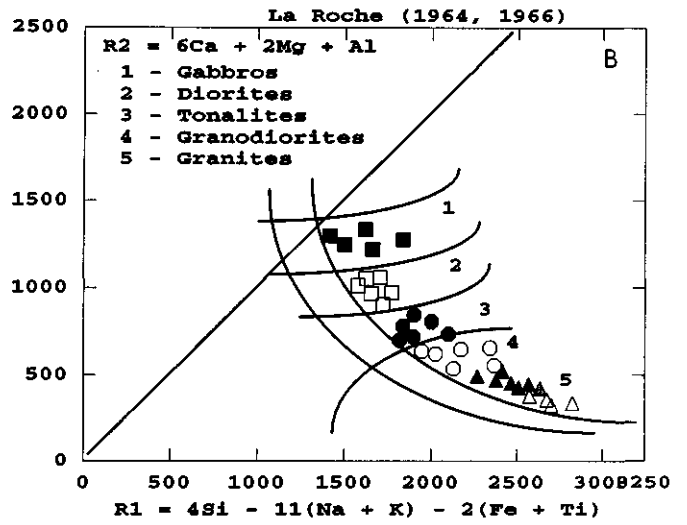
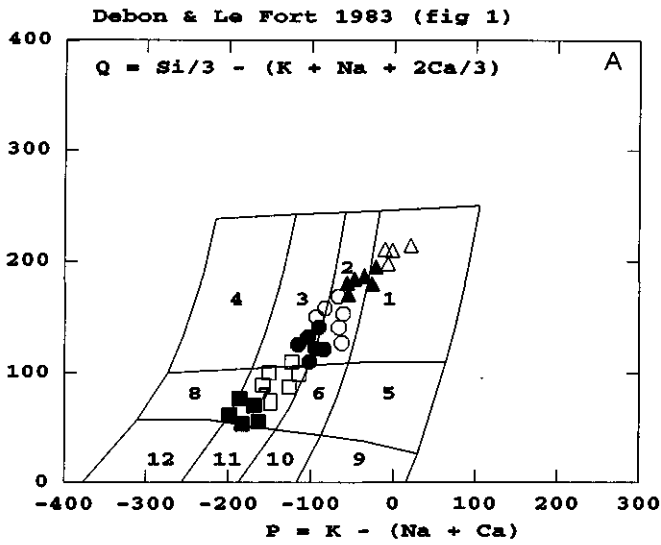


Figure 5 - P x Q (A); R1 x R2 (B); AFM(C); A/(CNK) x A/(NK) (D); SiO₂ x K₂O (E) and Rb/Sr (F) diagrams for rocks from the São Vicente/Caicó suite, State of Rio Grande do Norte, NE Brazil. Legend as in Figure 3.

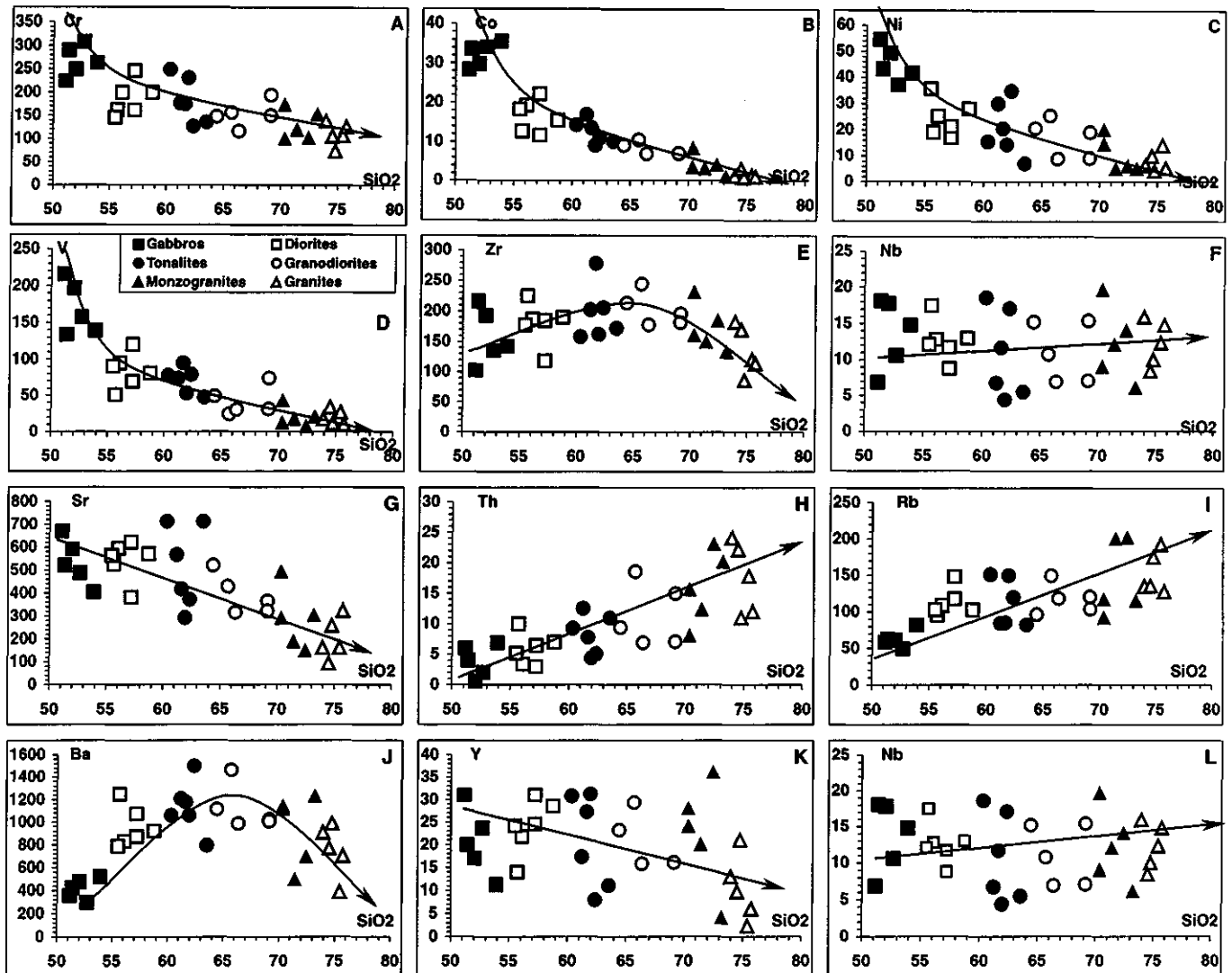


Figure 6 - Trace elements Marker diagrams of rocks from the São Vicente/Caicó suite, State of Rio Grande do Norte, NE Brazil. Legend as in Figure 3.

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