EVIDENCE FOR “FROZEN-IN” MAGMA MIXING IN BRASILIANO CALC-ALKALINE INTRUSIONS: THE SANTA ANGÉLICA PLUTON, SOUTHERN ESPÍRITO SANTO, BRAZIL

R. SCHMIDT-THOMÉ* and K. WEBER-DIEFENBACH*

ABSTRACT The Brazilian Coastal Mobile Belt in Southern Espírito Santo consists of Archean to Upper Proterozoic granulite-facies rocks, amphibolite-facies gneisses, and migmatites. Towards the end of the Brasiliano Event (680-450 Ma) numerous calc-alkaline plutons intruded these deep-seated rocks. They form elliptic (50-150 km²) bodies with complex, roughly concentric internal structures: basic rocks predominate in the center, whereas acidic rocks become more dominant in the outer portions. Mixing and commingling of contrasting magmas is a widespread phenomenon in these plutons. The Santa Angélica pluton, of the most complex and best investigated intrusions in this area, exhibits spectacular commingling structures: schlieren and banded textures of granite within hybrid rocks, as well as schollen of hybrid rock within granite preserve different stages of mechanical mixing. Fine-grained hybrid rocks show phenocrysts from both gabbroic and granitic parental magmas. Phenocrysts have not been in equilibrium with the hybrid melt and therefore show corrosion, corona, and/or mantling structures. A model is presented for the Santa Angélica pluton: mantle derived basic magma of transitional or alkaline basalt affinity intruded the lower crust causing anatexis and production of granitic melts. Convection during diapirc ascent led to commingling of the contrasting magmas. Different stages of homogenization are preserved within the hybrid rocks which originated from commingling. They now represent “frozen-in” magma mixing.

RESUMO O cinturão móvel costeiro brasileiro, no sul do Espírito Santo é constituído de rochas arqueanas a proterozóicas superiores de fácies granulítica, gnaisses de fácies anfibolítica e migmatíticas. Próximo do final do Evento Brasiliano (680 a 450 Ma), numerosos plutons calc-alaclinos foram intrudidos nessas rochas basais. Os plutons formam corpos elípticos (50 a 100 km²) com estruturas internas complexas, “grosso modo” concêntricas. Rochas básicas predominam na porção central dos corpos enquanto que nas porções externas as rochas tornam-se mais ácidas. A mistura de magmas contrastantes é um fenômeno generalizado nestes plutons. O pluton de Santa Angélica, uma das estruturas mais complexas e melhor investigadas da área, exibe marcantes estruturas de mistura. Texturas “schlieren” e bandadas de granito no interior de rochas híbridas, bem como texturas “schollen” de rochas híbridas no interior de granitos, mostram a presença de diferentes estágios de mistura mecânica preservados. Rochas híbridas de textura fina mostram fenocristais de magmas parentais tanto gábróides como graníticos. Os fenocristais não estiveram em equilíbrio com o líquido híbrido e, portanto, mostram estruturas de corrosão, “corona” e/ou de recubrimento. Um modelo é apresentado para o Plutão de Santa Angélica. Magma básico derivado do manto, de afinidade transecional ou basáltica alcalina, introduzindo-se na crosta inferior, causou anatexia e produção de massas graníticas. Convecção durante a ascensão diaprírica levou à mistura de magmas contrastantes. Diferentes estágios de homogeneização estão preservados no interior das rochas híbridas originadas pela mistura, representando, atualmente, misturas congeladas de magmas.

INTRODUCTION The area of interest is located in the southern part of the Brazilian federal state of Espírito Santo. It is approximately limited by the 20° and 21° of southern latitude and 41° and 42° of western longitude.

The Brazilian Coastal Mobile Belt comprises multiple deformed regional metamorphic and plutonic rocks of Archean to Upper Proterozoic age. A wide variety of granulite facies rocks occurs together with various amphibolite facies gneisses, metatexites, and diatexites as well as supracrustal rocks, i.e. quartzites, marbles, and calc-silicate rocks.

Pressure and temperature estimations are 8-10 kbar and >750°C for granulite facies and 6-7 kbar at 600-700°C for amphibolite facies metamorphism (Schultz-Kuhnht 1985). The latter corresponds with our data, which yield 5-6.5 kbar and 620-750°C for amphibolite facies rocks (Bayer et al. 1985).

The metamorphic framework was intruded by numerous complex concentric plutons and smaller stocks of calc-alkaline composition. The plutonic suite includes gabbroic, intermediate, syenomonzonitic, and granitic rocks. Magma mixing is a widespread phenomenon in these intrusions. Temporal classification of deformation phases and metamorphic events are still extremely controversial (Bayer 1987): the high-grade granulite-facies metamorphism is attributed either to Archean (Hasui & Oliveira 1984) or Lower Proterozoic events (Leonardos et al. 1976) or even to the Upper Proterozoic Brasiliano Event (Almeida et al. 1976). The latter is supported by absolute age determinations of Siga et al. (1982).

Amphibolite facies metamorphism, which caused widespread anatexis and remelting, is attributed to the Brasiliano event (680-450 Ma) according to Almeida & Hasui (1984).

However, granulite and amphibolite facies rocks occur side by side or even grade into each other within a single outcrop.

According to Janardhan et al. (1982) and Friend (1983) such an intimate relationship between rocks of different metamorphic facies can result from variation of volatile activities within one pressure-temperature regime causing

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dehydration associated with very high-grade metamorphism and/or anatexis with remelting. This may explain the generation and side by side occurrence of granulite facies rocks together with amphibolite facies gneises, metatexites and diatexitic within the same crustal level.

**COMPLEX INTRUSIONS**

The Southern Espírito Santo gneiss-migmatite terrain is widely interspersed with numerous basic-intermediate to acid intrusions of calc-alkaline composition, which intruded towards the end of the Brasiliano Event. We can distinguish at least three intrusion types:

I. Complex diapirs, like the Santa Angélica pluton, which form circular to elliptic bodies, each of them covering 50–150 km². Typically they show inverse structure, i.e. basic rocks predominate in the centers whereas acidic rocks prevail in the outer portions. Large volumes of intermediate hybrid rocks observable in these plutons result from magma mixing processes (Bayer et al. 1985, Wiedemann et al. 1986, Schmidt-Thomé 1987).

II. Minor intrusions of elliptical or irregular shape covering 2–15 km². They comprise gabbronorites, gabbros or diorites with cumulus textures like the Jacutinga pluton (Wiedemann & Ludka 1984) of Mimoso do Sul. These intrusions are not associated with acidic rocks.

III. Finally, there are discordant granitic stocks (5–20 km²), crosscutting granitic dikes, as well as pegmatites.

**COMINGLING STRUCTURES**

Agmatites Basic rocks are intruded by netlike granite veins forming angular and, to a lesser extent, rounded blocks. The contacts of basic rocks to granite are discrete; chilled margins have not been observed. Granite veins exhibit well developed flow textures, the typical K-feldspar-xenocrysts are not present in small veins.

Agmatites are restricted to local occurrences in the outer area of the intrusion. Transitions to other commingling structures, such as rounded inclusions of diorite in granite, have often been observed.

Schöllen structure in porphyritic granite Numerous oval pillow-shaped schöllen intermediate in color and composition (size up to several meters) are embedded in coarse-grained porphyritic granite. They are oriented parallel to the flow texture of the granite. Sometimes they appear to be bent out of shape, show diffuse contacts, disintegrate laterally and are incorporated into the granite groundmass. (Fig. 2). Both fine-grained and coarse-grained varieties containing mafic xenocrysts, like amphibole, pyroxene and/or mantled K-feldspar-xenocrysts have been observed. Chilled margins as described by Taylor et al. (1980) from basaltic pillows in granitic dykes are not developed.

**THE SANTA ANGÉLICA PLUTON**

The Santa Angélica pluton is one of the most complex and best investigated plutons and is therefore referred to in the following text (Fig. 1).

In contrast to all other Espírito Santo plutons so far known it does not exhibit a clearly defined “mixing zone” between an inner, more or less unaffected gabbro core and an outer granitic shell. Commingling structures of basic and acidic magmas (now rocks) as well as intermediate hybrid rocks spread out over the whole area covered by the pluton (Fig. 1). Magma mixing processes apparently have not been restricted to a small “mixing zone”, but have been active within the whole pluton. However, two-pyroxene-biotite-monzogabro and monzodiorite clearly predominate in the center of the intrusion. Two varieties can be distinguished: a coarse-grained one without any preferred orientation of crystals, and a fine-grained porphyritic one with occasionally developed flow texture. Both grade into each other, coarse-grained gabbro being sometimes intruded by the fine-grained gabbro.

In the outer parts of the intrusion a very coarse-grained porphyritic allanite-bearing granite (granite 1) predominates. Locally it grades into a medium-grained porphyritic sphene-bearing granite (granite 2). Granite 2 has also been observed in discordant dykes and stocks in the surrounding gneises and migmatites. Hybrid rocks, resulting from commingling of basic and acidic magmas are widespread in the Santa Angélica intrusion. Mechanical mixing of two magmas with contrasting physical properties resulted in typical structures, such as schlieren, agmatites etc.

Mixing of magmas with less contrasting physical properties resulted in more homogeneous hybrid rocks, exhibiting xenocrysts with disequilibrium features like mantling and corona structures.

**COMINGLING STRUCTURES**

Agmatites Basic rocks are intruded by netlike granite 1 veins forming angular and, to a lesser extent, rounded blocks. The contacts of basic rocks to granite are discrete; chilled margins have not been observed. Granite veins exhibit well developed flow textures, the typical K-feldspar-xenocrysts are not present in small veins.

Agmatites are restricted to local occurrences in the outer area of the intrusion. Transitions to other commingling structures, such as rounded inclusions of diorite in granite, have often been observed.
Figure 1 - Geological map of the Santa Angélica intrusion. It shows a roughly concentric structure with basic rocks predominating in the center, and granitic rocks prevailing in the outer portions. Hybrid rocks originated by commingling of basic and acidic magmas are exposed over wide areas.

Schlieren and banded texture. Granite 1-schlieren (some centimeters to several meters wide) pervade dioritic to granodioritic hybrid rock. Flow textures are typical for both basic and acid rocks. Massive granite schlieren thin out laterally and disintegrate into smaller separate schlieren and numerous subparallel bands. A banded texture with a rhythmic change of light acid and dark basic rocks is often developed in the range of a few centimeters.

Flow movements result in structures like bending, folding, and disintegration into small units by shearing. Schlieren and bands disintegrate into irregularly shaped feldspar aggregates (Fig. 3). Those can be almost
Figure 2 — Schollen of fine-grained hybrid rock (dotted) within coarse-grained granite (white). Schollen disintegrate and grade into granite matrix. Coarse feldspar phenocrysts illustrate flow texture of granite. Tracing from photograph completely assimilated in basic rock resulting in a patchy structure of fine-grained intermediate rock with individual feldspar and quartz xenocrysts. All transitional stages to hybrid rock have been observed in the Santa Angélica pluton. Rounded inclusions in granite (schollen structure), granite schlieren, and banded texture in basic and intermediate rock are interpreted as remnants of mushy-mushy interaction of two contrasting magmas.

Figure 3 — Granite schlieren and banded texture (white) within dioritic to granodioritic hybrid rock (dotted). Magmatic flux during commingling of basic and acidic magmas causes homogenization. Schlieren thin off and separate laterally into several bands. Bands were folded and finally sheared into small granitic blebs and individual feldspar megacrysts, which are embedded in fine-grained matrix of intermediate composition (upper part of figure). Tracing from photograph

Figure 4 — Hybrid rock (dotted) with several small granite bands (white). Feldspar phenocrysts are irregularly distributed within the fine-grained matrix. Density of dots reflects inhomogeneities resulting from incomplete mechanical mixing. Tracing from photograph

Typical are mantled feldspar and quartz xenocrysts which show, unlike the crystals in granitic schlieren, no preferred orientation. They appear to be rotated, fine-grained matrix flows around them.

PETROGRAPHY Mantling and corona structures, developed by processes involving magma mixing are described by Goldie (1977), Wiebe (1980), Hibbard (1981), and Vogel et al. (1984).

The xenocryst population of the Santa Angélica hybrid rocks is the key to the understanding of the mixing and homogenization processes involved during commingling of the contrasting magmas (Schmidt-Thomé 1987).

The above-mentioned feldspar xenocrysts in hybrid rocks are corroded perthitic microclines (up to 8 cm), exhibiting oligoclase rims several millimeters thick (Fig. 5).

The compositional range of oligoclase mantles is that of the hybrid rock matrix plagioclase. Quartz grains (up to 2 cm) are rimmed by pyroxene, amphibole, and biotite.

Mantled microcline and rimmed quartz occur in hybrid rocks; however, no such features have been observed in granite. Mafic xenocrysts exhibit corona structures. Pyroxene is rimmed by amphibole, amphibole being replaced by biotite. Amphibole clusters, with poikilitic intergrowth of amphibole, quartz, and opaque minerals result from complete replacement of pyroxene.

Magmatically zoned plagioclase xenocrysts in hybrid rocks show andesine composition (An35-An48, occasionally up to An53) in the core, corresponding to the plagioclase composition in coarse-grained gabbro, whereas plagioclase from fine-grained gabbro is of more calcic composition.

Rim composition of mantled plagioclase xenocrysts in hybrid rocks is An20-An30 (oligoclase), corresponding to the composition of matrix plagioclase and plagioclase rims of K-feldspar xenocrysts.

Hybrid rocks Hybrid rocks are closely related to and grade into commingled rocks. They are fine-grained, of intermediate composition and colour and almost homogeneous. Commingled rocks, in contrast, show an extreme variety in color, structure, texture, and composition. But homogeneity is a mere question of scale: nebulous blebs, small wispy strings, and streaks of granitic material (often only a few grains thick), and mafic clots, along with individual mafic xenocrysts, consisting predominantly of amphibole-rimmed pyroxene, are still detectable on a microscopic scale (Fig. 4).
primary magma are not in equilibrium with the hybrid magma resulting from commingling and subsequent homogenization.

Quartz is rimmed by mafic minerals, the latter are partially replaced with formation of corona structures (pyroxene-amphibole-biotite).

Plagioclase xenocrysts from coarse-grained gabbrodiorite are not corroded, their original magmatic zonation is preserved (labradorite-andesite-calcic oligoclase) with an unzoned rim of sodic plagioclase, showing matrix plagioclase composition.

Hybrid rocks are the result of mechanical mixing and subsequent homogenization of two contrasting magmas.

Schlieren, rounded dioritic inclusions in granite, fluidal textures as well as the large number of xenocrysts within hybrid rocks suggest mushy-mushy interaction of felsic and basic magmas during commingling.

Mantled xenocrysts and corona structures, observed only in hybrid rocks, represent solid relics of the felsic and basic endmembers. They were transferred into the hybrid magma by mechanical interaction during commingling and homogenization processes.

Disequilibrium with the hybrid magma resulted in mantling and corona structures, the former are preserved in the hybrid rocks.

They are now preserved within solid hybrid rock, which therefore exhibits a state of frozen-in magma mixing.

**GENESES OF HYBRID ROCKS** Mantled feldspar xenocrysts in fine-grained intermediate rocks associated with contrasting magma types can be explained after Hibbard (1981) as testimonies of magma mixing.

Subhedral large K-feldspar xenocrysts from the granite magma are transferred into a more basic melt during commingling of granitic and gabbro-dioritic magmas. Corrosion of the crystals is caused by dis-equilibrium of K-feldspar crystals and the basic magma.

Homogenization during commingling results in the development of intermediate magmas. Feldspar crystallizes as matrix mineral as well as epitaxially on the corroded K-feldspar surface under formation of plagioclase mantles. Mantle plagioclase and matrix plagioclase are of identical composition.

Mantling of quartz and corona structures of mafic minerals, respectively, are frozen-in disequilibrium phenomena (Bell 1983). Xenocrysts from an acid or basic primary magma are not in equilibrium with the hybrid magma resulting from commingling and subsequent homogenization.

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**GEOCHEMISTRY** The extreme textural and compositional variation of the Santa Angélica intrusives makes geochemical investigations very difficult. Careful classification based on the specific field relations and detailed petrographical data is implied. Plutonic rocks from the Santa Angélica pluton were subdivided into four groups: fine-grained gabbro; coarse-grained gabbro; hybrid rock; and granite. Analyses of representative rock samples of Santa Angélica intrusives are given in table 1.

Field observations and petrographical investigations prove that intermediate and acidic rocks were not generated by differentiation processes from the gabbro. Rather mechanical mixing of acidic and basic magmas (now rocks) led to hybridization and generation of intermediate magma compositions (now rocks).

Silica variation diagrams for major and trace elements show that hybrid rocks plot between basic and acidic rocks on almost linear trends (Fig. 6). Linear trends on silica variations diagrams are reported from magmatic rocks elsewhere (e.g. Wiebe 1980, Whalen & Currie 1984, Brown & Becker 1986, among many others) and are interpreted as result of magma mixing.

All variation diagrams show a clearly defined gap between 62% and 65% SiO₂. Obviously, mechanical mixing only locally led to a complete chemical homogenization of coexisting basic and acidic magmas. In the case of complete homogenization, however, a continuous trend without a gap has to be expected. The interpretation of this gap by liquid immiscibility must be rejected, since field evidence and petrographic observations clearly confirm that mixing of the contrasted magmas did occur within the Santa Angélica pluton.

In the MgO versus silica diagram some samples of fine-grained gabbrodiorite plot off-set from the linear mixing
Table 1 – Major and trace element analyses (XRF) of 18 representative samples from the Santa Angélica pluton (after Horn 1987): fG, fine-grained; eg, coarse-grained; TB, average of 11 Transitional basalts (Nockolds et al. 1979); and AB, alkalibasalt, Snaefell, Iceland (Sigurdson 1970 quoted by Nielsen 1978)

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In the AFM-triangle the fields referring to both gabbro varieties overlap (Fig. 7), but the majority of the fine-grained gabbrodiorite are off-set from the linear trend. Scattering values of Ti and P observed on samples between 49% and 53% SiO2, and slightly higher values towards intermediate compositions may be an argument that some differentiation took place in the development of the basic Santa Angélica intrusives.

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The combined petrographical and geochemical data suggest differentiation of coarse-grained from fine-grained gabbro. Therefore, the latter must be classified as a more primitive rock with affinities towards alkali or transitional basaltic compositions (Tab. 1). In addition to the samples referring to the Santa Angélica intrusion the AFM-triangle displays the Hawaiian alkali basalt fractionation trend from MacDonald & Katsura (1964). The similarity of rocks created by such different processes as magma mixing and fractional crystallization is most striking. However, differentiation of basaltic magma would result in a more continuous trend, not observable in the AFM-triangle referring to Santa Angélica. As in the silica variation diagrams a gap is exhibited in the trend, which may result from prefered mixing ratios or more likely, from incomplete homogenization.

At the present, there exists only very limited Sr isotope information for the Santa Angélica rocks. For interpretation the effects of magma mixing have to be taken into account.

Initial Sr87/Sr86 ratios of about 0.705 for basic rocks (Besang et al. 1977) do not confirm pure mantle origin for the gabbro-diorite. Additionally, Besang et al. (op. cit.) did not recognize magma mixing within the Santa Angélica pluton and therefore they did not take into account this effect on the interpretation of the isotopic evolution of the Santa Angélica rocks.

Initial Sr87/Sr86 ratios of about 0.707 (Söllner pers. com.) support a crustal origin for the Santa Angélica granite. Söllner et al. (1986) stated, that his own new and the former Rb-Sr-data of Besang et al. (1977) are situated on a linear mixing trend. However, Wylie’s (1977, 1983) considerations on the origin and parentage of the basic members in granitoid intrusive series lead to the conclusion that heat and material of mantle origin influenced the genesis and evolution of the Santa Angélica intrusive rock series.

CONCLUSIONS

Investigation of many mixed magma associations has led to the common model of a shallow-levelled, stratified magma chamber with an upper acid section, underlain by basaltic magma.

Intermingling and mixing then occurred within the magma chamber by convection (Huppert et al. 1982), injection of new basic magma (Bell 1983, Thompson 1980) or eruption with subsequent cauldron subsidence, the latter featuring ring dikes and net veined complexes (Vogel 1982, Brown & Becker 1986).

Most commonly, magma mixing in a plutonic environment is masked by fractional crystallization (Wiebe & Wild 1983, Bateman & Chappell 1979). Mafic xenocryst assemblages within almost completely homogenized hybrid rocks, and the comparison with neighbouring, less homogenized mixed magma suites,
The fine-grained Santa Angélica gabbro is thought to be the closest relative to that primary magma of probable alkali or transitional basalt composition.

Further uprise of evolved basic magma into and together with its surrounding anatectic magma is the reason for the observed inverse structure of the Santa Angélica and Espírito Santo plutons (Fig. 8). Commingling and mixing of the contrasted magmas occurred during magma uprise and within diapirically ascending plutons. Within the Santa Angélica pluton those magma mixing processes are also responsible for the formation of intermediate hybrid rocks.

A lineamental control of intrusion (Pitcher 1979) is supposed for all Espírito Santo plutons and clearly visible for some plutons which are directly connected to major lineaments.

The observed mechanical mixing of basic and acidic magmas (now rocks) can be caused by three different mechanisms envisaged by Whalen & Currie (1984): buoyant convection, forced convection, and tectonic shearing.

All three above-mentioned processes might have been independently active. However, buoyant convection is considered the most effective driving mechanism, causing commingling of magmas in the Santa Angélica pluton (Bayer et al. 1987).

There is evidence for liquid-solid, and mushy-mushy interaction of the two contrasting magmas leading to typical commingling structures today observable in the Santa Angélica intrusives, such as agmatites, rounded...

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**Figure 6** - Variation diagrams MgO, CaO, Fe₂O₃⁺, (total Fe), K₂O, TiO₂, P₂O₅, Rb, and Sr versus SiO₂ for Santa Angélica rocks. Oxide contents in weight percent, Rb and Sr contents in ppm. Rombs: fine-grained gabbrodiorite (n = 8). Quadrangles: coarse-grained gabbrodiorite (n = 15). Circles: hybrid rocks (n = 30). Triangles: granite 1 (n = 26). Almost linear trends are exhibited between 50% and 70% SiO₂. Hybrid rocks therefore are interpreted as result of a mixture of basic and acidic magmas. Samples of fine-grained gabbrodiorite plotting off-set from the linear trend suggest certain influence of differentiation within the basic rock series.

inclusions, schlieren, and banded texture (Schmidt-Thomé 1987).

Rapid consolidation of the magma body prevented complete homogenization of the commingled magmas, thus preserving a state of frozen-in magma mixing.

Ascent mechanism for granitoid plutons are controversially discussed (see, for example, Bateman 1984, 1985 and Marsh 1982, among others).

There is sufficient evidence confirming diapiric ascent for the Santa Angélica magma (Schmidt-Thomé & Bayer, in prep.) and preservation of the pluton within a deep crustal level environment (Schmidt-Thomé 1987).

**Acknowledgements**

We thank Mr. Bayer for fruitful discussion and critical review of the manuscript. Financial support by the DAAD (Deutscher Akademischer Austausch Dienst) and the DFG (Deutsche Forschungsgemeinschaft) is acknowledged. Special thanks to Mrs. Cristina Wiedemann (Universidade do Rio de Janeiro) for help during field work and stimulating discussion.

**REFERENCES**


... Os que se alienam na ciência, embora cumprindo com um dos objetivos da universidade, o fazem produzindo conhecimento que não responderá às necessidades sociais, ou ainda pior, que não responderá às próprias necessidades de conhecimento, em um momento de inflexão na história das ciências onde, mais que avanços no conhecimento 'tradicional', tornam-se necessários novos paradigmas de conhecimento.

C. Buarque, 1986, Das idéias de revolução à revolução das idéias, Pau Brasil, 14: p. 6