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Commingling of Contrasted Magmas in Various Geodynamic Settings

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Abstract: Three acid-basic associations taken in various geodynamical settings are studied: the gabbro-granite association of Porto (Corsica), the associations of the Guevgueli (Greek Macedonia), and the associations of the Piracaia complex (Brazil). The diversity of field relations, the degree of mingling, the origins of the melts are debated for each association, using petrological and geochemical tools for each acid-basic association. An origin by hybridization is assumed for the intermediate rocks of the Porto association, it is tested by numerical calculation. Then, we focus on the mixing process between the comagmatic components. Mixing of melts may have happened by thorough mingling and chemical diffusion under disequilibrium conditions attested by textural characters of the hybrid rocks. The mixing between the contrasted melts can not be complete, it appears that the mean effective ratio between the two mixed components (the effective mixing ratio) in the hybrids is weak compared with the acting volume of mafic magma during the magmatic brecciation, it may be the result of the difference between thermal and chemical rates.

Değişik Jeodinamik Yerleşimlerde Farklı Magmaların Heterojen Karışımları

Özet: Üç farklı jeodinamik yerleşimine ait asidik-bazik toplulukları çalışılmıştır. Bunlar; Porto (Korsika)nın gabro-granit topluluğu, Guevgueli (Yunan Makedonyası) toplulukları ve Piracaia kompleksine (Brezilya) ait topluluklardır. Bu çalışmada asidik-bazik toplulukların saha ilişkisi farklılıkları, heterojen karışım (mingling) dereceleri, magma kökenleri, petrolojik ve jeokimyasal veriler kullanılarak tartışılmıştır. Proto topluluğunun ortaç bileşenli kayaçlarının hibritleşme kökeni sayısal olarak test edilmiştir. Ayrıca eşzamanlı magmatik bileşenlerin karışım işlemleri üzerinde durulmuştur. Hiprid kayaçların dokusal özelliklerinden yararlanarak eriyiklerin karışımının, heterojen karışımlı ve dengede olmayan koşullar altında kimyasal difüzyon yolu ile oluşabileceği sonucuna varılmıştır. Farklı eriyikler arasındaki homojen karışım (mixing) tamamlanmamıştır. Hibrid magmalarda iki karışan bileşen arasındaki ana etkileşim oranı (karışım oranı etkisi) mafik magmanın magmatik ayrışma oranına göre zayıftır. Bu oranın zayıf olması her iki ürünün farklı ısı ve kimyasal orana sahip olmasından kaynaklanmış olabilir.

Introduction

The spectacular aspect of mafic-felsic associations, related to enclaves and subsequent commingling and mixing processes between magmas have been the subject of long debate since the work of Bunsen (1851). Very frequent in calc-alkaline orogenic volcanic (Eichelberger, 1975) and plutonic formations (Didier, 1973; Didier and Barbarin, 1991), mafic-felsic associations are also very frequent in High-K orogenic and post-orogenic magmatism (Barriére, 1980). In extensional geodynamic setting like marginal basins, mid-ocean ridge magmatism, alkaline intraplate oceanic or continental magmatisms, these mafic-felsic associations always exist despite of their more restricted frequency (Turner, 1962; Blake, 1966; Bébien, 1977; Vellutini, 1977; Bonin, 1980; Wiebe, 1980, Platevoet, 1982; Platevoet and Bonin, 1991; Wiebe, 1991).

A comparison between three types of associations taken in three different geodynamic settings will be made: the gabbro-subsolvus granite association of Porto which belongs to the alkaline anorogenic province of Corsica, the Guevgueli complex (Greek Macedonia) which belongs to the ophiolitic part of the Vardar zone (Bébien, 1977), it is interpreted as a marginal Jurassic sea-floor like the Japan sea (Bébien et al. 1986; Platevoet and Bébien, 1997). The third example will be taken in the batholite of the Sao Paulo State (Brazil): the monzonitic-monzodioritic complex of Piracaia is typically a tardi-orogenic high-K magmatism with clear shoshonotic affinities (Gomes and Platevoet, 1995; Gomes, 1995), associated with the main shear zones active during the last transpressive events of the Brasiliano Orogenesis. The mingling and mixing processes will be especially studied in the acid-basic association of Porto to define the possibilities and the limitations of hybridization process between two contrasted magmas of an alkaline series.

The Acid-Basic Association of the Alkaline Subvolcanic Complex of Porto, Corsica

General Structure, Lithology and Petrology of the Complex

The complex of Porto is a subvolcanic ring complex which belongs to the Permo-Triasic alkaline province of

Corsica. It is formed by two successive intrusions: the first one is composite with the intimate association of gabbro and subsolvus biotite granite. The second intrusion is a ring dyke of subsolvus peraluminous granite (Figure 1).

The gabbro-granite association can be observed in the central part of the complex. It is composed of a gabbro dissociated in hectometric masses within the subsolvus granite. Intermediates rocks consist of magmatic breccias and also fine-grain, relativelly homogeneous monzogranites, granodiorites and quartz-diorites. These intermediate rocks are mainly present in the contact zones between gabbro and granite, they represent only 2% of the exposures. Many types of relations has been described in this mafic-felsic association (Van Telligen, 1954; Vellutini, 1977; Platevoet, 1983). The comagmatic character is deduced from the existence of lobate or crenulate margins between all rock types, pillow-like basic or intermediate masses, mutual injections, net-veined acid-basic complexes, magmatic breccias (Figure 2).

In the mafic component, thick chilled margins, quench textures with skeletal crystals (plagioclase, apatite, ilmenite) suggest strong thermal contrast between the melts coming into contact. Heating of felsic melt by the mafic component causes convective motions and interface deformations. Density instabilities is responsible of intense plastic deformation of the mafic component within the acid melt, viscous fingering can sometimes happen like between two fluids of contrasted viscosity. The intensity of deformation is so great that the surface contact between the components takes a fractal geometry (Mandelbrot, 1975; Bébien et al., 1987; Platevoet and Bonin, 1991). However, rapid chilling of gabbro often stops its plastic deformation.

The magmatic breccias (Figure 2) result from thorough convective stirring between the melts. Lobate or angular enclaves indicate that mafic component is dissociated at different physical state in the acidic melt. The process of intense mingling is rarely observed at the level of final injection of the association and the majority of magmatic breccias are probably formed in the magmatic chamber or in the feeder dykes of the ring complex.

Geochemistry

Mechanical and chemical interactions in commingling melts are attested first by xenocryst incorporation: rounded quartz or plagioclase of granitic origin are observed in the gabbro. It is the first cause of chemical modification and these crystals are partially remelted.

The existence of intermediate rocks and magmatic breccias in this association needs to test the possibility of hybridization to generate these particular rocks. Major element data can be compared by normalizing data against the two extreme poles of the association. Normalized patterns are plotted by calculating for each oxide the theoretical ratio of the two components in the rock which is supposed to be hybrid (Fourcade and Allegre, 1981; Platevoet, 1982). At the interface, gabbro and granite are chemically modified (Figure 3): gabbro is strongly enriched in Fe, Ti and alkalies, while granite is depleted in alkalies and Al. Patterns of mafic enclaves and quartz diorites are not compatible with a simple mixing process. Only monzogranites and granodiorites have near perfect mixing patterns which

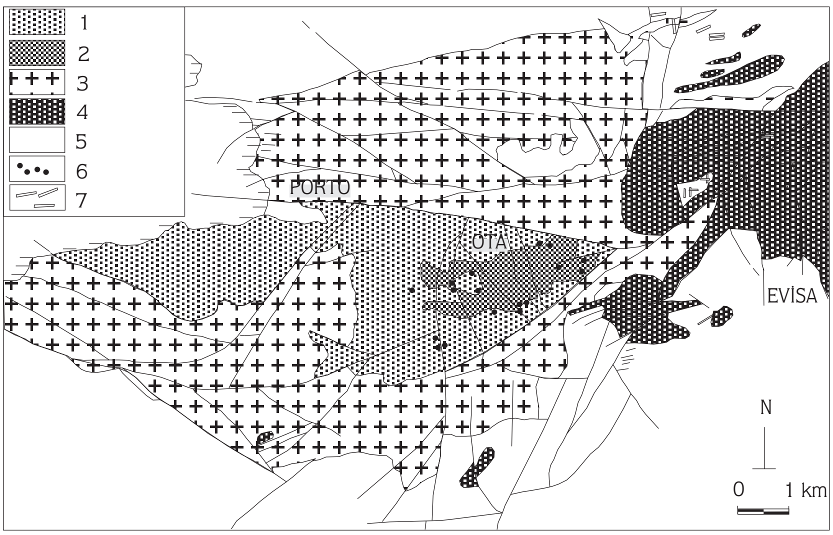

Figure 1. Geological map of the Porto complex. 1: subsolvus white granite. 2: gabbro. 3: subsolvus red granite. 4: peralkaline granites of Evisa complex. 5: calc-alkaline basement. 6: hybrid rocks and magmatic breccias. 7: acid-basic dykes.

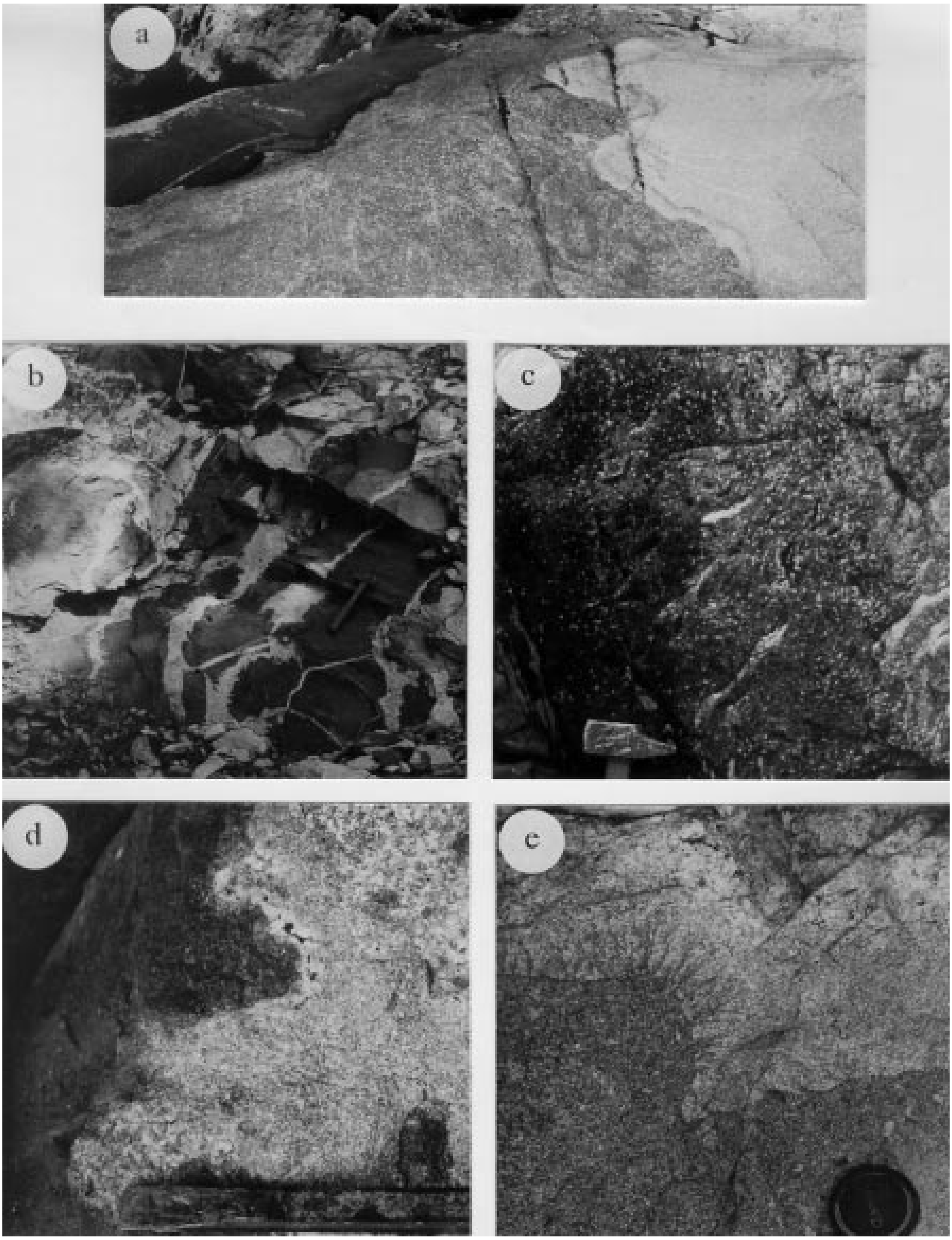

Figure 2. a: association of gabbro, magmatic breccias and granite. b: net-veined complex between gabbro and granite. c: formation of magmatic breccias. d: pegmatitic pocket along the contact between gabbro and granite. e: tree-like structures between quartz-diorite and granite, note the 15 cm thick intermediate rock-type.

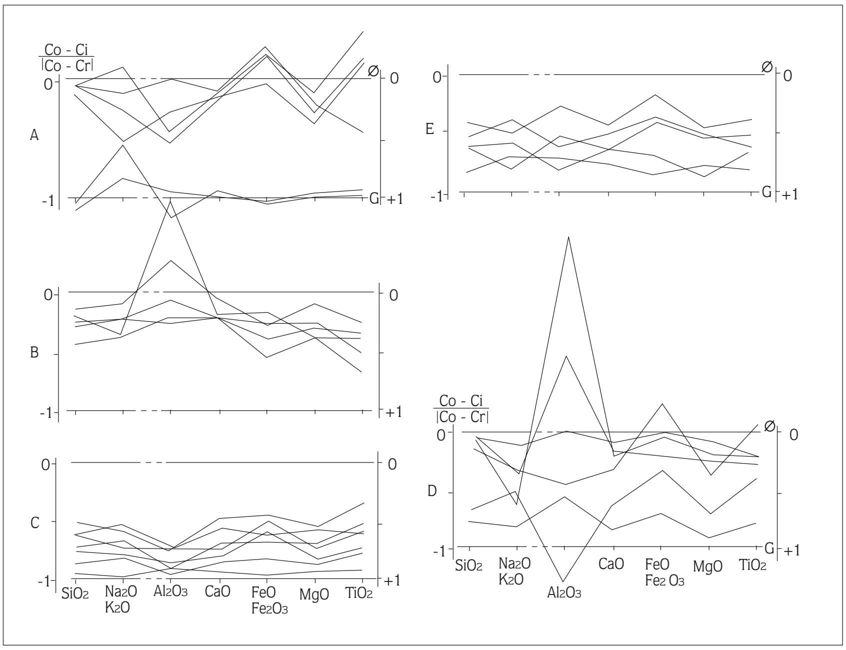

Figure 3. Normalized diagrams for Porto association. A: gabbro and granite into contact. B: quartz-diorite. C: monzogranites and granodiorites. D: enclaves within magmatic breccias. E: matrix of magmatic breccias.

support the origin by hybridization. This is also supported by similar mixing patterns for the matrix of magmatic breccias, however their patterns are not so perfect due to remnant heterogeneity of the rocks. Some trace elements for the intermediate rocks are also in good agreement with the mixing hypothesis (Figure 4). However, Y, Zn, Zr, REE and Ba deviate strongly from the mixing trend. Early precipitation of phenocrysts and segregation, selective diffusion of alkalies and late mobility of some elements (like REE) through a discrete fluid phase, exsolved from the granitic melt, may have strongly modified the chemistry of the rocks, especially their trace element contents. Mixing tests (Table 1) have been calculated using major elements of the supposed hybrid rocks. They yield good result (with a correction which takes into account the existence of a late albitization process).

An intemediate zone between a quartz diorite and the granite shows evidence of direct interaction through the interface, by injection of radiate tree-like fingers of dioritic melt in the more viscous granitic melt. This intemediate zone has also been analyzed across the contact. Normalized data are plotted according to the interface position (Figure 5). Inversion points in compositions can be located not directly at the interface but within the intermediate zone, with the exeption of MgO. Two processes may have produced these patterns: (i) liquid migration through interface, (ii) diffusion and homogenization between dioritic fingers and the granitic melt.

Interpretation

In the association of Porto, the matrix of magmatic breccias and the granodiorites and monozgranites are very similar, these rocks may be the result from liquid-liquid hybridization between gabbro and granite melts. This process needs prior thorough mingling between the two melts which takes place probably before and during the definitive emplacement of the association at the level of ring complex. The extreme components of the mixing are chemically and physically very contrasted, they are comagmatic but probably not cogenetic. The association of the two melts probably came into contact in a magmatic chamber where the resident melt is the granitic melt. Refilling of the chamber by new mafic magma, rising from the underplating zone at the limit between the deep crust and mantle, instigates thorough convective stirring in the granitic melt. Impulse of the mafic melt associated with the granite melt finally intrudes the basement at the level of subvolcanic complex. Hybridization between the two melts takes place but the process seems to be very restricted and minor volume of hybrid rocks were produced.

The Acid-Basic Associations of the Guevgueli Ophiolitic Complex, Greek Macedonia

General Structure, Lithology and Petrology of the Complex

In the Greek part of Macedonia, the Guevgueli complex is one part of Jurassic Hellenic Ophiolitic Belt (Mercier, 1966; Bébien, 1977). Its eastern unit is

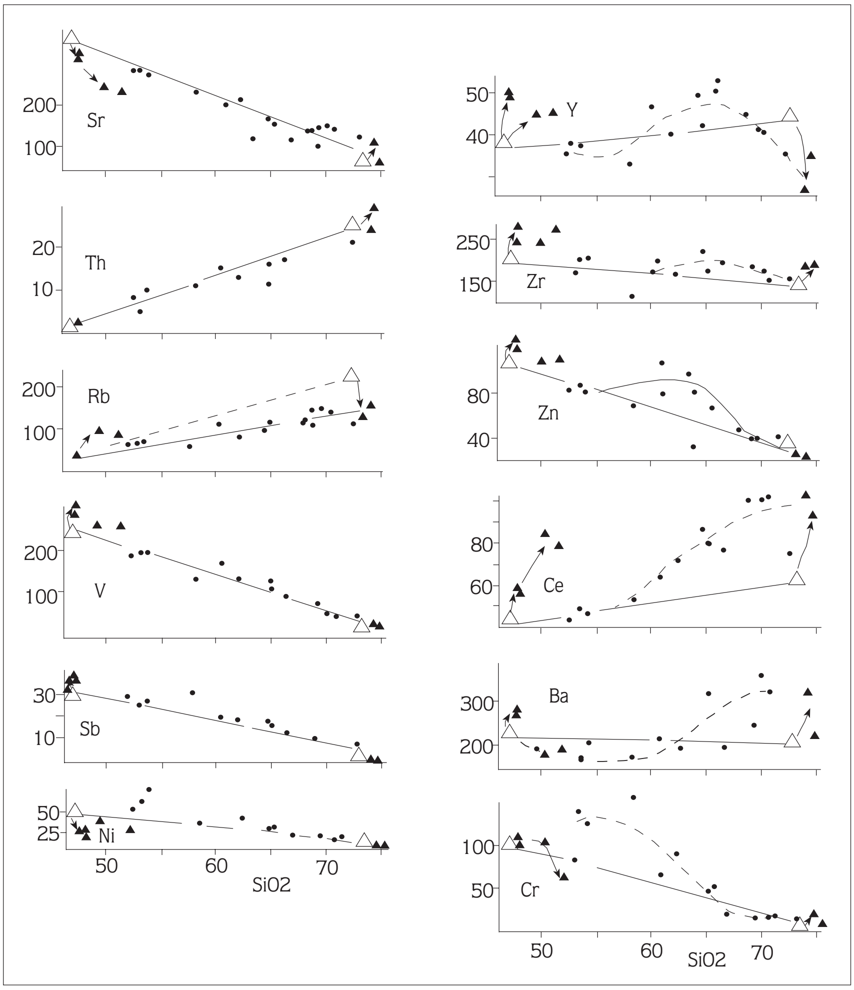

Figure 4. Trace elements versus silica in the Porto association. Dots: monzogranites, granodiorites and quartz diorites. Open triangles: granite and gabbro. solid triangles: granite and gabbro into contact.

Rock No	granite %	gabbro %	Albite	Orthoclase	Residue R2
010	83 %	16 %			0.52
109	92 %	08 %			0.69
124	69 %	31 %			0.49
8123	67 %	33 %			0.86
8106	57 %	42 %	+5 %	-4 %	0.30
084	96 %	09 %	+5 %	-10 %	0.30
8121	70 %	30 %			0.67
8112	51 %	49 %	+4 %	-5 %	1.74
V19	74 %	22 %	+9 %	-5 %	0.55
V20	71 %	22 %	+8 %	-2 %	0.51
V21	74 %	22 %	+6 %	-2 %	0.44
mean value	73 %	26 %	+3 %	-2 %	0.64

Table 1. Mixing tests for the plutonic association of Porto. All the tested rocks belongs to the monzogranite-granodiorite group.

composed of a sheeted complex of hypabyssal rocks, a basic complex cut by abundant magmatic breccias and many dykes of granitic rocks. The basic complex is in tectonic contact with the migmatites of Piyi. The granitic pluton of Fanos intrudes both the basic complex and the migmatites (Figure 6).

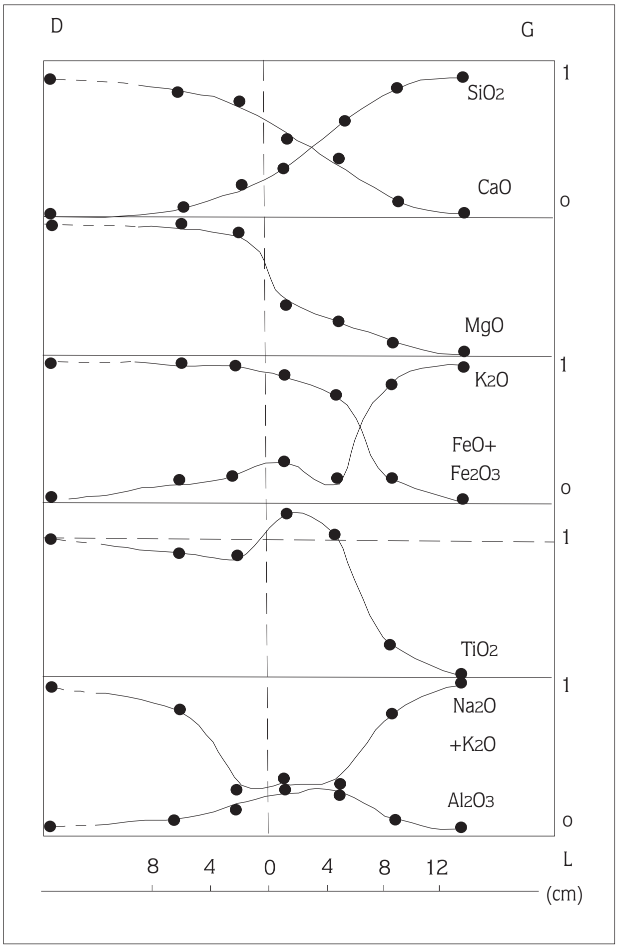

Figure 5. Normalized oxide variation diagrams in the quartz diorite-granite association (Porto complex). Normalized is made between quartz diorite D and granite G compositions (wt. %). Data are plotted against the distance L from the interface between basic and acid rocks.

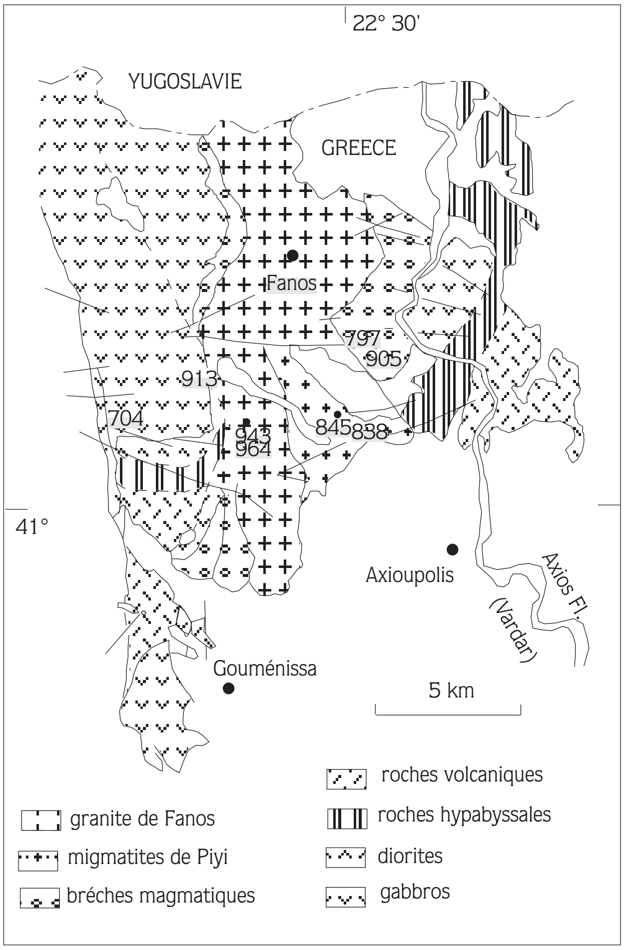

Figure 6. Simplified geological map of the Guevgueli complex.

The basic complex (Figure 6) is composed of its plutonic part by a first unit (A) of layered gabbronoritic cumulates injected by many basic and acidic dykes. These dykes crosscut each other, and sometimes, at the intersection of magmatic conduits, composite dykes are formed by doleritic enclaves with chilled margins, enclosed in a trondhjemitic matrix. At some outcroups, gabbronoritic cumulates are plastic-deformed and disrupted by pegmatitic trondhjemite. The second unit (B) is formed by ferrodioritic cumulates frequently disrupted and transformed in magmatic breccias enclosing also mafic doleritic enclaves within the trondhjemitic matrix. The third zone (C) of microdiorites and sills are not associated with more acidic melts.

The migmatites are very heterogeneous, with abundant amphibolite enclaves, restitic melanocratic enclaves, but also doleritic enclaves with crenulate chilled margins indicating that a basic magmatism was contemporaneous of migmatization. Small intrusions of aplite injected locally the migmatites.

At last, the granite of Fanos intrudes the basic complex and the migmatites which are both injected by many aplitic dykes. Obviously, these aplites are difficult to distinguish from the other acidic rocks described before.

Geochemical and Mineralogical Signature of the Acidic Rocks

If all the mafic rocks belong to a typical ophiolitic complex with a clear tholeiitic affinities (Bébien, 1977, 1982), the variety of basic-acidic associations observed in the Guevgueli complex needs to search for some mineralogical and geochemical characters to mark easily the origin of granitic melts involved in these associations.

Two particularly discriminant characters have been found. The first one is the zircon typology (method of Pupin, 1980) based on the morphology of zircon crystals. Three types of zircon populations have been found in granitic rocks (Figure 7). Some aplitic dykes are clearly related with the migmatites. The acidic matrix of magmatic breccias (MB1) associated with gabbronoritic cumulates and ferrodiorites have the typical zircon population of plagiogranites. The Fanos granite, other aplites and some magmatic breccias (MB2) intruding cumulates have a clear calc-alkaline affinities. Finally, zircon typology applied to the granitic rocks of the Guevgueli complex reveals three different origins for the acidic rocks.

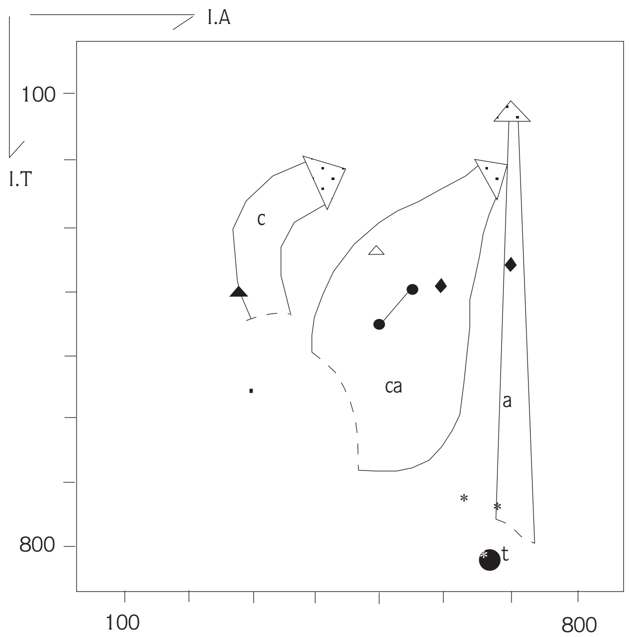

Figure 7. Distribution of the mean points compared to the main typological trends of zircon populations in granitic rocks. c: crustal-derived granites. ca: calc-alkaline series. a: alkaline series. t: plagiogranites or trondhjemites. Black triangle: Piyi migmatites, open triangle: associated aplite. Dots: Fanos granite. Rhombs: matrix of magmatic breccias. Stars: trondjemites. I A: index related to agpaicity. IT: index related to temperature of crystallization.

Multi-element spiderdiagrams (Figure 8) are also very discriminant. Using Rock/ORG normalization (Pearce et al., 1984), the spiderdiagram of acidic matrix of breccias MB1 are relatively low and flat, confirming the tholeiitic character of the MB1. The migmatites and their related aplites are enriched in LIL elements and poor in HFS elements and REE, such characters are observed in crustal anatectic melt. The pattern of the Fanos granite

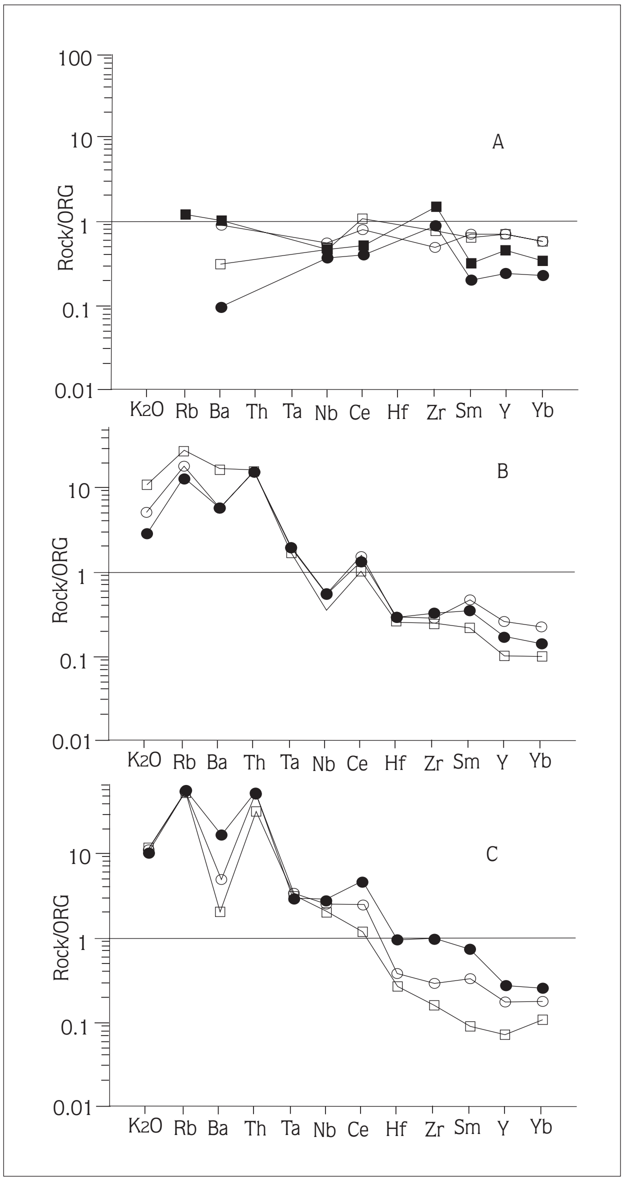

Figure 8. Rock / ORG Spider diagrams for the acidic rocks of the Guevgueli complex (ORG normalization values have been taken after Pearce et al., 1984). A: matrix of magmatic breccias and plagiogranites. B: migmatites of piyi and aplite. C: granite of Fanos.

and MB2 have the negative anomalies common in calc-alkaline granites but an important crustal anatectic component cannot be ruled out.

Interpretation

Geochemical data confirm that the acidic components of the Guevgueli complex includes at least three origins. (i) Plagiogranites correspond to the ultimate stages of the differentiation of tholeiitic magmas. The residual melts seem to have been expelled from the ferrodioritic cumulates and have also injected more primitive cumulates. At the same time, new primitive basic melts (picritic basalts) rising from the mantle have intruded the crystallizing cumulates at the top of the magmatic chamber. They are comagmatic with the acidic melts with which they have mingled to form the magmatic breccias MB1; (ii) Calc-alkaline granites with the Fanos granite and some breccias (MB2) may testify that the marginal basin of Guevgueli was opening near a still active island arc (the Paikon massif); (iii) At last, anatectic granitic melts are also generated in the continental crust dismembered during the opening of the Guevgueli basin.

The Associations of the Monzonitic-Monzodioritic Complex of Piracaia, Brazil

General Structure, Lithology and Petrology of the Complex

The plutonic complex of Piracaia (32 km^2, Figure 9) intrudes the so-called "Itapira Group" metamorphic complex and the porphyritic granite of Bragança-Paulista which is deformed and yields K-rich calc-alkaline affinities. The complex is composite with several intrusions. The petrographic rock types are essentially intermediate with scarce monzogabbros, coarse or fine-grained monzodiorites, monzonites, quartz-monzonites and syenites. Very mafic rocks are not observed, and there is no intrusion of granite. So, it is typically an intermediate series as it has been described by Campos Neto and Arthur (1983), Janasi (1986), Janasi and Ulbrich (1987, 1991). It is also clear that all the different intrusions are made up by the intimate association of two or several chemically contrasted rocks. The contacts between the two components are generally lobated or crenulated, some associations look like net-veined complexes (Blake et al., 1965) with pillow-like structures. Capture of phenocrysts by the mafic component also indicates that the magmas were contemporaneous, and locally, the mingling has been sometimes strong enough to generate mechanical

Figure 9. Geological map of the composite complex of Piracaia (after Janasi and Ulbrich, 1987).

trapping of phenocrysts between the melts, minor chemical mixing and hybrid rock formation.

Frequently, the associations of rocks are thoroughly deformed. When the streching of the two components is drastic, it becomes ribbons associations. The rocks become foliated with a strong planar fabric, this tectonic foliation is correlated with the regional deformation (Janasi and Ulbrich, 1987). The textures of rocks are various, depending largely on the tectonic constraint during crystallization. They are often protoclastic or more recrystallized, but the primary magmatic paragenesis are partially preserved in spite of metamorphic overprint in the greenschist facies (Janasi and Ulbrich, 1987).

Geochemistry

The entire series is characterized by high values of total alkalies and specially K_2O (K_2O/Na_2O >0.6 in the most mafic rocks). In the K_2O versus SiO_2 diagram (Figure 10), the entire series is situated in the shoshonitic area defined by Peccerillo and Taylor (1976), near the limit of ultra-K series. This potassic magmatism is very similar to non ultra-K series from the Roman Province (Italy) and more potassic than the potassic magmatism from Vosges (France) or the mafic-intermediate associations from the Ploumanac'h complex (France). The rocks are silica-saturated, their TiO_2 content can reach 2.4 % in the cumulative monzogabbro but are less than 1.8 % in the monzodiorites.

In the chondrite normalized spiderdiagrams (Thompson, 1982) the entire series (Figure 11) yields a permanent negative anomalie for Nb, Ta, Th and a positive one for Ba, Rb, LREE, and K, Sr, P in the mafic rocks-types. The REE patterns are relatively fractionated even in the more mafic examples, the Ce/Yb and La/Yb (normalized) ratios are similar to the same ratios of the shoshonitic series from Grenville (Canada). There is no negative Eu anomaly, no outstanding enrichment in total REE and in LREE relative to HREE with fractionation since the syenites.

The relatively low values in Ni, Cr, MgO, even in the less evolved types, indicate that mafic magmas are not primary magmas. In the spiderdiagrams, some negative anomalies appear, which become more and more prominent along the entire series, in realtion to the magma fractionation. The negative anomalies of Sr, P, Ti, Ba and K evidence the fractionation of plagioclase, apatite, oxide, biotite and K-feldspar. The relative stability of the REE pattern can be explained in the same way with global distribution factors around 1.

To test the fractionation processes, calculations have been made on major and trace elements using least square mixing method and Rayleigh fractionation equation. Several steps illustrate fractionation between the less evolved monzodiorites which are taken as the first parent magma, to the syenites. Results show that some monzogabbros are partially cumulative rocks, monzonites and syenites can be taken as residual magmas after respectively 69 % and 83 % of crystallization (Gomes 1995). The calculated cumulates are biotite-rich gabbros and monzonites. Apatite, allanite and zircon fractionation can not be neglected in the fractionation model.

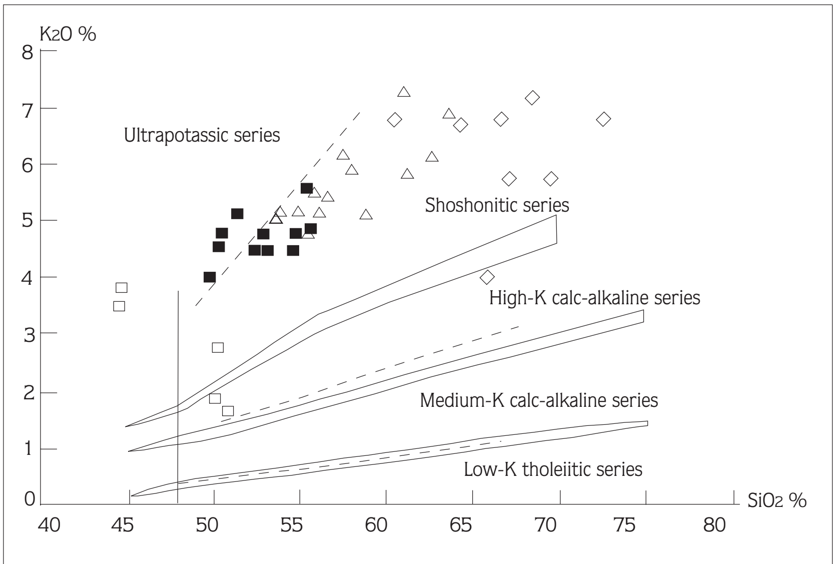

Figure 10. K_2O versus SiO_2 diagram. Open square: Diorites; Black squares: monzogabbro-diorites; Triangles: monzonites; Rhombss: quartz-monzonites and syenites.

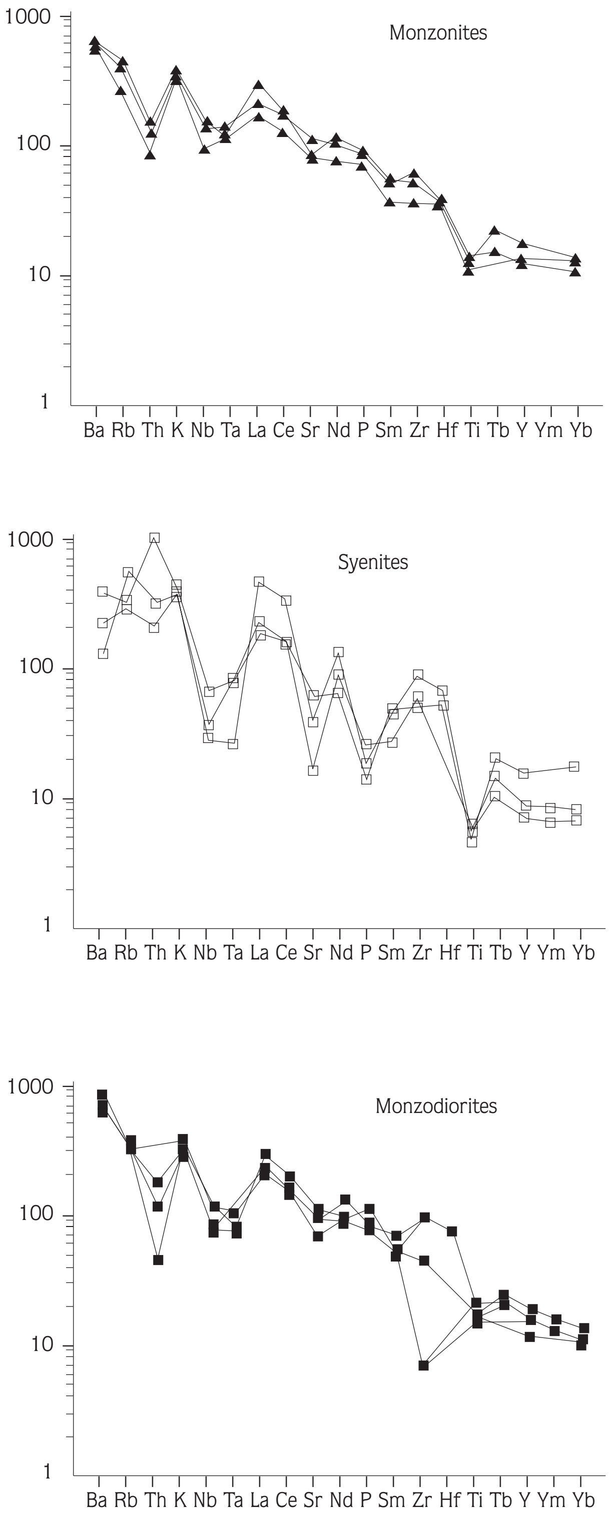

Figure 11. Chondrite-normalized spidergrams (Thomson, 1982) for the Piracaia complex.

Interpretation

This magmatism yields clear shoshonitic affinities, the main process which is responsible of the entire series at Piracaia is fractional crystallization of a primitive monzogabbroic magma.

Commingling of magmas of various compositions is one of the main character of the Piracaia complex, indicating that different batches of more or less evolved magma have coexisted in a zoned magma chamber where fractional crystallization took place. Mingling of magmas probably takes place during the periods of refilling of the chamber by primitive monzogabbroic magma. Periodic refillings also instigate intermitent discharges at a higher structural level of the new magma mingled with various volumes of more evolved monzonitic or syenitic magmas. These features would explain the various intrusions and associations evidenced in the Piracaia Complex. The best location of the main magma chamber is probably at the limit between ductile and brittle crusts. The injections took place at the bottom of the brittle crust, not so far from the top of the magma chamber. This short course to the final emplacement as well as the minor volume of magmas acting, prevent drastic mixing and hybridization between contrasted batches of magma.

Finally, the Piracaia complex is made up of several intrusions and associations which are all cogenetic and comagmatic. The different melts may be generated by fractional crystallization in the main magma chamber. The magmatic zonation of the chamber has been disturbed during the periods of refilling and discharge. However, the subsequent convective stirring was only moderate, preventing important chemical mixing between the different batches of magma.

Mixing Process: Possibilities and Limitation in the Acid-Basic Association of Porto

Mixing process of intimately mingled magmas and generation of hybrid melts are also a subject of great interest for geologists. Obviously, in these three situations, hybridization is very restricted or even missing. Many factors inhibit the possibility of mixing in these associations: (i) small volumes of magma, (ii) rapid crystallization at high structural level location, (iii) high chemical, temperature and viscosity contrasts between the melts causing rapid chilling of the mafic component. These last factors are the main factors governing the mixing process.

In the complex of Porto, hybridization process is greatly suspected, and rocks of intermediate composition could be the result of hybridization. However, the abundance of hybrid rocks is very restricted (2%). The rocks which their origin by mixing is suspected, have a restricted range of composition. Calculations show that the more mafic hybrid rock has 49 % of basic component (Table 1): this is to say that the mixing between gabbro and granite melts can not be complete. The mean calculated ratio of mafic melt in the hybrids is 26 % with a standart deviation of ± 20, showing that range of composition is extremely large compared to the total abundance of hybrid rocks.

The constraints of mixing between melts have been largely studied in the last ten years, through theoretical considerations, numerical calculations and experimental works (Yoder, 1973; Mc Birney, 1980; Sparks and Marshall, 1986; Koyaguchi and Blake, 1991).

Thermal and chemical diffusion rates are so different that thermal equilibration always occurs prior to chemical equilibration. So, the evolution of rheological properties of associated melts are determinant to obtain complete hybridization.

In the graphical representation of Sparks and Marshall (1986) applied to the example of Porto (Figure 12), the complete mixing between gabbro and granite can only happen if the basic component exceedes 50 %. In fact, it is probably largely more than 50 % because the gabbro and the subsolvus granite of Porto both contain phenocrysts. The two melts are below their respective liquidus temperature when coming into contact. The very heterogeneous character of the Porto magmatic breccias indicates that this condition of complete mixing is not reached, and we have no homogeneous hybrid rocks with such a high ratio of the mafic component. On the contrary, it may be paradoxal that the only homogeneous hybrid rocks at Porto are relatively poor in mafic component.

If we look at the textures of the hybrid rocks of Porto, it is interesting to note that rounded quartz or plagioclase from the granitic melt exist in the hybrids, they testify the reheating of the acid melt. Coexisting with the partially remelted phenocryst, the groundmass texture of the hybrid rocks evolved rapidly from fine-grain to aplitic and to subvariolitic quench texture (with skeletal crystals of plagioclase, amphibole, ilmenite and apatite). In one hand, the melt was superheated, in the other hand, it was supercooled and the degree of supercooling is strictly connected with the increasing basicity of the melt. Persistance of partially remelted phenocrysts and quench texture development are indicative that the hybridization process takes place in disequilibrium conditions in the Porto association.

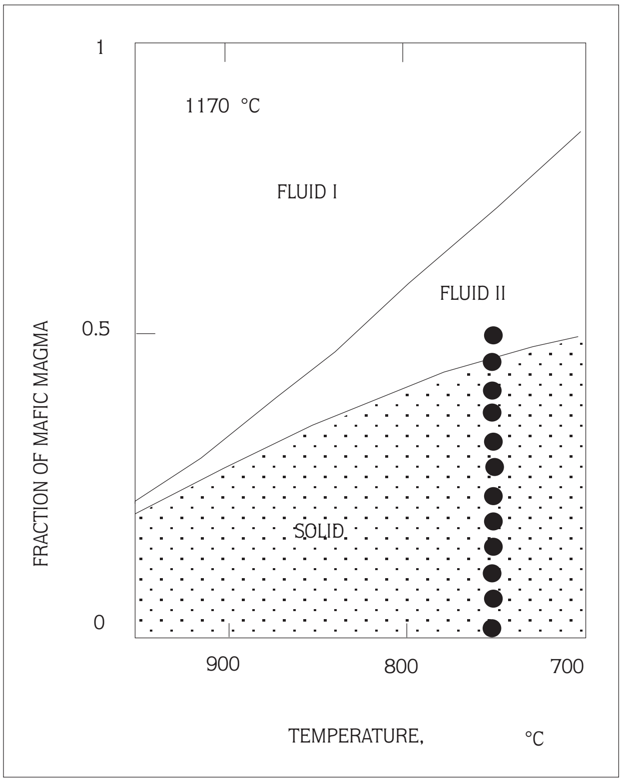

Figure 12. Location of the hybrid rocks of Porto in the silisic magma-mixing diagram of Sparks and Marshall (1986).

In the schematic binary diagram (Figure 13) used by Mc Birney (1980): (i) after a period of reheating, intermediate liquid composition must coexist with metastable phenocrysts, (ii) quench texture can develop if the hybrid liquid composition is such that the liquidus corresponding to the mafic component is crossed over, the hybrid liquid is then supercooled.

At last, the best explanation for the formation of hybrids rocks in the acid-basic association of Porto implies:

1. Thorough mechanical mixing and formation of magmatic breccias;

2. Near approximate thermal equilibration between the components;

3. Thermo-chemical disequilibrium conditions during hybridization which is governed by chemical diffusion of elements;

4. The acidic melt only has a mean value of 25 % of effective hybridization by the mafic melt, hardly less important than the ratio of mafic melt engaged in the mingling process; if the ratio increases to reach 50 %, the hybrid melt is physically supercooled.

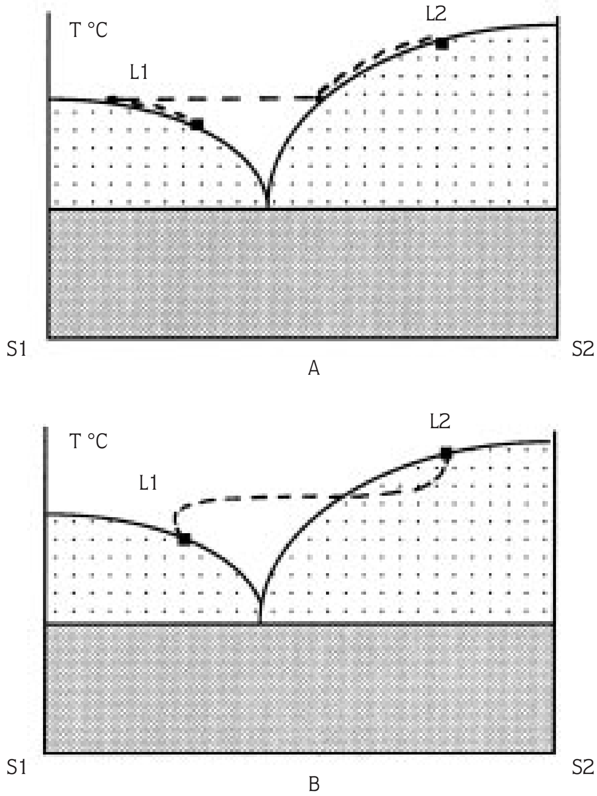

Figure 13. Schematic binary diagrams showing the mixing patters between the two melts. A: in equilibrium conditions, after remelting its phenocrysts, L1 mixes with L2 for every ratio L1/L2. B: L1 leaves its liquidus before the phenocrysts are totally remelted, L2 is undercooled, the mixing process takes place in disequilibrium conditions, the hybrid melts are undercooled for high ratio of mafic component.

5. Partial extraction from the magmatic breccias of hybrid melts by gravity or convective shorting of mafic enclaves, in the magma chamber or during the ascent of the acid-basic association.

Diversity and Complexity Degree of Commingling Associations

The main distinctive characters of the three examples are summarized in Table 2. Through these different geodynamic settings, it is clear that the maximum complexity of acid-basic associations is observed in orogenic situation. In the Guevgueli complex, the diversity of the magmatic associations observed in this fragment of oceanic crust is extreme: probably three acidic melt of different origin may be comagmatic with mafic tholeiitic magmas replenishing the magmatic chamber. When the Guevgueli marginal basin opened, at least 4 different sources of magma may be active at the same time: the mantle generates basalts of tholeiitic affinities to build the sea-floor and feed the crystallizing magmatic chamber where differentiation takes place. Commingling associations in chambers occur between the residual liquids and the crystallizing zones, but also with new rising primitive basalts. The chamber is also intruded by various acidic magma linked to continental crust melting and neighbouring arc activity.

In post orogenic or anorogenic setting, the magmatic activity is more restricted. Only one or two sources may be involved where mingling of magmas occurs.

The commingling associations are the result of convective instabilities produced during the refilling of the magma-stratified chambers. These processes have been recently experimented. The net-veined complex formation, which are so common in commingling associations, are particularly well explained by Saffman-Taylor or Rayleigh-Taylor instabilities reproduced in fluid-mechanic experiments (Snyder and Tait, 1995). The pillowing observed in composite dykes is also generated by instability of the interface between the two contrasted fluids. Convective entrainment during the replenishment of chamber is also a possible mechanism able to produce mingling of magmas. Within a silicic magma chamber or a magma-stratified chamber, hot basic magma injections can cause the convective entrainment of basic magma by silicic reheated magma. During the folowing discharge at a subvolcanic or volcanic levels this entrainment can explain the association of the two contrasted melts (Snyder and Tait, 1996). This is probably the case in the acid-basic association of Porto and Piracaia.

In these three examples, the mixing of magmas is very restricted or absent. However, in the Porto association, hybrid rocks have been observed in restricted volume. The mixing process implies two steps: magmatic breccia formation by thorough mingling of magmas and diffusion of elements between the acid melt and highly fragmented basic melt. The gravity sorting of the hybrid melts from the magmatic breccias occurs in the chamber or during the injection at a higher level. At Porto, the hybridization process may occur in disequilibrium conditions. Because the physical and chemical conditions for complete mixing, between the two much contrasted melts, are not satisfied, the effective ratio of hybridization is at least 3 times under the acting volume of mafic magma during brecciation. It may be a "palliative" to the difference between thermal and chemical rates.

Table 2. Main distrinctive characters of the three described basic-acidic associations.

	PORTO	GUEVGUELI	PIRACAIA
Geodynamic	anorogenic	orogenic	post-orogenic
situation	alkaline series	various affinities	high-K series
Type of association	bimodal	bimodal	plurimodal
Sources of magmas	2	4	1
Cogenetic melts	no	no	cogenetic
size of the complex	small	-	small
Reservoir	ductile/brittle	hypabyssal	ductile/brittle
location	crust	chamber	crust
size	large ?	very small	large
volume of silisic	important	very small	zoned chamber
magma in the chamber			Several batches of magma
mingling	small volumes	small volumes	small volumes
intensity	thorough		thorough
moderate			
melt contrasts			
density			
viscosity	large	large	weak
temperature			stable progressive
composition			gradients
hybridization	restricted	very restricted	very restricted
main processes	FC; R/D	FC; R/D	FC; R/D
in the chamber			

FC: Fractional Crystallization; R/D: Replenishment/Discharge.

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