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Alkaline Rocks and Geodynamics

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Abstract: Origin of A-type alkali feldspar granites is currently the subject of a world-wide debate. Contrasting hypotheses have been proposed, which range from an entirely crustal origin to an almost complete mantle derivation. A-type alkali feldspar granites belong to either unimodal granite (rhyolite)-dominated association, or bimodal gabbro (basalt)-granite (rhyolite) suite. It is argued that (i) the ultimate mantle origin of basic to intermediate rocks is beyond doubt, (ii) highly evolved felsic rocks may be produced by other processes besides crustal involvement through anatexis and (iii) large volumes of felsic rocks are a normal and direct consequence of extensive crystal fractionation processes.

After a review of current hypotheses, it is concluded that A-type alkali feldspar granites are likely to be produced from mantle-derived liquids. Consideration of physical parameters (essentially density) of mantle, crust and liquids suggests that crust plays obviously a major role, not as a direct source for liquids, but operates as a density filter for migrating liquids and as a provider of the water required to generate silica oversaturated residual liquid and to fasten kinetics of differentiation processes. Anorthosite, rapakivi magmatism and A-type ring complexes are closely related in a coherent model of magma ascent and differentiation from the upper mantle up to the crustal surface.

Alkalin Kayaçlar ve Jeodinamik

Özet: Alkali feldispat granitlerin kökeni günümüz yerbilimi dünyasında tartışma konusudur. Kabuk kökenli olmasından tamamen mantodan ayrımlaşmasına kadar kökenleri hakkında farklı hipotezler öne sürülmüştür. A-tipi alkali feldispat granitler ya tek tip granit (riyolit) baskın topluluğuna ya da iki tip gabro (balazt)-granit (ryolit) takımına bağlıdır. Ulaşılan bilgilere (i) bazikten ortaç bileşimli kayaçlara kadar değişen manto kayaların varlığı kuşkuyla karşılanmaktadır, (ii) ileri evrimleşmiş felsik kayaların oluşumu kabuksal ergime dışında kalan olaylarla ilgili olmalıdır ve (ii) felsik kayaçların büyük bir bölümü normal olarak ileri derece fraksiyonal kristalleşme ürünleridir.

Mevcut hipotezler değerlendirildiğinde A-tipi alkali feldispat granitlerin manto kökenli eriyiklerden türediği sonucuna varılmaktadır. Mantonun fiziksel parametreleri gözönüne alındığında (yoğunluk başta olmak üzere) kabuğun doğrudan kaynağını oluşturmadığı anlaşılmaktadır. Kabuk daha çok sıvıların göçünde filitre görevi yapmakta ve silikaca doygun kalıntı sıvıların kristalleşmesi için su verici ve ayırımlaşma aşamalarını hızlandırıcı bir rol oynamaktadır. Anortozit, rapakivi magmatizması ve A-tipi ring kompleksleri üst mantodan kabuk yüzeyine kadar yükselen ve ayırımlaşan bir magma modeli ile ilişkilidirler.

Introduction

"Alkaline" is an ambiguous term, which has been used with at least four different senses (Bates and Jackson, 1980). According to Shand (1922), alkaline plutonic rocks should be defined by high alkali contents relatively to silica and alumina, using the cationic ratio 1:6:1. This view has been commonly accepted (S̄rensen, 1974) and the major alkaline rock types are therefore:

(i) silica undersaturated rocks which may be either alumina saturated, or undersaturated, corresponding respectively to miaskitic and agpaitic associations. The felsic end-member of the suites is feldspathoid-bearing syenite.

(ii) silica (over) saturated peralkaline rocks. The felsic end-members are sodic amphibole-and/or aegirine bearing-alkali-feldspar syenite and granite.

Though not strictly alkaline, metaluminous and peraluminous syenite and granite are coeval with peralkaline types (Bonin and Giret, 1985). Examples of metaluminous-peraluminous-peralkaline granite-syenite associations have been substantiated throughout the world (Jacobson et. al., 1958; Ba et. al., 1985; Bonin et. al., 1987; Eby and Kochhar, 1990; Nardi and Bonin, 1991). Hereafter, "alkaline" is not used in its chemical sense, but with the meaning "belonging to the alkaline magma series" (see Bates and Jackson, 1980; Bonin, 1986).

In the silica saturated alkaline suites, alkali feldspar granite is extremely abundant and may constitute with volcanic equivalents (rhyolitic ignimbrite) the prevailing magmatic products. In other instances, basic rocks - gabbro and basalt- are also exposed and magmatic suites yield a characteristic bimodality (Martin and Piwinskii, 1972; Bonin et. al., 1994), with intermediate compositions being notably scarce. Explanation of bimodalty is presently a matter of debate. This paper is slightly updated from a previous one (Bonin, 1996) where the interpretation of bimodality, based on the role played by crustal layers as density filters promoting effective liquid differrentiation by mineral fractionation within crustal reservoirs, was presented and discussed.

The Bimodality of Alkaline Magmatic Suites

Many alkaline magmatic suites emplaced in continental rift and oceanic island settings display transitional to midly alkaline Ne-normative basalt and a typical basalt (gabbro)-trachyte (syenite)-rhyolite (granite) association. The most salient feature of the series is the association of low-DI Ne-normative mafic types with high-DI Qz-normative felsic types and the relative scarcity of intermediate-DI Ne-and/or Qz-normative types. *Mafic* and *felsic* are used here according to the recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks. DI stands for Differentation Index, expressed as the CIPW normative sum of the salic components Or + Ab + Qz + Ne + Lc (for precise definitions of the terms, see Le Maitre, 1989). To explain the origin of the bimodality of the magmatic suite requires, first, to consider the possible origins of the two mafic and felsic end-members and, then, to examine the thermodynamic conditions which govern magma production and differentation.

Origin of Basic and Intermediate Alkaline Rocks

As Bailey (1974) quotes, "it is safe that alkali basalts, basanites and nephenilites are primarily of mantle origin" (page 436). Most transitional to midly alkaline Ne-normative basalts contain peridotite xenoliths, interpreted as evidence for an ultimate mantle origin. Upper mantle sources have also been proposed for a large range of volcanic rocks, because they host peridotitic and pyroxenitic enclaves of high-pressure mineralogy as well as high-pressure xenocrysts, such as olivine, pyroxenes, Ti-amphibole, plagioclase, and anorthoclase (e.g. see Duchesne, 1984; Aspen et. al., 1990).

In the oceanic islands of the Society Archipelago (French Polynesia), besides primary picrite and alkali olivine basalt, mantle xenoliths are encountered within a large range of rocks from hawaiite through mugearite, benmoreite, to trachy-phonolite and even phonolite, which are exposed as lava flows, domes, and hypabyssal dykes (Léotot, 1988; Gisbert, 1989). However, though they enclose mantle xenoliths, their mg-number (100 * Mg/Mg + Fe^{2+}) is generally below that expected for primary mantle liquids and these magmas are likely to be derived from more primitive compositions through high-pressure olivine + clinopyroxene ± kaersuitic amphibole fractionation (Green et. al., 1974). Examination of occurrences of mantle xenoliths and high-pressure xenocrysts within both continental and oceanic areas reveals that a large range of basic to intermediate liquids can be produced within the upper mantle.

Bonin and Giret (1990) calculate densities and viscosities of a large range of basic to intermediate liquids for a temperature of 1100 °C, corresponding to average mineral-liquid equilibria within analytical errors of ± 50 °C (e.g. Duchesne and Hertogen, 1988; Platevoet, 1990) and a total pressure of 1 G/pa, corresponding to a 30 km-deep mantle-crust boundary. Basaltic and near-basaltic liquids yield densities in the range of 2.95 to 3.00 g/cm^3, while intermediate liquid densities are lower and range from 2.94 down to 2.60 g/cm^3.

Assuming average densities of upper mantle and lower crust respectively of 3.30 g/cm^3 and 2.90 to 3.00 g/cm^3, Bonin and Giret (1990) interpret the large compositional range of peridotite xenoliths-bearing liquids as evidence for the mantle-crust boundary playing the role of a density filter, the most basic liquids being trapped below the Moho within mantle reservoirs where they underwent high-pressure crystal fractionation. Buoyant and moderately viscous ($10^{1.5}$ to $10^{3.5}$ Pa-s) intermediate liquids produced within the mantle reservoirs may migrate upwards forcefully across the crust-mantle boundary. However, intermediate rock types are scarce in bimodal associations, while felsic end-members are abundant. The discrepancy between the actual observed distribution of rock types and the fact that intermediate liquids can be generated within upper mantle has to be explained.

Origin of Alkaline Felsic Rocks

No concensus concerning the origin of alkaline felsic rocks exists presently. In the $NaAlSiO_4$ - $KAlSiO_4$ - SiO_2 "petrogeny's residua system" (Bowen, 1937), they plot along two thermal valleys diverging from the $KAlSi_3O_8$ - $NaAlSi_3O_8$ join, indicating that they can be generated either by (mafic minerals + feldspar) fractionation of more mafic liquids (Bowen, 1928; Tuttle and Bowen, 1958), or conversely by partial melting of any materials containing enough salic components (Bailey, 1974). Three types of origin have been proposed:

(i) felsic liquids are produced by fractional partial melting of mantle (Presnall, 1969; Yoder, 1973; Bonin and Lameyre, 1978). To generate felsic liquids directly from the mantle necessitates very low amounts of partial melting, probably less than 1%, in the presence of fluids,

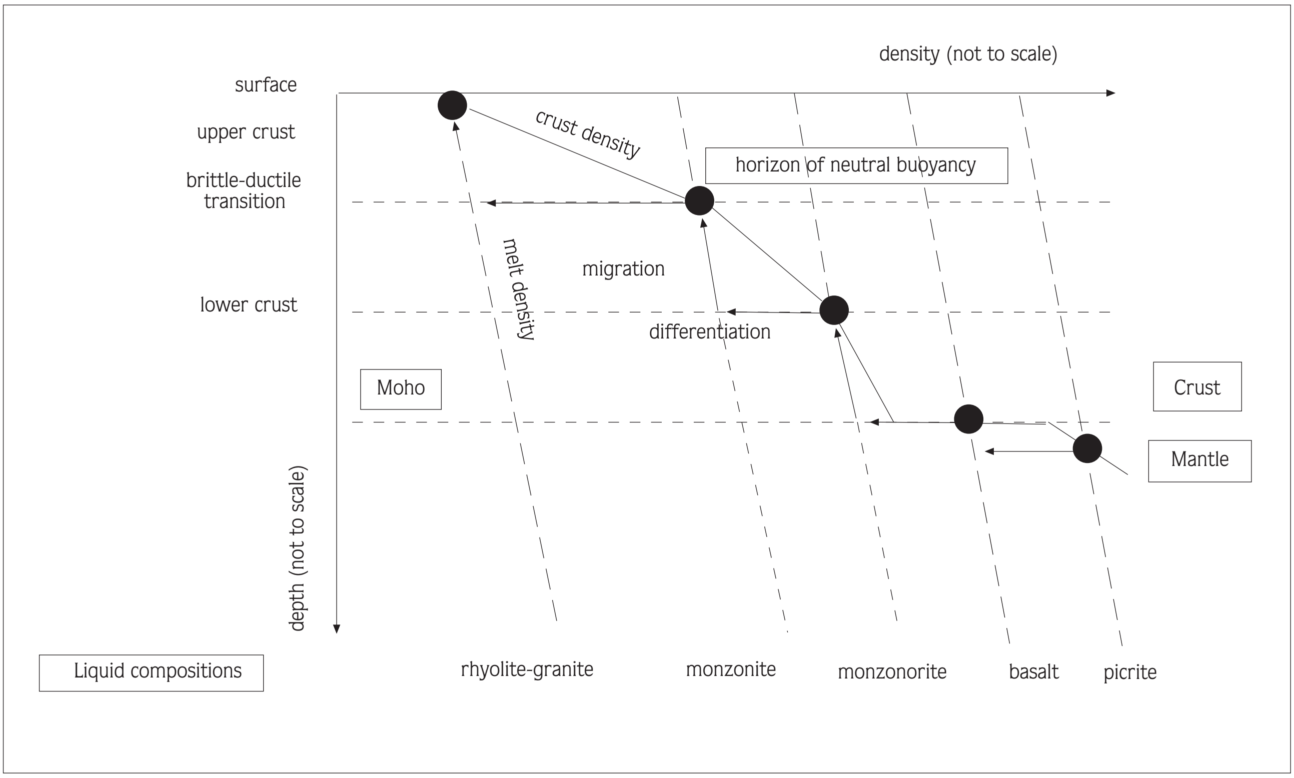

Figure 1. Density versus depth within crust and upper mantle. Each liquid of specific composition is capable to migrate upwards to its horizon of neutral buoyancy, where it is stored within a magma chamber and differentiates into a lighter more evolved residual liquid. The residual liquid can in turn migrate upwards to its own horizon of neutral buoyancy. A liquid can erupt at the surface level only in case of extension-driven decompression and displacement along wide conduits open well below its horizon of neutral buoyancy.

mainly CO_2 and minor H_2O, and/or hydrous minerals (kaersutite, phlogopite).

It has been argued that it would be extremely diffucult to extract from the solid matrix such a low percentage of liquid. But McKenzie (1989) claims that very small liquid fractions can move easily in the mantle, which can explain the particular asthenosphere rheology. Feasibility of the process is substantiated by immiscible ultramafic and carbonate liquid inclusions in metasomatised mantle xenoliths (Frezzotti et. al., 1994, and references therein). In some cases, cogenetic silica-rich (benmoreitic) and carbonate-rich liquids have been observed as trapped inclusions within mantle minerals (Schiano et. al., 1994, and references therein) and alkaline siliceous liquids are considered as one possible vector for metasomatism of the upper mantle.

(ii) both silica under- and oversaturated felsic liquids are highly evolved residual liquids produced from basaltic (Bowen, 1928; Coombs and Wilkinson, 1969; Bardintzeff et.al., 1988) to intermediate (Bonin and Giret, 1984, 1985, 1990) mantle-derived magmas. They originate from their parent liquids by low-pressure fractionation of Ca-pyroxene + Ca-amphibole + plagioclase + accessory minerals ± alkali feldspar (Maury et. al., 1980; Bardintzeff et. al., 1988). Their extraction from the mafic cumulate pile is promoted especially when DI intervals between the parent magma and the residual liquids are relatively low.

(iii) Ne-normative liquids are mantle-derived, but Qz-normative felsic liquids are produced by lower crust anatexis, induced and/or enhanced by intrusion of basaltic (Huppert and Sparks, 1988) to intermediate (Duchesne, 1984, 1990; Emsile and Stirling, 1993) mantle-derived liquids. The nature of potential crustal sources is a matter of controversy, the depleted F- and Cl-enriched felsic granulite facies source, first favoured, was recently disputed.

No unequivocal evidence for one of the three hypotheses is presently available. Alkaline silica oversaturated felsic rocks, the so-called A-type granites

(Loiselle and Wones, 1979), share a lot of common characteristics (mode of emplacement through cauldron subsidence, mineral and whole-rock compositional trends), whether they are emplaced in oceanic (e.g. Kerguelen Archipelago, Lameyre et. al., 1981; Giret, 1983; Bonin et. al., 1994) or in continental areas.

Sources of A-Type Alkali Feldspar Granites: A Discussion

The different petrogenetic schemes proposed for the origin of A-type granites should be tested by various ways. The basis of the two current and contrasting models will be examined briefly: (i) crustal anatexis process requires knowledge of the source rock compositions that are likely to generate magmas which match the exact range of A-type compositions, (ii) mineral fractionation of basaltic to intermediate liquids should be examined at the light of magma kinetics.

What Crustal Sources?

The alleged crustal origin of A-type granites is mainly based on data of Sr-Nd-Pb isotope systems. For example, Proterozoic and Phanerozoic A-type granites emplaced in continental areas yield Sr-isotope initial ratios ranging from mantle values (≈ 0.702-0.705) up to extremely high values, such as 0.752 in the Ririwai complex of northern Nigeria and even 0.863 in the Noqui complex of Zaire (for a review, see Bonin, 1986, p. 128-141).

Considering that, in the Gardar province of South Greenland, high Sr-isotope initial ratios (above 0.707) have invariably been found in altered and mineralised rocks, while the lowest ratios characterise non-altered rocks, Blaxland et. al. (1976) suggest that high values linked with Rb enrichment are the result of leaching ^{87}Sr out of the basement either by the chemically very active alkaline liquid or by associated peralkaline hydrotermal fluids. Same features have been observed in the Ririwai complex of northern Nigeria (Van Breemen et.al. 1975), in which non-altered fayalite granite and arfvedsonite granite display a Sr initial value 0.708, Sn-Zn-Cu-mineralized biotite granite a value of 0.729 and U-Th-Nb-REE-enriched albite-arfvedsonite-aegrine granite a value of 0.752. This was described again in Corsica (Bonin et. al., 1987; Bonin, 1988) and interpreted by extreme ^{87}Sr mobility during hydrothermal processes, so that it is not necessary to invoke crustal anatexis to explain high Sr-isotope initial values. F-rich peralkaline aqueous fluids carry elements, such as Rb, Sr, Zn, Th, U, Zr, Nb, Y, REE…, that can at least partially be extracted by leaching from the wall-rock basement.

However, the role played by hydrothermal fluids was often considered as negligible and Sr-Nd-Pb systematics have been interpreted as reflecting source rock compositions. In the Malani igneous suite of northern Peninsular India, Eby and Kochhar (1990) attribute the Sr initial ratio of 0.70948 for the Tosham granite to a crustal source which could be either a depleted granulite facies crust, or a metasomatised crust, while the Jalor syenite and granite are considered as differentiates of a mantle-derived magma. Three types of crustal source rocks have been claimed recently:

(i) the popular depleted F- and Cl-enriched felsic granulite facies source model (Barker et. al., 1975; Clemens et. al., 1986; Whalen et. al., 1987) should be tested. Numerous field and laboratory data substantiate that A-type granites do not contain any restitic materials and were emplaced in a crystal-free completely molten state. Experimental studies on synthetic, not natural, systems (Bohlen et. al., 1983) suggest that it is possible to produce liquids of appropriate compositions from a metagreywacke source at temperatures higher than 830 °C and pressures less than 1G/pa, typical of a 30 km-thick crust. But partial melting of natural apatite-bearing charnockite, granulite and diorite, all common rock types in the lower crust, failed to yield A-type liquid compositions (Beard et. al., 1994).

No depleted granulitic terrain showing anatexis with generation of an A-type felsic liquid was described in the literature so far. Creaser et. al. (1991) dispute the residual source model, arguing from the examination of natural xenoliths that the depleted lower crust protolith contains low SiO_2, K_2O, and high Al_2O_3, MgO, total FeO, CaO contents, all characteristics in conflict with those expected.

(ii) tonalitic to granodioritic meta-igneous sources were suggested by Anderson (1983). Creaser et. al. (1991) also favour this type of source rocks and propose a multi-stage melting model where, by repeated melting processes, the juvenile M-type granites may produce I-type tonalites, which may in turn generate K-enriched I-type granodiorites and ultimately A-type granites. Again, like for depleted granulitic terrains, no A-type granitic leucosome is exposed in meta-igneous undepleted migmatitic terrains.

Numerous experiments focus on partial melting of metaluminous and peraluminous crustal compositions at conditions resembling those prevailing in the lower crust, i.e. fluid-absent conditions at 0.3 to 1.5 G/pa (Conrad et. al., 1988; Beard and Lofgren, 1991; Rushmer, 1991;

Patino Douce, 1995; Skjerlie and Patino Douce, 1995). Dehydration-melting liquids never yield the alkaline to peralkaline granite compositions postulated by the model. On the contrary, within the stability field of amphibole, i.e. below 1000 °C and 2.0 G/pa (Rapp, 1995), only moderately to strongly peraluminous (up to 7 wt % normative corundum) tonalite-granodiorite compositions are produced.

(iii) as a third hypothesis, fenitisation of lower crust on a regional scale (e.g. Jones et. al., 1983; Morogan and Martin, 1985) deserves serious consideration. The basic assumption is that: "if metasomatic transformations occur at a sufficiently high temperature, the metasomatic assemblages will be involved in melting reactions" (Morogan and Martin, 1985, page 1114). Xenoliths of fenitised metagranite and metagabbro within the alkali carbonatitic magma of Oldoinyo Lengai, Tanzania, underwent disequilibrium partial melting. Quenched glasses yield intermediate (DI = 54-66) K-rich, peralkaline silica-undersaturated or metaluminous silica-oversaturated compositions. In this scheme, the transformation of plagioclase into calcite+nepheline (von Eckermann, 1948) is a critical step in order to promote an alkali-rich liquid.

The lower crust located directly above degassing mantle would be the optimum setting, because of high amounts of CO_2 in fluids. There is a lot of evidence regarding upper mantle metasomatism (Menzies and Hawkesworth, 1987). However, no vast areas of fenitised lower crust have been documented and the scale at which fenitisation does occur in the crust remains largely conjectural.

(iv) final remarks. The remarkable similarities of continental A-type granites, whether they were emplaced during Precambrian or Phanarezoic times, and their oceanic counterparts preclude any model in which typically continental compositions play a significant role. In other words, continental-derived meta-sedimentary formations, such as metagreywackes, can not represent likely source rocks for A-type magmatism, even if they can influence through wall-rock assimilation and contamination the final compositions of residual liquids (e.g. Foland et. al., 1993).

Fractional Crystallization within a Magma Chamber

In this model, A-type granite liquids represent residual liquids produced by differentiation processes occurring within a network of magma chambers emplaced at various depths one above the other (Figure 2). These reservoirs are filled up with continuously differentiating liquids and can evolve with or without periodical replenishments and tappings (see O'Hara and Mattews, 1981). Cooling of a magma chamber ultimately leads to formation of thick cumulate piles and of limited amounts of residual liquid. For a given suite, successive crystallisation paths can be computed from a primary magma 1 to the most evolved residual liquid n, through crystallization of cumulates 2, 3,..., (n-1) and n. At the last stage, assuming perfectly closed system conditions (e.g. no loss of volatile through a discrete vapour phase), the crystal-liquid relationship becomes (Bonin and Bardintzeff, 1989): magma 1 = $\sum(2, n)$ cumulates + liquid n, where $\sum$ (2, n) cumulates represent the total sum of cumulates formed during the entire process.

The most evolved residual liquids yield density and viscosity grossly lower than wall-rocks and crystals, favouring in-situ accumulation of early formed crystals and trapping of late-stage liquids immediately below the roof the chamber. Then, because of their buocancy, residual liquids can escape up to the surface level, providing that fractures be open and propagating upwards according to the regional stress field and the internal magmatic pressure (Anderson, 1936; Phillips, 1974).

Distribution of Alkaline Felsic in Within-Plate Magmatism

Bonin et. al. (1994) stress that high DI felsic rock types are extremely abundant in silica over-saturated suites, while they are rare in silica undersaturated ones (Table 1). They interpret the distribution of alkaline felsic rocks as essentially controlled by the efficiency of differentiation processes, which are in turn governed by water activity in the different reservoirs.

Liquid differentation is governed by anhydrous minerals, essentially olivine, plagioclase and Ca-pyroxene, and by hydrous minerals, chiefly Ca-amphibole (see Bonin and Giret, 1984, 1985). Though containing dissolved water, mantle-derived primary magmas are water-deficient and amphibole is never a liquidus mineral. The amounts of water dissolved in residual liquids evolve as a function of both anhydrous vs. hydrous mineral crystallization and wall-rock dehydration (for a discussion, see Bardintzeff and Bonin, 1987; Bonin and Bardintzeff, 1989).

In the case of near-water saturation, amphibole precipitates massively, leading to production of large volumes of A-type silisic liquids. Plutonic-volcanic complexes of the silica oversaturated association are chiefly composed of A-type granite-rhyolite and low DI rock types are scarce. If water is available at moderate to

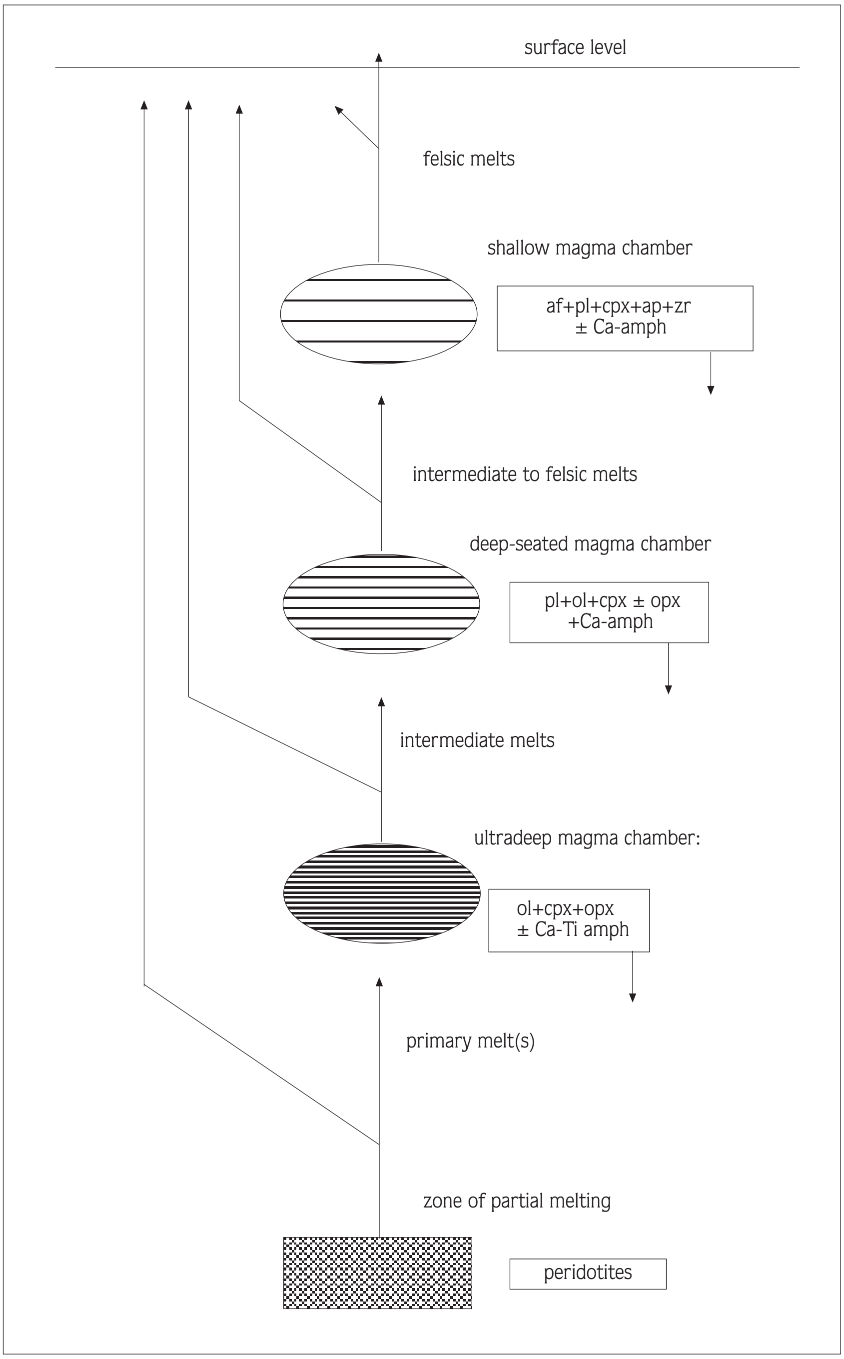

Figure 2. Fractional crystallization processes within a network of magma chambers emplaced at various depths. Primary liquid(s) originate from partial melting of upper mantle and evolve ultimately into felsic residual liquid at each level, the average fractionating mineral assemblage is specified. Arrows indicate the schematic pathways used for channeling the ascent of liquids up to the surface.

low amounts, amphibole is rapidly resorbed and Ne-normative felsic liquids are produced. However, fractionation processes are poorly developed and high DI feldspathoid-bearing syenite is scarce relatively to low DI rock types.

Water, essential to generate silica-oversaturated felsic residual liquids, plays the additional role of a catalyst. Kinetics of chemical reactions are quickened when aqueous fluids are abundant and strongly slackened when they are poorly developed. In this scheme, water is supplied by crustal host rocks to mantle-derived liquids evolving within magma chambers. The volume of crustal water necessiated to enhance amphibole precipitation and A-type residual liquid generation is a function of the

DI range of values	Corsica ring complexes	Mont-Dore caldera volcano	Tahiti-Nui plutonic complex
<50	≈1 %	48 %	95.5 %
50-65	≈1 %	15 %	3.0 %
65-80	2 %	25 %	no sample
80-97	96 %	12 %	1.5 %
Evolutionary trend	Silica-oversaturated	Mixed silica-saturated and oversaturated	Mixed-silica-saturated and undersaturated
Felsic end-members	A-type granite and rhyolite, alkali syenite	A-type rhyolite, trachy-phonolite, rare agpaitic phonolite, alkali syenite (xenoliths)	Alkali syenite nepheline syenite

Table 1. Rough estimates of rock-type distribution within selected alkaline igneous centres (modified from Bonin et. al., 1994).

volume of magma differentiating within the magma chamber and the amount of water around the magma chamber, either circulating along fracture networks, or bound in hydrous minerals of wall-rocks.

Nature and Depths of Emplacement of Evolving Alkaline Magmas

As A-type granites derived from mantle magmas represent less than 10 % of the mass of a basaltic parent magma, very efficient differentiation processes are active since the generation of the parent magma by upper mantle partial melting up to the final emplacement of A-type granite and rhyolite at shallow depths (less than 4 km). Migration of liquids through upper mantle and lower crust within dykes is a very fast process, as velocities from 10^2 to 10^{-4} m/s have been calculated (Nicolas, 1986; Emerman and Marrett, 1990) and only very limited flowage differentiation can occur. On the contrary, if liquids are trapped within magma chambers, they can undergo extensive fractionation processes.

Volumes of Magma Necessitated for A-Type Igneous Complexes

According to Crisp (1984), ratios of intrusive to extrusive volumes of magma are typically 5:1 in oceanic areas and 10:1 in continental areas. In the Quaternary Yellowstone caldera system (Hildreth et. al., 1991), the estimated 6.000 km^3 of rhyolite ejecta correspond to a total volume of A-type felsic liquids of 66.000 km^3 and, assuming that 1 volume of silisic liquid corresponds grossly to 10 volumes of a basaltic parent magma, to a total volume of parent magma of ca. 660.000 km^3. Abuot 594.000 km^3 of cumulates have been generated for the production of A-type silisic liquids.

By comprasion, the contemporaneous 100 km^3 of basalt lava flows were produced from only 1100 km^3 of a basaltic parental magma, 1000 km^3 of it having crystallised as hypabyssal dykes and sheets. In the volcanic field, basalts are negligible magmatic products (1.6 % of the total surface area and 0.17 % of the total magma volume). The total volume of parental magma corresponds to a 100-125 km-high column covering the same surface area as the caldera system, implying that most of the differantiation processes, i.e. evolution from basaltic to intermediate compositions, must occur within the upper mantle, as substantiated by geophysical data.

The Quaternary Yellowstone caldera system is a typical A-type silisic magmatic complex (Hildreth et. al., 1991). Nearly identical volumes of magma can be calculated for ring complexes of other anorogenic provinces, such as Niger-Nigeria (Jacobson et. al., 1958), Corsica (Bonin, 1980; Mercury et. al., 1994), Kerguelen (Giret, 1983), Adrar des Iforas (Ba et. al., 1985).

The Neutral Buoyancy Theory

While transport and storage of a magma are likely to be triggered and enhanced by tectonic disturbances along shear and fault zones, their rates are essentially governed by buoyancy (see section subtitled origin of basic and intermediate alkaline rocks). Ryan (1992) clarifies the model and identifies the following liquid buoyancy zonation from bottom to top (Figure 1):

(i) region of positive buoyancy. Liquid is less dense than wall-rocks and seperated progressively from its melting source or from an evolving magma chamber. It migrates toward its horizon of neutral buoyancy via a successive set of microporous networks, vein swarms and dykes.

(ii) horizon of neutral buoyancy. Identical liquid and crust densities set up a local gravitional equilibrium, favouring magma storage and intra-reservoir differentiation. Along with the dominant crystal-liquid separation, supplementary processes involve solid-liquid diffusion-controlled and/or fluid-controlled contamination and assimilation of wall-rocks, which are in turn responsible for the crustal isotopic signatures so frequently encountered in felsic rocks (see section subtitled what crustal sources?).

(iii) region of negative buoyancy, essentially from the volcanic surface to less than 1.5 km depth. Because of a large network of open fractures, bulk density of the crust is lower than liquid density. Liquid descends under negative buoyancy forces. To erupt, a magma must traverse this region aided by volumetric displacements and deeper lift.

Application of the Neutral Buoyancy Theory: The Structural Level Model

According to the model, to each magma composition corresponds its specific horizon of neutral buoyancy (Figure 1), where it is subsequently converted into a (crystal cumulate+residual liquid) assemblage (Figure 2). The ductile-brittle transition at the lower-upper crust boundary provides the most favourable site for magma storage and differentation. As the upper crust behaves as a brittle zone, any liquid can migrate upwards only if its internal magmatic pressure is high enough to fracture the overlying formations by hydraulic brecciation (Anderson, 1936; Philips, 1974; Bonin, 1986, 1992; Bonin et. al., 1994). Liquid ascent is favoured when pre-existing fractures are stirred up by tectonic disturbances. At the different structural levels (Figure 3), contrasting magma and rock compositions are exposed:

(i) At the deepest level, within an asthenospheric dome cerated under distensional post-orogenic and/or extensional non-orogenic tectonic regimes, partial melting produces primary liquids of picritic to basaltic compositions, that are buoyant with respect to the enclosing mantle and can migrate upwards. If there exists a large network of wide open fractures, the primary magmas can go directly to the surface and erupt as lava fountains. If there is no extensive fracturation, the primary magmas can not pass through the Moho mantle-crust boundary (Bonin and Giret, 1990).

(ii) They are stored in reservoirs at the mantle-crust boundary. High pressure fractionation of (olivine + orthopyroxene + Ca-clinopyroxene ± Ti-rich Ca-amphibole) (Green et. al., 1974) results in the deposition of amphibole-bearing wehrlitic cumulates, that are indistinguishable from the peridotitic upper mantle by geophysical methods (e.g. gravimetric studies). Giant crystals of orthopyroxene and plagioclase can grow from residual liquids yielding intermediate (monzonoritic) to evolved (phonolitic) compositions. These buoyant liquids can move upwards across the Moho, whether they are crystal-free or carry significant volumes of orthopyroxene +plagioclase crystalline mush (Duchesne, 1984, 1990).

(iii) Within the lower crust, dyke-like conduits pipe up monzonoritic to mangeritic liquids (Owens and Dymek, 1992) which feed 20-30 km-deep magma chambers arranged in tiers. The so-called Apophysis of Bjerkreim-Sonkndal, Rogoland (Bolle, 1995) can represent such a feeding conduit. Cumulative magmas are emplaced at the lower level as giant sill-like structures represented by anorthosite massifs, displaying foliated margins and mushroom shapes (Michot, 1961), and containing the giant crystals produced at lower depths (e.g. Maquil and Duchesne, 1984; Woussen et. al., 1988). Non-cumulative magmas are emplaced by successive injections into lopoliths where medium-pressure fractionation of (Ca-clinopyroxene + Ca-amphibole + plagioclase ± accesory minerals) generates intermediate to felsic residual liquids. Huge lopoliths, such as Bjrekreim-Sokndal, Rogoland (Michot, 1960; Duchesne, 1990; Duchesne et. al., 1992), and Monte Peloso, Corsica (Platevoet, 1990), are made up of km-thick layered formations, overlain by quartz-monzonitic (quartz-mangeritic) rocks (Dymek, 1993).

(iv) Monzonitic liquids can in turn migrate upwards and be stored at the 14-20 km-deep ductile-brittle transition of the lower-upper crust boundary. Low-pressure differentiation leads to massive deposition of (Ca-clinopyroxene + apatite + alkali feldspar ± Ca-amphibole ± biotite) within layered alkali-feldspar syenite massifs (Conceiçao et. al., 1991; Mitchell and Platt, 1994). The major fractionation process is accompanied by solid-liquid diffusion-controlled and/or aqueous fluid-driven contamination and assimilation of wall rocks, generating the cogenetic peralkaline and peraluminous trends (Bonin and Giret, 1984, 1985), as well as quartz and nepheline-bearing residual liquids (Foland et. al., 1993). Rapakivi massifs can represent disrupted and floated alkali-feldspar cumulates removed by new monzonitic to granitic magmas refilling the consolidated magma chamber (Conceiçao et. al., 1991). Rapakivi textures provide abundant evidence of small to large-scale disequilibria and hybridisation (Wark and Stimac, 1992; Eklund, 1993; Salonsaari, 1995). On the other side of the igneous spectrum, liquid immiscibility in the highly silica-undersaturated systems induce exsolution of carbonate liquids.

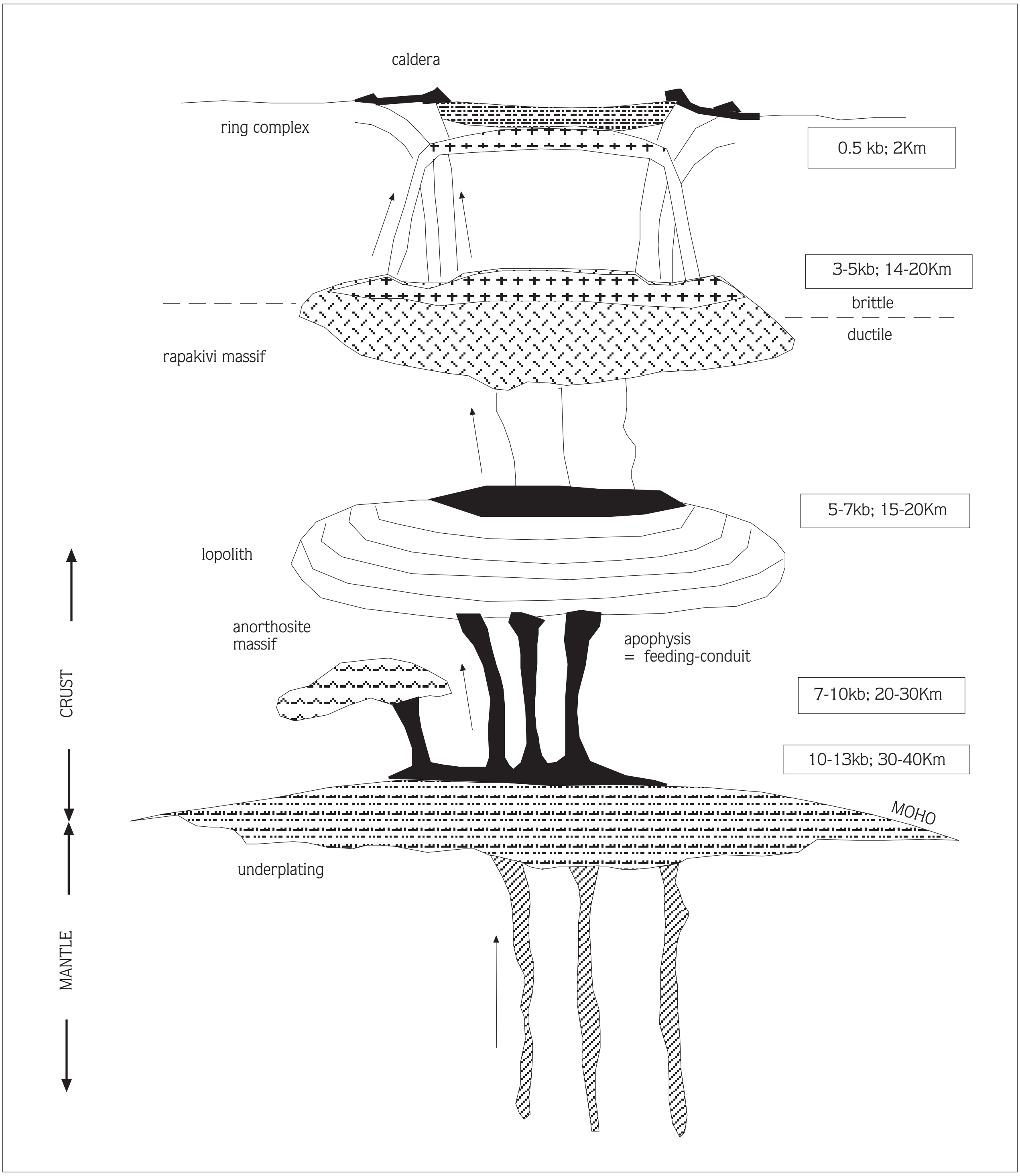

Figure 3. Structural levels of alkaline magmatism (Bonin, 1996): 1. Surface level: caldera volcano; 2. Subvolcanic level (1 to 4 km depth): ring complex, cone sheets and dyke swarms; 3. Magma chamber levels (14 to 30 km depth), from bottom to top: apophyses (black), anorthosite massif, mafic layered lopolith, rapakivi granite massif with alkali feldspar cumulates (dashes) and granitic residual liquids (crosses), 4. Crust-mantle boundary: storage of primary magmas formed within deeper asthenosphere. Though inappropriate ("intraplating" would be more adequate), "underplating" is maintained, because no other word has replaced it formally.

In every cases, the physical parameters (density, viscosity) of the cumulative assemblages are similar to those of their wall rocks. Gravimetric studies do not identify positive Bouger anomalies, as expected for ultramafic cumulates derived from a basaltic magma. Magnetic studies are useful to delineate underground alkaline massifs, due to high magnetic susceptibilities promoted by elevated Fe-contents.

(v) When sufficient volumes of A-type granitic liquids are trapped below the roof of the magma chamber and when a discrete vapour phase is liberated, the internal magmatic pressure may exceed the wall-rock strength. Cone sheets and radial dykes are created, which provide conduits up to the surface. Exsolution of excees fluids promotes explosive eruptions and ultimate hydrothermal brecciation and alteration. Silicate (and carbonate) liquids, which can carry primocrysts formed at depths, are emplaced in caldera volcanoes as ignimbritic deposits of A-type rhyolite, trachyte, phonolite, and s¯vite-natrocarbonatite association.

Relaxation of the internal magmatic pressure due to almost complete degassing of the liquid is then responsible for the creation of a set of tensile ring fractures, favouring underground cauldron-subsidence below volcanoes. A-type granitic, nepheline syenitic and carbonatitic magmas are emplaced at a completely molten state at shallow (about 1-2 km) dephts within ring complexes (for reviews, see Bowden, 1985; Bonin, 1986). Fast cooling and crystallization prevent any significant differentiation process. The low density of ring complex formations relatively to upper crust is reflected by negative Bouguer anomalies (Ajakaiye, 1970).

The Anorthosite-Rapakivi Magmatism-A-type Granite Ring Complex Connection

According to the "conventional wisdom", the coexistence of basic and silisic rocks and the concomitant scarcity of intermediate rocks are commonly used as an argument for a dual (mantle+crust) protolith. However, it is not necessary to postulate such a dual protolith. In a simple differentiation scheme, at each step, a cooling parent magma undergoes precipitation of its liquidus mineral phases and *disappears* in favour of a more evolved residual liquid. When differentiation is efficient enough to produce an A-type granitic liquid, there is no more basic to intermediate magmas in the magma chamber. The predominance of A-type felsic rocks over intermediate and basic rocks is, therefore, a normal and direct consequence of the crystal fractionation principle and should not be used as a proof of crustal sources. Instead, if basic and intermediate rocks are common and felsic rocks scarce, it does imply that differentiation was uncompleted within the magma chamber because of frequent replenishments relative to liquid tappings and/or low crystallisation kinetics due to low amounts of fluid acting as catalysts.

This reasoning can be applied to the relatively small (about 15 km in diameter) Phanerozoic A-type massifs, which are almost always represented by clusters of subvolcanic ring complexes along transcurrent faults. The much larger (hundred kilometer scale) Proterozoic anorogenic A-type granite and associated anorthosite complexes correspond mostly to deeper felsic magma chambers emplaced at the ductile-brittle boundary within the crust. These magma chambers have fed more than one ring complex, but the subvolcanic massifs have disappeared now by erosion. Because they correspond to different levels, it is not surprising that Proterozoic and Phanerozoic complexes yield contrasting sizes.

The different levels of the crust play obviously significiant roles, but *not* as direct sources for silicate liquids. They operate principally as *density filters* for migrating magmas and as *providers of the more or less crust-contaminated water* which is required to produce silica-oversaturated alkaline felsic residual liquids and to fasten kinetics of chemical reactions. Accordingly, isotope signatures varying from mantle to upper crust values provide crude indications on the nature of the crustal layers underlying A-type ring complexes and on the extent of interactions between mantle-derived water-deficient liquids and crustal hydrothermal fluids.

The anorthosite-rapakivi magmatism-A-type granite ring complex connection was examined by Emslie (1978) who relates Proterozoic anorthosite and rapakivi granite emplacement with the onset of the North American mid-continent rift (see also Anderson, 1983).

"Anorthosite" is "a leucocratic plutonic rock consisting essentially of plagioclase often with small amounts of pyroxene" (Le Maitre, 1989, p.47). Its origin(s) and definition(s) have been the subject of long-lived debates (for history of the term, see Feininger, 1995) and, as for granites, there are "anorthosite and anorthosite" (for reviews, see e.g. Michot and Michot, 1969; Morse, 1982; Duchesne, 1984). Most anorthosite massifs are clearly composed of cumulative plagioclase issued from crystal fractionation of within-plate magmas.

"Rapakivi" stands for "a variety of granite... characterised by the presence of large oval grains (ovoids) of orthoclase which are usually mantled by plagioclase" (Le Maitre, 1989, p. 111). First coined as early as in 1694, the term "rapakivi" is now defined for "A-type granite characterised by the presence, at least in the larger batholiths, of granite varieties with rapakivi texture" (Haapala and Rämö, 1992, p. 165; Rämö and Haapala, 1995, p. 129). The origin of the texture was largely debated, as the primary magmatic mechanism can be obscured by products of late-stage magmatic and subsolidus processes.

"A-type granite" is "a general term for granitic rocks typically occurring in rift zones and in the interiors of stable continental plates" (Le Maitre, 1989, p. 40). In its original definition, the prefix A was used for "anorogenic" (Loiselle and Wones, 1979) but, as Bowden (1985, p. 26) points out, could stand also for "anhydrous, alkaline, anorogenic as well as aluminous".

According to these definitions, the common association of anorthosite, rapakivi granite and

A-type granite ring complex define an igneous suite of cumulates and liquids:

(i) anorthosite massifs are contstituted by cumulates issued from intermediate liquids which were emplaced either at the mantle-crust boundary at high pressure (1.0-1.5 GPa), or within lower crust at comparatively low pressure (0.6-0.8 GPa).

(ii) rapakivi granite magmatism develops at the ductile-brittle boundary level (0.3-0.5 GPa), replenishment of older magma chambers results in removing of early alkali-feldspar cumulates by new liquids.

(iii) A-type ring complexes represent the shallowest plutonic level (pressure ranging from less than 100 MPa down to as low as 25 MPa). They are associated with caldera-related explosive volcanism and induce large geothermal activity.

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