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A-type granites and related rocks: Evolution of a concept, problems and prospects

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Abstract

Although A-type granites have long been recognized as a distinct group of granites, the term A-type was coined first less than thirty years ago. A-type suites occur in geodynamic contexts ranging from within-plate settings to plate boundaries, locations and times of emplacement are not random. Rare in the lower crust, as some charnockite suites, they are fairly common at shallower depths, especially at the subvolcanic level where they form ring complexes rooting caldera volcanoes. Characteristic features include hypersolvus to transsolvus to subsolvus alkali feldspar textures, iron-rich mafic mineralogy, bulk-rock compositions yielding ferroan, alkali-calcic to alkaline affinities, high LILE+HFSE abundances, and pronounced anomalies due to high degrees of mineral fractionation. Isotopic features evidence sources containing a large mantle input. Experimental data show that A-type magmas contain dissolved OH–F-bearing fluids, crystallised under reduced and oxidized conditions, and yield high-temperature liquidus, favouring early crystallisation of anhydrous iron minerals, such as fayalite. Though many petrogenetic models imply solely crustal derivation, no convincing A-type liquids were produced experimentally from crustal materials, nor have any leucosomes of A-type composition been detected within migmatitic terranes. As it occurs in association with mafic igneous rocks in continents as well as on the ocean floor, A-type granite is likely to come from mantle-derived transitional to alkaline mafic to intermediate magmas. Rare felsic materials found in the meteoritic and lunar record yield dominantly A-type features. Contrary to the more common types of granite, A-type granite is, therefore, not typical of Earth and was produced in planetary environments differing from those prevailing on Earth.

Keywords: A-type granite; Alkaline; Anorogenic; Mantle; Crust; Ring complex; Batholith; Lopolith; Terrestrial planets

1. Introduction

Granitoids are extensively studied for the following reasons: (i) they are the most abundant rocks in the Earth's upper continental crust, (ii) like other igneous rocks, they represent probes into the deep planetary interiors, and (iii) they are closely connected with tectonics and geodynamics. Even now, the proportion of granitoids and associated volcanic rocks present on Earth is low, about 0.001 of the bulk Earth (Clarke, 1996). Such a small proportion corresponds nevertheless to a total mass of at least 10^{22} kg and a volume of about $3.74 * 10^9$ km^3 (Bonin et al., 2002). Roughly 86 vol.% of the upper continental crust is granitic in composition (Wedepohl, 1991). Granite occurs also,

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albeit in smaller amounts, within lower continental crust, oceanic crust, upper mantle and meteorites (Bonin et al., 2002; Bonin and Bébien, 2005, and references therein). Overviews of the conflicting ideas on the origin of granite and their evolution in time can be found in Raguin (1946), Gilluly (1948), Roubault and Sadran (1955), Read (1957), Clarke (1992), Pitcher (1993), Bonin et al. (1997) and Young (2003).

The conventional wisdom states that granite and Earth's continental crust are tightly connected, as illustrated by White (1979) who quoted: "The chemical composition of granites precludes the possibility of direct mantle derivation. This is consistent with granite distribution. Granites are rocks of the continental crust and margins". The fact that granites do occur in oceanic areas has largely been overlooked. For example, Leake starts a discussion on the origin of granite magmas by stating: "I find it difficult why granitic bodies appear to be totally absent from the oceanic crust if granitic magma is commonly derived from the mantle. Not only are oceanic granites unknown, but geophysical evidence does not support the existence of buried batholiths in the oceanic crust" (Leake et al., 1980, page 93). That statement is not true, as A-type granites have long been recognized in continental and oceanic igneous suites.

Crisp (1984) evaluated a current rate of intra-continental output of volcanic magma at 0.03–0.10 km^3 yr^{-1} and of plutonic magma at 0.1–1.5 km^3 yr^{-1}, corresponding to 1.0–2.5% of the 26–34 km^3 yr^{-1} global rate of magma emplacement. Oceanic island output is higher and amounts to 0.3–0.4 km^3 yr^{-1} of volcanic magma and 1.5–2.0 km^3 yr^{-1} of plutonic magma. Pearce (1987) developed an Expert System for Characterization Of Rock Types (ESCORT), in which the *a priori* evidence was calculated by estimating the volume of lavas erupted in each environment since the Paleozoic (the Precambrian evidence is not considered), multiplying each value by the probability of a lava from that environment being preserved in the geologic record. Pearce recognized that these values are clearly only approximations. Intra-continental igneous formations, emplaced in post-collision and within-plate settings, amount to 52% of the total volume of the continental crust, magmatic arc formations to 41%, oceanic crust preserved as ophiolite massifs to 5%, and oceanic island formations to 2%. A-type igneous suites would constitute a major component of the continental crust, with roughly 30% basic rocks, 18% intermediate rocks and 6% granites and syenites. In Precambrian continental terranes, most A-type igneous rocks, referred to as anorogenic or cratonic (Lameyre et al., 1974), were preserved from erosion and tectonic destruction, implying that Pearce estimates are probably underestimated.

The definitions proposed so far to the term A-type and its history will be discussed. Problems concerning sources, evolutionary trends, and various modes of emplacement will be reviewed and provisional answers will be suggested. It will be emphasized that some of the scarce granitic samples recovered so far from the other terrestrial planets yield affinities with Earth's A-type granitoids. The possibility that A-type granites, though less frequent on Earth than the other types of granitoids, could be more abundant than expected within the Inner Solar System, will be explored.

2. The A-type concept

During the 70s, Chappell and White (1974, 1992) developed an internally consistent scheme, in which all granites are issued from the partial melting of crustal formations. The 'genetic alphabet soup', referred to as S-I-A-M (e.g., Clarke, 1992, pages 13 and 215), or S-I-M-A (e.g., Sial et al., 1987, page 20), was in vogue during the last decades of the 20th century. At the GSA Annual Meeting held at San Diego in November 1979, White offered a summary of the genetic alphabet scheme, with four types differing by their compositions and source rocks (Table 1). In addition to the S- and I-types already defined (Chappell and White, 1974), he introduced the M-type, inferred to be formed

Table 1
The alphabetical classification of granite types, according to White (1979)

Granite type	Chemical features	Specific minerals	Source rocks
S (1)	Peraluminous ASI ≥ 1.1	Peraluminous mafic minerals (cordierite, garnet, etc.)	Meta-sedimentary sequences
I (1)	Metaluminous ASI < 1.1	No peraluminous mafic minerals occurrence of hornblende	Igneous materials from deep crustal levels
M (2)	Volcanic arc signature		Subducted oceanic crust
No letter attributed (3)	Alkaline affinities and anorogenic	Fe-rich mafic silicates	Granulitic residue from a previous melting event

Notes:
1. S- and I-types are the oldest defined granite types (Chappell and White, 1974).
2. M-type is akin to Archean TTGs and modern adakites (for an overview, see Martin et al., 2005).
3. The type with no letter attributed corresponds to A-type.

by partial melting of subducted oceanic crust. Though White stated: “these (granites) are the only mantle or M-types”, M-refers actually to mantle-derived sources and mantle conditions, not to mantle sources (Clemens, written communication, 2005). A fourth type of granites, yielding alkaline affinities, was defined as emplaced in anorogenic settings and derived from a source considered to be the residue from a previous partial melting event. No letter was attributed to this fourth granite type.

At the same GSA Annual Meeting, Loiselle and Wones (1979) defined anorogenic or A-type granites that occur in rift zones and stable continental blocks, are usually mildly alkaline and crystallised under low H_2O and oxygen fugacities and relatively high HF/H_2O ratios in the magma. A-type granites are enriched in incompatible trace elements, including LILE and HFSE, but low in trace elements compatible in mafic silicates (Co, Sc, Cr, Ni) and feldspars (Ba, Sr, Eu). Examples include the Pikes Peak batholith, the White Mountain Magma Series of New Hampshire, the Nigerian Younger Granites, and the Gardar Province, Greenland. The most important point was that A-type granites are considered as dominantly non-crustal in origin and issued from fractionation of variously contaminated mantle-derived alkali basalt. The original concept of A-type granite contrasts sharply with the general philosophy of the overall crustal genetic alphabet. Instead, a scheme of mantle-derived mafic magmas interacting at various degrees with the overlying crust is created, which involves both mantle and crust in granite petrogenesis. The basic idea is explained at the end of the abstract: “In compressive orogenic belts, basaltic magma (or its latent heat) commonly interacts with a thick crustal sequence to produce calc-alkaline (I-type) or peraluminous (S-type) granitoids. Continental blocks undergoing rifting or fracturing provide minimal opportunity for interaction between basic magma and the crust”. A stands for Anorogenic and (mildly) Alkaline. The idea itself was not new (e.g., Chapman and Williams, 1935, on the White Mountain Magma Series of New Hampshire) and agrees with Bowen’s conceptions on granite petrogenesis (Bowen, 1928; Tuttle and Bowen, 1958). The introduction of a “mantle” letter within a “crustal” alphabet was the first crack in the crustal monument erected by Chappell and White.

Actually, the fourth unnamed granite type of White’s published abstract was presented orally as R-type, with R- for residual (crust) source (Christiansen, written communication, 2005). The R-type concept is entirely consistent with the other definitions of the genetic alphabet. The R- vs. A-type rivalry was the matter of long discussions in 1979 when Wones visited White and his collaborators in Australia. R-type was finally discarded, because the residual crust model was considered as “just too interpretative to use as a basis for nomenclature” (Collins, written communication, 2005), though this was also the case for the famous S- and I-types. A-type, a more descriptive term, was favoured, a decision ratified in the GSA Meeting.

Loiselle and Wones abstract became rapidly one of the most frequently cited abstracts in the granite literature. This paradoxical status – an abstract is rarely cited during such a long period of time after its presentation – results from the fact that Loiselle and Wones published no subsequent paper on A-type granite. A manuscript was indeed submitted, but rejected in 1980 and never re-submitted (Barker, written communication, 2005). The first published paper using the term A-type (Collins et al., 1992) concerned Australian occurrences and developed the residual source model.

3. Should the term A-type be abandoned?

The original A-type concept was fairly clear, but was further obscured by speculations on the meaning of the term A. For example, Bowden (1985, page 26) stated: “Syenites and alkaline granites as ring complexes … form collectively part of the A-type spectrum (where A stands for anhydrous, alkaline, anorogenic as well as aluminous) to distinguish them from the well-known classification of S- and I-types”.

3.1. *Is S-I-M-A classification OK?*

The clearly genetic assumptions explain the fast success of the original alphabet classification since the 70s of the last century and constitute also its major weakness. They caused and still provoke hot debates in the granite community. This is probably the reason why no new letters have been added, with the exception of C-type, proposed in the 2nd Hutton Symposium on Granites held in Australia (Kilpatrick and Ellis, 1992). C-type was not successful in gaining wide acceptance. Other attempts to refine the classification failed, e.g., G-type for Granite source (Wang et al., 1991) and H-type for Hybrid origin (Castro et al., 1991). The S-I-M-A classification remains an achievement of the 70s of the last century and many terms have fallen into disrepute.

Many reasons explain why the letter classification should be abandoned (e.g., Frost et al., 2001): (i) it is basically genetic, assuming an *a priori* knowledge of the source of granitic magma, (ii) it implies no magma

Table 2
Major features of A-type granite igneous suites (updated from Bonin, 1986, 1988; Bonin et al., 1998)

A-type granites	Monzogranite–syenogranite–alkali feldspar granite		
Associated rock types IUGS nomenclature Le Maitre et al. (2002)	Anorthosite–gabbro–diorite		
	Monzogabbro–monzodiorite–monzonite		
	Syenite–alkali feldspar syenite–nepheline syenite		
Rock-forming mineralogy	Felsic assemblage	Quartz	Purple to brown to black euhedral ß-shaped crystals
		Feldspathoids in associated silica-undersaturated rocks	Anhedral crystals
		Feldspar hypersolvus type (Tuttle and Bowen, 1958)	Mesoperthite with two discrete alkali feldspar phases
		Feldspar subsolvus type (Tuttle and Bowen, 1958)	Discrete crystals of K-feldspar and plagioclase ($An<15$)
		Feldspar transsolvus type (Martin and Bonin, 1976)	Mesoperthite cores with K-feldspar rims, K-feldspar and albite discrete crystals
	Mafic assemblage	Liquidus assemblage	Fayalite+pyroxenes+iron oxides
		Late magmatic calcic amphibole trend (Giret et al., 1980)	Hastingsite–ferro-edenite–ferrohornblende
		Subsolidus sodic–calcic–sodic–iron amphibole trend (Giret et al., 1980)	Barroisite–winchite–richterite–arfvedsonite–riebeckite–grünerite
		Subsolidus mica associations (Bonin, 1986; Martin et al., 1994; Azzouni-Sekkal et al., 2003)	Annite–siderophyllite; Zinnwaldite–trilithionite, Montdorite; Celadonitic muscovite; Clay minerals
	Accessory mineralogy	Fe–Ti Oxides	Ilmenite–ulvöspinel–magnetite
		Silicates	Aenigmatite–zircon–thorite–elpidite–allanite–chevkinite–topaz±titanite±tourmaline±garnet
		Phosphates (low abundances)	Apatite–monazite–xenotime
		High-tech metal ores	Fergusonite–polycrase–chernovite–pyrochlore–genthelvite–...
		Ores	Cassiterite–molybdenite–wolframite–sphalerite–galena–pyrite±pyrrhotite–chalcopyrite–mimetite–...
		Others	Fluorite-REE fluorides±carbonates
Bulk-rock chemistry	$FeO/(FeO+MgO)>0.446+0.0046\times$ wt.% SiO_2 (Frost et al., 2001)		Ferroan A-type group
	$FeO^T/(FeO^T+MgO)>0.486+0.0046\times$ wt.% SiO_2		
	For low Ga/Al and (Zr+Nb+Ce+Y): $FeO^T/MgO>16$		A-type granites
	$4<FeO^T/MgO<16$		Fractionated felsic granites (FG)
	$FeO^T/MgO<4$ (Whalen et al., 1987)		Unfractionated granites (OGT)
	ASI=A/CNK=molar $Al_2O_3/(CaO+Na_2O+K_2O)=Al/(2\ Ca+Na+K)$ (Shand, 1922)		
	$ASI>1$		Peraluminous
	$ASI<1$	$NK/A=(Na+K)/Al<1$	Metaluminous
		$NK/A>1$	Peralkaline
	For any ASI values	$NK/A>0.85$ (Giret et al., 1980; Whalen et al., 1987)	Alkaline or A-type suites
		$NK/A>0.88$ (Liégeois and Black, 1984)	
	Trace-element discrimination	$Y+Nb>50–55$ ppm (Pearce et al., 1984)	Within-Plate Granite (WPG)+
		$Yb+Ta>6$ ppm	Oceanic ridge granite (ORG)
		$10000\times Ga/Al>2.6$ (Whalen et al., 1987)	A-type granite
		$Zr+Nb+Ce+Y>350$ ppm	
		$Y/Nb<1.2$ (Eby, 1992)	A1 subtype, intra-plate rifting
		$Y/Nb>1.2$	A2 subtype, post-collisional
	REE contents and patterns	High contents in metaluminous and peralkaline types	Gull-wing shape
		Low contents in evolved topaz-bearing peraluminous types	
		Non-mineralized types	Slightly fractionated $(La/Yb)_N<30$ Varying Eu negative anomalies
		Mineralized types: pronounced tetrad effects	Unfractionated $(La/Yb)_N$ down to 0.3 Eu negative anomalies down to 0.01
	Stable and radiogenic isotopes	A-type suites yield no specific values in the Sr–Nd–Hf–Pb–O systems. Depleted mantle to highly evolved crustal signatures have no obvious correlations with ages of emplacement and tectonic settings, thus suggesting either a mixture of various sources, or complex differentiation processes, or both.	

mixing, a so obvious process in most complexes, (iii) there is a large compositional overlap between the various types, (iv) the lettering procedure lacks precision, e.g., making A-type granite both I- and M-type. Even the validity of the 1974 cornerstones, S- and I-types, is currently questioned.

S-type granites are basically peraluminous, with Alumina Saturation Index (ASI) higher than 1.1. The petrogenetic model involves partial melting of supracrustal rocks having suffered some extent of weathering effects (alkali removal with respect to alumina). Two main subtypes are recognized: (i) two-mica leucogranite representing pure crustal melts of thermal minimum composition, (ii) cordierite- or garnet-bearing granitoids explained as retaining a strong Al-rich restitic component (Chappell et al., 1987). Hence, S- stands for (meta-) sedimentary sources. Greywackes and pelites are generally considered as fertile enough to constitute suitable materials. However, Sr–Nd isotopic data show that two-mica leucogranite could result exclusively from the melting of metagranites (Turpin et al., 1990) and experimental studies (Patiño Douce, 1991, 1999) show that incorporation of at least 50% basalt into 50% metapelite is required to generate liquids of S-type composition in equilibrium with garnet-bearing gabbronorite cumulates, not restites. The meta-sedimentary source model is, therefore, invalidated.

I-type granites contain amphibole, an alumina-deficient mineral, and yield metaluminous to slightly peraluminous (ASI < 1.1) compositions. The petrogenetic model involves partial melting of formations that did not experience surface processes and the tonalite–granodiorite–monzogranite suite is assumed to be controlled by mafic restites variously diluted within thermal minimum melts (Chappell et al., 1987). Two subtypes are recognized (Chappell et al., 1998): low-temperature I-type contains abundant inherited zircon, and high-temperature I-type lacks inherited zircon. Hence, I- stands for (meta-) igneous sources of mafic to felsic compositions. However, U–Pb (zircon) and Zr (bulk-rock) studies of low-temperature I-type granites reveal that they crystallised from zircon-undersaturated magmas and inherited zircon crystals reflect melting and assimilation of a meta-sedimentary source (Kemp et al., 2005a). The data evidence input of a significant evolved supracrustal component and invalidate the igneous source model.

3.2. The status of A-type: is this group of rocks so well-defined?

The original concepts of S- and I-types being no longer valid, what about A-type itself? Several papers were published after 1979 (e.g., Pearce et al., 1984; Bonin, 1986) without feeling the need to use the term, thus questioning its usefulness and legitimacy. What are the merits of A-type definition? A-type granites are commonly associated with mafic and intermediate rocks, which constitute a compositionally expanded association with a real unity (Table 2). A-type igneous suites are fairly easy to discriminate on the basis of mineral assemblages. A-type granites plot dominantly, but not only, within the Within-Plate Granite (WPG) field (Pearce et al., 1984). Because they have specific bulk-rock compositions, they appear as a distinctive field in all discrimination diagrams based on LILE and HFSE contents.

As verified in all attempts to establish rules, there exist apparent exceptions. Aluminous subsolvus granites do not always yield all specific features of A-type granite, because they are issued from magmas evolving through protracted accessory mineral fractionation, resulting into progressive HFSE depletion (Table 2). Some compositions plot within the Volcanic Arc Granite (VAG) field (Pearce et al., 1984), but close to the VAG–WPG boundary, and the Fractionated Granite field (Whalen et al., 1987). Their A-type affiliation is not questionable for those that are exposed within anorogenic complexes (e.g., Conway granite of the White Mountain Magma Series). In the case of postorogenic igneous suites, in which they are abundant, it is not always straightforward to define whether they are A-type, or highly fractionated I-type. Field criteria are helpful, e.g., euhedral shape of purple–brown–black-coloured quartz crystals and anhedral shape of biotite flakes.

Origin

There is no consensus on their origin so far. Current petrogenetic models include partial melting of lower crustal sources of residual (Collins et al., 1992, the first to use A-type nomenclature), meta-igneous (Creaser et al., 1991) or alkali-metasomatized (Martin, 2006) compositions, involvement of mixed OIB-crust sources (Eby, 1990, 1992) and derivation from mantle-derived mafic and intermediate magmas (Bonin and Giret, 1990; Turner et al., 1992). To paraphrase Read (1957), should we conclude that there are A-type granites and A-type granites?

3.3. All things considered, what does the term A-type stand for?

The significance of A-type should be critically re-examined. But does A-really mean anything and is its use necessary?

Table 3
Selected A-type igneous suites, according to stages of a Wilson orogenic cycle

Locations	Orogenic stages	Tectonic contexts	Examples	Ages	References
Continents	Post-collision	Transcurrent shear zones	Finland–Russia border	2.44 Ga	Lauri et al. (2006)
			Post-kinematic suite of Finland	1.88–1.87 Ga	Nironen et al. (2000)
			Adrar des Iforas, Mali	560–540 Ma	Liégeois and Black (1984)
			Taourirt suite, Hoggar, Algeria	c. 530 Ma	Azzouni-Sekkal et al. (2003)
			Western Mediterranean province	280–235 Ma	Bonin et al. (1987, 1998)
			Comendite, San Pietro Island	15 Ma	Morra et al. (1994)
	Cratonic	Re-activation of transcurrent shear zones within uplifts and swells	Bushveld complex, S. Africa	2.05±0.01 Ga	Kleeman and Twist (1989)
			Rapakivi magmatism, S. Finland	1.7–1.5 Ga	Rämö and Haapala (1995)
			Rogaland, Norway	930–920 Ma	Schärer et al. (1996)
			Aïr, Niger	c. 410 Ma	Liégeois et al. (1998)
			Damagaram S Niger	320–258 Ma	Rahaman et al. (1984)
			Younger Granites, N Nigeria	213–141 Ma	Rahaman et al. (1984)
			Snake River Plain and Yellowstone, USA	17–0 Ma	Christiansen et al. (2002)
			Salton Sea geothermal field, USA	c. 0.016 Ma	Robinson et al. (1976)
	Rifts	Extensional regime	Oslo Rift	c. 280 Ma	Neumann (1978)
			Tadhak province, Mali	262–161 Ma	Liégeois et al. (1991)
			Topaz rhyolites, Western USA	50–0 Ma	Christiansen et al. (1986)
			Latir intrusives, USA	25–19 Ma	Johnson et al. (1989)
			Jibisi ring complex, East African Rift	20–15 Ma	Key (1989)
			Pantellerite, Pantelleria Island	0.33–0.003 Ma	Mahood and Hildreth (1986)
	Passive margins	Diverging plate Extensional regime	BTIP	c. 50 Ma	Richey et al. (1961)
			Limmo massif, Afar, Ethiopia	23 Ma	Black et al. (1972)
			Western border of the Yemen Plateau	30–20 Ma	Capaldi et al. (1987)
	Active margins	Converging plate Extensional regime	Papua-New Guinea and Mayor Island, New Zealand	5–0 Ma	Smith et al. (1977)
			Ashizuri massif, S Japan	14±1 Ma	Stein et al. (1992)
Oceans	Oceanic ridges	Diverging plate boundary	Plagiogranite, Faeroe–Shetland Basin	Eocene	Kanaris-Sotiriou and Gibb (1989)
			Austurhorn, SE Iceland	7–6 Ma	Furman et al. (1992)
			Argo Fracture Zone, Indian Ridge	?	Engel and Fisher (1975)
	Oceanic islands	Within-plate	Seychelles archipelago	809–703 Ma	Tucker et al. (2001)
			Seychelles younger intrusives	c. 63 Ma	Dickin et al. (1986)
			Ascension Island	7–1.5 Ma	Harris and Bell (1982)
			São Miguel, Azores	0.2–0.01 Ma	Widom et al. (1993)
	Oceanic plateaus	Within-plate	Rallier-du-Baty ring complex, Kerguelen	18–0 Ma	Gagnevin et al. (2003); Bonin et al. (2004)
Terrestrial planets	Moon	KREEP magmatism	Granite clasts	4.4–3.9 Ma	Warren et al. (1983)
	Mars	Pathfinder site	Sulphur-free rock	?	McSween et al. (1999)
		SNC meteorites	Silicic melt inclusions	4.5 Ga–180 Ma	Bonin and Bébien (2005)
	Asteroids	Chondrites, IIE irons,	Quartz feldspar assemblages	4.5–3.5 Ga	Bonin et al. (2002)
		Howardite–eucrite–diogenite (HED)	High-silica melt inclusions		Bonin and Bébien (2005)
	Venus	Equatorial zone	Pancake domes	?	Fink et al. (1993)

Anorogenic? Though spatially disconnected to orogenic disturbance (Bates and Jackson, 1980), A-type igneous suites are temporally related to orogenic events. Emplacement ages range from immediately after a collisional episode to up to 500 My after, when they are replaced by silica-undersaturated alkaline rocks. On a global scale, they are distributed within-plates of both continental and oceanic compositions. “Within-plate” refers to areas that were not plate boundaries when A-type igneous episodes occurred. But some provinces are emplaced close to plate boundaries (Table 3).

Alkaline? A-type granites are alkali-rich, some types being peralkaline or hypoaluminous (Jacobson et al., 1958). This chemical term is ambiguous as it conveys different meanings in the literature (Bates and Jackson, 1980). Iddings (1892, page 183) first subdivided "alkali" and "subalkali" rocks, by defining an alkali rock as containing more alkali metals than is considered average for the group of rocks to which it belongs, and regarded alkali igneous rocks as a separate group of genetically related rocks. Shand (1922) restricted somehow that definition, by stating that alkaline rocks should be either silica-deficient, or alumina-deficient, or both. Peacock (1931) used the term "alkalic" for rocks having an alkali-lime index below 51. The not strictly identical definitions induced much confusion in the nomenclature.

Miyashiro (1974) retained the original Iddings definition and regarded alkalic rock series as a category in igneous series classification and not as a class in petrographic-chemical systematics. He delineated a specific alkalic field, separated from the subalkalic field by a boundary identified in the total alkali vs. silica (TAS) diagram for silica contents ranging from 44 up to 75 wt.%. Three differentiation trends were considered: (i) the silica-undersaturated Kennedy trend from basanite to phonolite, (ii) the alkali-rich silica-saturated Coombs trend from silica-saturated basalt to peralkaline rhyolite, (iii) the straddle trend from alkali basalt to quartz-normative acid compositions. The Coombs alkaline trend is frequently ignored and referred to as tholeiitic (e.g., Frost and Frost, 1997; Dall'Agnol et al., 2005), or transitional (e.g., Furman et al., 1992).

Then, A-type associations, even those bearing non-alkaline rocks, such as biotite subsolvus granites, which are non-alkaline in the strict chemical sense, but are related to peralkaline rocks, are undoubtedly alkaline (Fig. 1). A number of authors continued after 1979 to use the word 'alkaline' to define A-type igneous suites, as they were not fond of the term A-type for two main reasons: (i) A-type is a part of the alphabet classification, which needs re-interpretation, (ii) 'alkaline' is a well-established word to define a group of igneous series.

Anhydrous? A-type magmas yield the lowest water fugacities recorded in the realm of silicate magmas. Lunar granite clasts are completely anhydrous A-type rocks. On Earth, A-type granites almost always contain small volumes of F-bearing hydrous minerals (Table 2), mainly amphibole and mica, with scarce exceptions in the mangerite–charnockite group. The common [quartz+fayalite±pyroxenes±iron oxides] liquidus assemblage indicates initial conditions below or at the FMQ buffer and water-deficient parental magmas. Calcic amphibole precipitates after and display euhedral crystals, produced mostly from the breakdown of liquidus assemblage by reaction with increasing amounts of water dissolved in residual liquids. The other hydrous minerals crystallise late from reaction with exsolved fluids at solidus to subsolidus temperatures and display anhedral crystals moulding the felsic assemblage (Bonin and Giret, 1985; Bowden, 1985). Experimental studies support petrographical observations. Crystallisation paths that fit better the mineral sequences observed in natural rocks correspond to low, yet significant, water amounts, i.e. 2–5 wt.% in reduced magmas (Clemens et al., 1986; Klimm et al., 2003) and 4.5–6.5 wt.% in oxidized magmas (Dall'Agnol et al., 1999).

Aluminous? Aluminous A-type granites are not alkaline, but constitute a significant part of the A-type igneous association (Fig. 2). Metaluminous types contain amphibole and biotite. Peraluminous types show a large variety of micas, including Li-micas, such as zinnwaldite, named from Zinnwald subsolvus granite (Table 2). Highly evolved peraluminous A-type granites are F-rich enough to yield topaz as a rock-forming mineral, whereas phosphates are rare, due to extremely low, less than 0.05 wt.%, P_2O_5 contents. These Rb-, REE-, Y-, and Th-rich, non-alkaline, rocks plot near the WPG–Syn-collisional Granite (SYNCOLG) boundary and within the A2 subtype field. They correspond to the low-P subtype of topaz granite (Taylor, 1992). The high-P (0.4–1.6 wt.% P_2O_5) subtype of topaz granite is composed of highly evolved S-type rocks, displaying a large number of phosphate species and P-bearing alkali feldspar (London, 1992; Fryda and Breiter, 1995; Morgan and London, 2005). P_2O_5 abundances and phosphate mineralogy constitute reliable criteria to discriminate A-type from S-type leucogranites.

Other meanings were suggested, e.g., *After*, as A-type post-collisional igneous suites postdate earlier granite plutons (Liégeois, 1998), and *Atlantic*, in the sense of Harker (1909, pages 88–109) who distinguished alkaline rocks produced under the distinctive tectonic conditions prevailing in anorogenic areas around the Atlantic Ocean.

The last meaning, *Ambiguous* (Whalen, 2005), illustrates the lack of consensus about A-type magma origin and suggests that A-type granites do not form a genetically connected group of rocks. Indeed, Creaser et al. (1991) proposed that the term A- be abandoned, as it conveys a different meaning from the other members of the alphabet classification. To their opinion, A-type is nothing by a subtype of I-type, an idea previously set up by Collins et al. (1992). It is noteworthy that the ambiguity issue can apply to the other terms of the genetic alphabet. The actual ambiguity results from flourishing genetic models, mostly based on chemical data handling, but ignoring field and experimental constraints. Calculations using the least square method

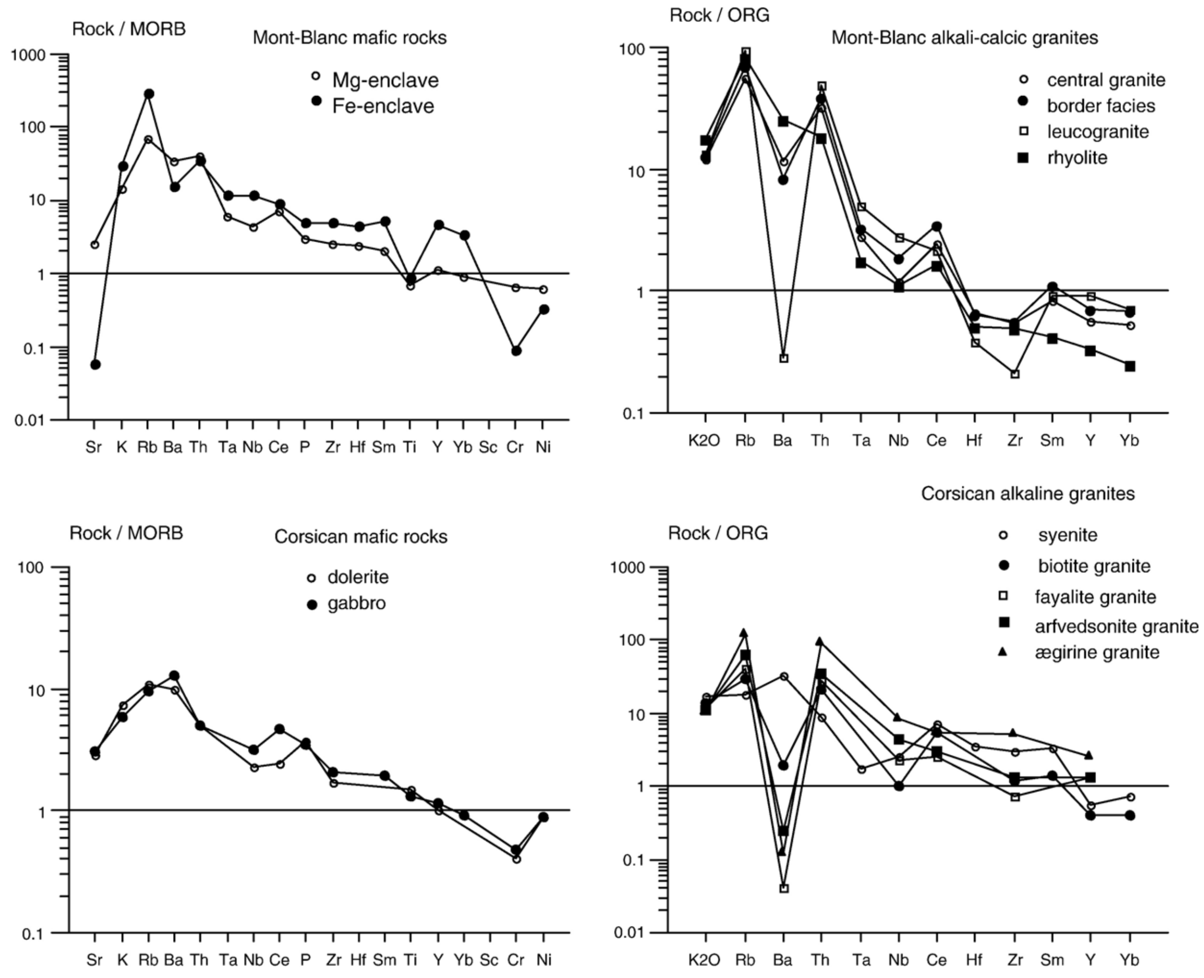

Fig. 1. Comparative chemical compositions of MORB-normalized (values from Pearce, 1983) mafic and ORG-normalized (values from Pearce et al., 1984) felsic rocks of Corsica and Mont-Blanc (after Bonin et al., 1998).

may give a statistical probability, not the proof that a natural process is identified (Le Maitre, 1982; Maaløe, 1985, pages 215–229).

3.4. A new classification scheme and the fate of A-type

About 20 different classification schemes have been set up over the past 30 years (review in Barbarin, 1990), but no genetic scheme has gained wide acceptance. The mineral composition of granite, i.e. quartz and feldspars, plus a small volume of mafic and accessory minerals, is apparently simple, but hides a real complexity issued from the number of processes that can generate granitic magmas. The last attempt to set up a granite classification is basically non-genetic and non-tectonic (Frost et al., 2001). It is merely a classification of igneous suites, incorporating the major chemical features relevant to granite mineralogy: silica, Fe* number [$FeO^T/(FeO^T+MgO)$], the modified alkali-lime index MALI (Na_2O+K_2O-CaO) and Alumina Saturation Index ASI. The straightforward use of the three parameters against silica leads to the definition of granite types, namely ferroan–magnesian, alkaline–alkali-calcic–calc-alkaline–calcic, and peraluminous–metaluminous–peralkaline.

The classification ignores deliberately the alphabet soup, but retains the term A-type to define a group of rocks comprising ferroan, alkaline to alkali-calcic, metaluminous, slightly peraluminous, and peralkaline varieties (Table 2), also designated as ferro-potassic, because of fairly high K contents and Fe/Mg ratios (e.g., Ferré et al., 1998; Vander Auwera, 2003). Scarce exceptions at high-silica contents result from large uncertainties in calculation of ratios of elements in low amounts. The classification has the merit to re-introduce a well-defined group of rocks that differ strikingly from the magnesian calcic to calc-alkaline suites and the peraluminous leucogranites. In this scheme, A- has

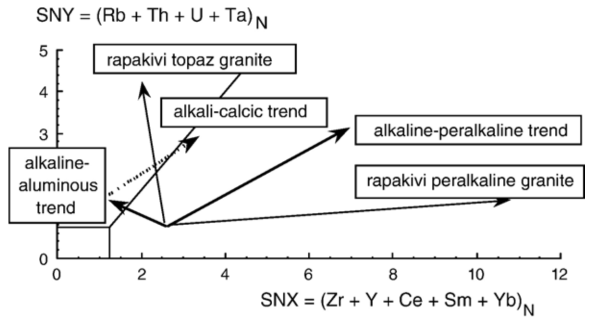

Fig. 2. Chemical compositions of different A-type suites plotted in the sliding-normalization diagram of Liégeois et al. (1998). The reference suite used for normalization is the alkali-calcic A-type Yenchichi–Telabit dyke swarm, Adrar des Iforas, Mali. Fields correspond to: syn-collision suites (lower left), potassic to ultrapotassic post-collision suites (upper left), and alkaline suites (right). Note that not all A-type suites plot in the alkaline field, especially the postorogenic aluminous ones, but, contrary to potassic to ultrapotassic post-collision suites, all A-type suites yield increasing SNY with differentiation (after Bonin et al., 1998).

not to mean anything, but its use is simple, compared with the correct appellation "ferroan, alkaline to alkali-calcic, metaluminous, slightly peraluminous, and peralkaline".

4. A summary of the history of research on A-type granites

A-type granite studies have a long history, 1979 constituting one of its great turning-points. During the long-lasting history of geology, A-type granite played a role during critical episodes. Some major advances in the development of ideas on magmatism and metamorphism come from field observations on high-silica A-type granites.

4.1. A-type granite before A-type granite, or from Hutton to Loiselle and Wones

To illustrate the role played in the past by A-type granite, some examples will be described. The first example, dating from the late 18th century, is dealing with the famous neptunian vs. plutonic granite controversy. In his studies of Scottish granites (Hutton, 1795, 1899), Hutton visited in 1786 and 1787 the Isle of Arran, in the off-shore of Glasgow (see Young, 2003, pages 64–68). Hutton observed in the northern part of the Isle a circular massif of granite, an Eocene A-type subsolvus granite (Dickin et al., 1981). At a short distance south of the granite, the central ring complex, a dominantly felsic volcano, rests upon sedimentary units (McKerrow and Atkins, 1985). In the west coast, the so-called Judd's dykes, after the geologist who first described them in detail (Judd, 1893), comprise dolerite selvages and cores of quartz porphyry and/or pitchstone. After having eagerly searched for, ultimately discovered, and carefully observed field relations of granite, felsic dykes, and rhyolite, Hutton (1794) claimed that he demonstrates definitively that these rocks came from below and are younger than the surrounding sedimentary strata and folded schists, a conclusion that was confirmed later on by isotopic age determinations.

In 1911, Goldschmidt published an influential paper on contact metamorphism in the Oslo (formerly Kristiania) Rift. A Paleozoic mixed sedimentary series has been invaded by Permian igneous plutons and capped by volcanic plateaus (for a review, see Oftedahl, 1978). The igneous suite (Barth, 1945; Neumann, 1978) ranges from alkali gabbro (Morogan and Sørensen, 1994) to monzonite (Neumann, 1980) to nepheline syenite, alkali feldspar syenite (nordmarkite) and A-type granite. Syenite and granite yield either peralkaline (ekerite), or aluminous compositions (Bonin and Sørensen, 2003, and references therein).

The 'plutonist' paradigm, issued from Hutton, faced the 'room problem'. In his classical study of Ascutney Mountain, Vermont, Daly (1903, pages 90–113) created the concept of 'magmatic stoping'. The igneous complex, a Cretaceous ring complex (Foland et al., 1971), comprises volcanic rocks, syenites and A-type granites of the White Mountain Magma Series. Daly envisaged the rising magma making way for itself by engulfing blocks of country rocks disrupted from the roof and walls of the magma chamber, since blocks of country rocks are not uncommon within the intrusives. Though Daly awarded credit for this theory to earlier workers, it is he who finally elaborated and developed it. The theory became rapidly one of the most widely accepted explanations for the emplacement of large igneous bodies and triggered the 'cauldron subsidence' concept (Clough et al., 1909). But, because of severe heat loss through the roof and walls of magma chambers, its efficacy appears now restricted to local piecemeal effects, even in the case of Ascutney Mountain (Chapman and Chapman, 1940, pages 203 and 208).

Field and experimental studies offer various solutions to emplace a volume of magma within solid country rocks. One simple and elegant solution is 'cauldron subsidence'. In their seminal paper on the district of Glen Coe, Argyllshire, Scotland, Clough et al. (1909) described for the first time a cauldron, in the sense of an eroded caldera with inverted relief, formed by subsidence having affected an area, roughly oval in shape, and delineated by a boundary fault. They considered (page 665) as probable "that the magma advanced upwards largely by the process known as stoping", acknowledging Daly's illuminating contribution. More recent investigations (Moore and Kokelaar, 1997) confirmed that subsidence did not occur through simple piston collapse, but was largely piecemeal and irregular, probably influenced by strike-slip movements c. 415 Ma ago along the nearby Great Glen Fault (Morris et al., 2005).

The concept of cauldron subsidence was applied successfully to a large number of igneous massifs comprising volcanic and plutonic formations. Richey (1928, 1932) was the first to interpret the volcanic and subvolcanic massifs of the British Tertiary Igneous Province (BTIP) as caldera-related ring complexes, while Anderson (1936) offered the first mathematical formalism to explain the shapes of cone sheets and ring dykes observed in the province. A-type rocks are associated with ultramafic rocks, alkali and tholeiitic basalts, and intermediate rocks (Richey et al., 1961). Though omitted in some reviews on A-type granite (e.g., Whalen et al., 1987; Eby, 1992), their chemical compositions (Pearce et al., 1984; Eby, 1990) yield A-type characteristics.

The first A-type ring complexes discovered outside Europe were the Cretaceous Ossipee Mountain (Kingsley, 1931) in the White Mountain Magma Series of New Hampshire (Billings, 1945) and the Jurassic Kudaru Hills (Bain, 1934) in the Younger Granites of Northern Nigeria (Jacobson et al., 1958). Both complexes were emplaced in old, respectively, Paleozoic and Precambrian, basements and comprise a suite of volcanic rocks, crosscut by syenite or porphyry ring dykes and, later on, by A-type granite cupolas. The White Mountain Magma Series share numerous features with the standard BTIP (Billings, 1945) and the Nigerian Younger Granites (Greenwood, 1951). These two provinces are the Phanerozoic examples of A-type granites referred to by Loiselle and Wones (1979).

An increasing number of alkaline ring complexes were discovered and interpreted as specific markers of continental anorogenic settings, i.e. as issued from magmatic events occurring within cratonizing terranes well after orogenic crises (e.g., Cox et al., 1965; Lasserre, 1966; Black et al., 1967). Volcanic–plutonic complexes represent the majority of A-type granite massifs, due to low rates of denudation within already eroded shields and ancient mountain belts. An important result was the discovery of the first non-Precambrian anorthosites related to alkaline ring complexes (Black, 1965), affording a supplementary evidence that mafic and felsic rock types can be linked and mantle-derived.

The recognition of Precambrian ring complexes constituted a further step, the Ahvenisto massif of South Finland being probably the first described (Buddington, 1959, page 685). Loiselle and Wones (1979) referred to two Precambrian provinces, the Gardar Province of Greenland (Wegmann, 1938) and the Pikes Peak batholith of Colorado (Barker et al., 1975), where ring structures are not so well preserved.

A major milestone in the study of alkaline granites, which were not yet named A-type, was the publication of "The Alkaline Rocks" by H. Sørensen (1974). In the more common igneous rocks, alkalis are associated with alumina and silica to form feldspar and mica, the molecular ratios (Na_2O+K_2O):Al_2O_3:SiO_2 being 1:1:6 in alkali feldspar and 1:3:6 in muscovite. Shand (1922, page 19) recommended that: "An alkaline rock … should be one on which the alkalis are in the excess of 1:1:6, either alumina or silica or both being deficient". In his review on alkaline oversaturated rocks, Bowden (1974) acknowledged that peralkaline granite and quartz syenite are commonly associated with metaluminous and slightly peraluminous varieties. Alkaline rocks were considered to be either volcanic, or subvolcanic, and to occupy mainly caldera-related ring complexes and associated dyke swarms. They were referred to as either silica-undersaturated (peralkaline and metaluminous, corresponding to agpaitic and miaskitic), or silica-oversaturated peralkaline, with but associated metaluminous and peraluminous varieties. High abundances of trace elements (with the exception of elements compatible with mafic minerals and feldspars) can lead to economic concentrations of Sn, W, Mo, Nb–Ta, REE and other 'high-tech' metals (e.g., Nigeria, where the Younger Granites were first described as 'tin fields'). Such elevated concentrations are thought to be acquired by extreme degrees of mineral fractionation from primary basalts (e.g., Chapman and Williams, 1935), or from intermediate magmas (e.g., Barth, 1945; Bonin and Lameyre, 1978) of mantle origin and to be enhanced by F-rich aqueous and/or carbonated fluids (Bowden, 1985).

Alkaline, or A-type, granite has long been considered to be synonymous of ring complex granite, which is not correct. Not all ring complexes contain A-type suites, as exemplified by the archetypal cauldron of Glencoe, zoned plutons in the Peninsular Ranges of Baja California (Duffield, 1968) and the Andean ring complexes of Peru (Bussell et al., 1976). Likewise, not all A-type granites were emplaced within subvolcanic ring complexes. Though this fact is no surprise, the recognition that A-type granites can occupy massifs emplaced deep within the crust constituted one of the major advances after 1979.

4.2. Evidence after 1979 for other kinds of A-type granites

Precambrian alkaline ring complexes occur, but less frequently than huge deeper-seated massifs. Examples include North America, which was the seat of discrete episodes of anorogenic magmatism, correlated to distal orogenic events but always under extensional regimes (Anderson and Bender, 1989; Windley, 1993; Anderson and Morrison, 2005, and references therein). Because of their exceptional distribution in Precambrian shields (Vander Auwera et al., 2003), Proterozoic cratonic granites were sometimes considered as basically different from Phanerozoic alkaline ring complex granites (Lameyre et al., 1974; Condie, 1992), which they yet resemble.

4.2.1. Re-appraisal of the rapakivi suite

Hjärne noted in 1694 that local people used to name a specific rock 'rapakivi', which literally means 'crumbly stone', because of its conspicuous pattern of weathering, and Tilas described in 1767 crystals that could be picked up in fields and gives them the name of "fältspat" — the first recorded use of the word 'feldspar' (quoted by Vaasjoki and Rämö, 1989). Sederholm (1891) defined the 'rapakivi texture' (review in Vorma, 1976, page 5). Using the characteristics featured by the Finnish rapakivi granites (e.g., Haapala, 1977; Rämö, 1991), Haapala and Rämö (1992) evidenced that the chemical and mineralogical peculiarities as well as the mode of occurrence and magmatic associations of the rapakivi granites meet the characteristics of subalkaline A-type granites and redefined rapakivi granites as "A-type granites characterized by the presence, at least in the larger batholiths, of granite varieties showing the rapakivi texture" (1992, page 165).

Not all rapakivi suites are Proterozoic in age (Haapala et al., 2005). Archean and Phanerozoic rapakivi granites occur, the oldest dated so far is Early Neoarchean, yielding c. 2785 Ma U–Pb zircon age (Moore et al., 1993) and the youngest is Tortonian, yielding a 9.8 Ma ^{40}Ar/^{39}Ar age (Calzia and Rämö, 2005). Two discrete, reduced and oxidized, suites were defined according to the conditions of crystallisation (see Frost and Frost, 1997; Anderson and Morrison, 2005, Dall'Agnol et al., 2005). Associated volcanic rocks are unevenly distributed and constitute bimodal suites of basalt flows and rhyolite ignimbrite sheets, typical of A-type volcanic formations. Calculated thermodynamic parameters correspond to depths varying from 20 km (magma chamber level) to about 4 km (emplacement level). The rapakivi association provides a unique record of the history of A-type magmas that moved within the brittle upper crust through fractures open up to the surface.

Actually, rapakivi granites differ from A-type ring complex granites only by feldspar texture evidencing disequilibrium and by less evolved compositions, as shown by lower silica contents. The classical wiborgite and pyterlite cannot represent liquid compositions. In the haplogranitic system, their normative compositions yield a high orthoclase component and plot either in the plagioclase field if anorthite is taken into account, or in the orthoclase field if fluorite and calcite are added to the system (Vorma, 1971, 1976). Contrasting explanations were offered, ranging from magmatic to subsolidus models (Cherry and Trembath, 1978; Hibbard, 1981; Eklund et al., 1993; Dempster et al., 1994; Salonsaari, 1995; Eklund and Shebanov, 1999). The possibility that ovoid alkali feldspar and the first generation of quartz could represent xenocrysts, not phenocrysts, has not yet been fully explored. Diabase dykes related to the Suomenniemi complex (Rämö, 1991) are crowded with quartz phenocrysts and K-feldspar megacrysts partly resorbed and mantled with thin plagioclase rims, thus mimicking rapakivi texture. Rapakivi texture can develop as the result of still plastic (hot) alkali feldspar± quartz cumulates disrupted intimately and incorporated into liquids of basic to acid compositions percolating though solidified magma chambers (Conceição et al., 1991). Supplementary evidence is offered by rounded felsic enclaves mantled by thin plagioclase rims, which are occasionally observed in wiborgite.

4.2.2. Layered igneous complexes

A-type granites occur frequently in association with mafic rocks. Mafic magmas can pond at certain depths within the crust and fill voluminous magma chambers, in which differentiation may yield small volumes of felsic residual liquid 'floating' above km-scale thick cumulates. Layered igneous complexes with associated A-type granites (Fitton and Upton, 1987; Cawthorn, 1996) are widespread in Precambrian shields but more recent massifs are known (Scottish and Irish centres of the BTIP, Richey et al., 1961; East Greenland, Nielsen, 1987). For example, the Skaergaard intrusion (McBirney, 1996) is crosscut by intermediate to silicic rocks. Transgressive granophyres (Hirschmann, 1992) and the granophyre zone of Basistoppen Sill (Naslund, 1989) fit the original definition and geochemical criteria of A-type granite.

The 2.05 Ga Bushveld Complex constitutes the most voluminous preserved igneous intrusion in the world, the estimated volume of magma could have exceeded 10^6 km^3 (Cawthorn and Walraven, 1998). The Lebowa Granite and Rashoop Granophyre suites form the largest known alkaline batholith (Kleeman and Twist, 1989; Wilson et al., 2000). The associated volcanic Rooiberg Group (Schweitzer et al., 1995) is a thick package including two felsic types interwoven with high-Ti basalt–high-Fe–Ti–P andesite and low-Ti basaltic andesite mafic suites (Hatton and Schweitzer, 1995). High-Mg felsites (dacite–rhyolite) plot within the VAG field (Twist and Harmer, 1987) and do not fit the requirements for A-type suites. Low-Mg felsites (trachydacite–rhyolite), similar in composition to the Lebowa Granite and Rashoop Granophyre suites, plot within WPG and A-type fields.

Similar features, at a different scale, are displayed by orthopyroxene-bearing complexes that contain A-type granites, such as the anorthosite–jotunite–mangerite–charnockite–granite association, collectively referred to as AMCG complexes (Emslie and Hunt, 1990; Emslie et al., 1994). The term granite in AMCG refers to rocks plotting in the granite field of the QAP diagram and devoid of orthopyroxene, whatever the feldspar textures could be. Coeval emplacement of AMCG complexes and rapakivi granites substantiates their close relationships in terms of petrogenesis (Emslie, 1978).

Anorthosite form either foliated diapir-like massifs, or cumulates down-sagging layers within large lopoliths, where the felsic suite is exposed. Giant orthopyroxene crystals with exsolved plagioclase lamellae substantiate that anorthosites did not consolidate at constant pressure. They began to crystallise at 1.5–1.2 GPa, i.e. 45–55 km depths, suggesting either a thickened crust, which is not postulated by the anorogenic character of the suite, or a crustal slab located within the sub-continental upper mantle (Duchesne et al., 1999). Then, plagioclase exsolved at 0.7 GPa, i.e. 25 km depth, within the lower crust, and final emplacement took place under mid-pressure granulitic regime at 0.4–0.3 GPa, i.e. 15–10 km depths (Duchesne et al., 1985).

The AMCG suite evidences an A-type liquid line of descent under reducing conditions (Wilmart et al., 1989). Amphibole-bearing and fayalite-bearing subtypes of charnockite represent late-stage residual liquids rooted into jotunite and mangerite intermediate magmas, respectively, and occur on top of the layered igneous complexes (Duchesne and Wilmart, 1997). Spectacular linear flow patterns within both the cumulates and the felsic rocks evidence that granitic material was down-dragged through sinking of its high-density mafic floor (Bolle et al., 2002). Downward gravity-driven flows of rocks within charnockite-bearing layered igneous complexes contrast with upward flows of buoyant massif anorthosites and can explain in part the chemical and structural complexity of the continental crust, a concept developed by Glazner (1994) and Glazner and Miller (1997).

4.2.3. The C-type–A-type granite connection

At the 2nd Hutton Symposium on Granites held in Australia in 1991, the Charnockite Magma Type was identified as a separate igneous association (C-type), distinct from S-, I-, M-, and A-type granites: "The C-type charnockite intrusions represent the products of very high-temperature crustal melting of "dry", but geochemically fertile, granulites occurring at temperatures well in excess to those needed for normal I- and S-type granites" (Kilpatrick and Ellis, 1992, pages 155–156). C-type magmas are rich in LILE and HFSE, suggesting that "a necessary prerequisite for charnockite formation is the earlier, subsolidus dehydration of hornblende to leave a fertile granulite which would then melt at much higher temperatures under fluid-absent conditions" (page 162). High-temperature metamorphism can originate through input of large volumes of basalt into stabilized granulitic lower crust. C-type granites differ from A-type granites by being issued from fertile, not residual, granulitic lower crust. This genetic definition is consistent with the general alphabet scheme.

C-type granites generally lack hornblende and their mineralogy resembles that of metamorphic charnockites, but includes magmatic inverted pigeonite, calcic alkali feldspar and potassic plagioclase, indicating temperatures constantly in the 950–1050 °C range. An important point supporting the idea of C-type magmas is the occurrence of volcanic equivalents, such as, e.g., the Jurassic Karoo and the Cretaceous Paraná–Etendeka provinces of Gondwana, with various basalt types, high-K dacite and trachydacite that are commonly but incorrectly referred to as quartz latite, and ` rhyolite.

As acknowledged by Kilpatrick and Ellis, C-type magmas have many geochemical features in common with A-type magmas. AMCG complexes comprise igneous rocks that are charnockites petrographically and A-type rocks geochemically. In Nigeria, the 590-Ma fayalite ferroaugite±ferrosilite quartz monzonite exposed at Bauchi was given the name of 'bauchite' (Oyawoye, 1972, and references therein). It occurs in association with norite and hornblende biotite granite. The plutonic suite was classified as ferro-potassic, A-type, post-collisional (Ferré et al., 1998).

The issue of C-type–A-type connection was addressed in Finland. Paleoproterozoic 1.88–1.87 Ga post-kinematic granites are subdivided into discrete types (Nironen et al., 2000), including A-type granites akin to the younger rapakivi granites of southern Finland and C-type plutons, which contain pyroxene either throughout, or in marginal facies, and are alkaline in composition. C-type and A-type post-kinematic plutons as well as A-type rapakivi massifs yield intensive thermodynamic parameters (P, T, fO_2) of the same order of magnitude (Elliott et al., 1998), illustrating a similar history in terms of magma storage, differentiation, ascent, and emplacement. In the field, C-type plutons appear as saucer-shaped intrusions, displaying flat inward-dipping magmatic foliations and filled up with layered cumulates of laminated olivine mangerite–amphibole biotite monzogranite–biotite syenogranite, from which A-type residual liquids escaped as late-stage aplite dykes. Compared with A-type magmas, C-type rocks (Elliott, 2003) yield higher contents of Zr and HFSE, Ba and Sr, with no to weak Eu negative anomalies. Zircon and feldspar accumulation features suggest that C-type rocks represent a solid, not liquid, line of descent and that no C-type magmas can be defined.

Similar cumulative plutons are known elsewhere, such as, e.g., the 2.1 Ga Itiúba syenite complex, Bahia State (Brazil), emplaced into a strike-slip shear zone within a granulitic terrane (Conceição et al., 1991). The complex is composed of cumulus Ba–Sr-rich alkali feldspar, hedenbergite, apatite, and zircon, moulded by inter-cumulus amphibole, biotite, and quartz (Conceição et al., 1991). Though chemically similar, it cannot enter the C-type group, as no orthopyroxene was observed, indicating pressures lower than the ferrosilite — (fayalite+quartz) transition curve.

Charnockites are commonly associated with more hydrous granitoids, so that C-type was never in common usage. In addition, many charnockites have not C-type compositions and belong to other lineages. For example, the Ansignan pluton, Agly massif, Pyrénées (Guitard, 1960) comprise coeval 314±7 Ma charnockite and norite, which induced the development of a leucocratic garnet muscovite biotite granite fringe derived from the partial melting of country rocks at 800 °C and about 0.6 GPa, i.e. 20–25 km depths (Andrieux, 1982). The Ansignan charnockite–norite association differs from C-type rocks by lower TiO_2 and HFSE (Nb, Zr, Y) contents, shares many geochemical features with high-K calc-alkaline granitoids and, accordingly, plots within the VAG field. To conclude, there is no need of a specific letter, C-type, for a charnockite type.

5. Geodynamic settings

The apparent and perplexing variety of A-type granites result mostly from the large range of geodynamic contexts in which they are emplaced. A-type granites are exposed on Earth's continents and ocean floors as well as on terrestrial planets and asteroids.

5.1. Continents

A-type granite complexes occur in all continental areas, whether they are stable old cratons and shields, or constitute newly consolidated fold belts (Table 3). How old is the oldest A-type granite? Alkaline complexes are known in Archean terranes, e.g., Superior Province, Canada (Sutcliffe et al., 1990; Ayer, 1998), and Yilgarn Craton, Australia (Smithies and Champion, 1999), but no age older than 2.8 Ga, corresponding to the Mesoarchean–Neoarchean boundary, is recorded so far.

Neoarchean silica-oversaturated alkaline igneous suites of monzonite–syenite–peralkaline granite share features with A-type granites, including high total alkalis, anhydrous mafic liquidus assemblage, apparent anorogenic settings, and high abundance of some HFSE, e.g. LREE and Zr. But they are potassic to ultrapotassic, have fairly low LILE compositions, except Ba and Sr, yield low to very low Y and Nb contents, and display no Eu anomalies, all characteristics akin to Phanerozoic potassic to ultrapotassic igneous provinces (Peccerillo, 1992; Liégeois et al., 1998). Whether potassic–ultrapotassic alkaline igneous suites are related to coeval subduction processes, or not, is a matter of debate (see Lavecchia and Stoppa, 1996; Peccerillo and Donati, 2003; Bonin, 2004). Anyway, they differ from the classical A-type sodic igneous suites.

More usual A-type associations were emplaced at the same period of time. In Botswana, southern Africa, the Gaborone granite suite and the associated Kanye volcanic formation (Sibiya, 1988) constitute a rapakivi association, which yields U–Pb zircon ages ranging from 2785 to 2783±2 Ma (Moore et al., 1993). In the Carajás Mineral Province, located southeast of the Amazonian craton (Pará, Brazil), the oldest complexes, emplaced at mid-crustal 7–11 km depths within 3.0 Ga greenstone belts, are the 2763±7 Ma Estrela massif (Barros et al., 2001) and the 2743±1.6 Ma Serra do Rabo stocks (Sardinha et al., 2006). In Kola Peninsula, HFSE-rich sodic alkaline syenite and granite yield U–Pb zircon ages of 2682±10 Ma and 2654±5 Ma, respectively (Zozulya et al., 2005). They represent the earliest examples of A-type within-plate igneous episodes involving a mantle source with OIB-like characteristics.

A-type granite compositions are influenced by the geodynamic context, merely the nature and history of subcontinental lithosphere mantle (SCLM) and overlying continental crust, from and through which A-type magmas originate and move. Pearce et al. (1984) noted, in Nb–Y and Ta–Yb log–log diagrams, that WPG constitute a well-defined group relative to VAG and SYNCOLG but that discrimination between WPG and ORG is marred by an overlap zone in the WPG field. The upper boundary of the overlap zone is marked, for increasing Nb, Y, Ta, and Yb contents, by Y/Nb ratios ranging from 1 to 2.5 and Yb/Ta ratios from 1.5 to 5. Eby (1990, 1992) suggested a twofold subdivision (Table 2) and A1–A2 discrimination diagrams should be used ONLY for granitoids plotting BOTH in WPG and A-type fields, a fact frequently ignored in the recent literature. The data set used by Eby does not evidence two discrete groups, but illustrate a continuous shift from post-collision A2 to postorogenic, straddling the A1–A2 boundary, to within-plate A1 suites. Though useful in a preliminary stage, geochemical diagrams should be carefully tested in the case of geologically unambiguous cases. In Corsica, Bonin (1988) noted that Ga/Al ratios measure rather alkalinity, peralkaline rocks yielding higher Ga/Al than metaluminous ones. Comparing mineral and chemical data from Corsica and Adrar des Iforas, Bonin (1990) suggested to subdivide alkaline granites that were emplaced a short time after the end of an orogenic episode into postorogenic PO and early anorogenic EA subtypes, based on more magnesian mafic silicate mineralogy and higher Ba and Sr contents in PO than in EA suites. PO suites (Bonin et al., 1998) plot generally within the A2 field but EA suites straddle the A1–A2 boundary, with aluminous types still in the A2 field (Martin et al., 1994; Hong et al., 1996). Eby (1992) noted exceptions, such as anorogenic rapakivi granites, plotting within A2, not A1 field.

In continental areas, A-type silicic rocks shows a secular evolution lasting hundreds of My from subsolvus to hypersolvus granite to nepheline syenite, or from rhyolite to trachyte to phonolite (Black et al., 1985). Water seems to play a major role (Bonin et al., 1987; Bonin, 1990). Postorogenic suites, characterized by pink to red rocks, are controlled by weak alkali feldspar fractionation, early Fe–Ti oxide precipitation, and crystallisation of Mg- and Mn-rich mafic silicates. Dominated by two-feldspar subsolvus granites, they reflect fairly high water pressure and late-stage oxidizing conditions, due to water saturation in evolved magmas, subsequent aqueous fluid exsolution, and thermal breakdown of H_2O. Early anorogenic suites, characterized by green to brown rocks, are controlled by massive feldspar fractionation, delayed Fe–Ti oxide precipitation and crystallisation of Fe–Mn-rich mafic silicates. Dominated by one-feldspar hypersolvus granites and associated syenites, they reflect more reducing conditions and lower water pressure (Bonin and Giret, 1985). The two types of suites take place in a newly consolidated crust a few My only after a major orogenic event. Anorogenic silica-oversaturated suites illustrate stabilizing cratonization process marked by continental lithosphere thickening. They are controlled by the same factors implying water-deficient regimes, but still permitting amphibole fractionation. Anorogenic silica-undersaturated suites predominate after a period of time of about 500 My after the last orogenic event. Water-poor magmas can no longer sustain amphibole fractionation and alkaline residual liquids become increasingly silica-undersaturated to yield phonolite–nepheline syenite compositions. Aqueous fluids are mixed with and replaced progressively by CO_2, responsible for late-stage carbonate alteration and generation of carbonatite magmas.

Ages of emplacement of within-plate alkaline suites are not random, but correspond to global events. This is not a new idea: Backlund in 1932 (cited by Sørensen, 1974, page 146) emphasized that emplacement in stable regions of alkaline magmas is simultaneous with orogenic processes occurring elsewhere and created the word “epirodiastresis” for the mode of emplacement by perforation of stable continental areas, a term lost in the geological literature. Synchronism of spatially separated alkaline igneous activity and orogenic events was substantiated for the ‘Caledonian’ and ‘Hercynian’ intrusions of Kola Peninsula, the Devonian, Carboniferous, and Jurassic Younger Granites of West Africa (Black and Liégeois, 1993) and the Mesoproterozoic rapakivi associations of the Baltic Shield (Åhäll et al., 2000). It applies to every short-lived alkaline igneous provinces on Earth (Black et al., 1985).

5.2. Oceans

The granite problem is often viewed as a case of continental recycling. The genetic alphabet classification constitutes a perfect illustration of this conception. However, granites were known since a long time within oceanic islands, e.g., Iceland and Kerguelen Archipelago (Table 3). More recently, they were observed in fracture zones within oceanic ridges. A-type granites were originally defined for continental areas, but most, if not all, granitic rocks emplaced within oceanic contexts share A-type characteristics and are associated with alkaline, transitional, or tholeiitic mafic rocks (e.g., Giret, 1990).

The Kerguelen archipelago (Fig. 3) constitutes the third largest oceanic island, after Iceland and Hawaii. Coarse-grained intrusive rocks represent a significant proportion of the archipelago, currently covering an area of about 8% of the land, whereas fine-grained intrusive rocks correspond to about 7% and volcanic, dominantly basaltic, units occupy 85%. Caldera-related ring complexes and stocks (Giret, 1983; Bonin et al., 2004, and references therein) are composed of (monzo) gabbro and syenite, with minor granite or nepheline syenite. Caldera volcanoes display bimodal associations of trachybasalt to trachyandesite and trachyte to rhyolite or phonolite. Alkaline mafic rocks occur as lava flows, cone sheets, and cumulate massifs, intermediate rocks are scarce (Bonin and Giret, 1990). Felsic rocks occur as pumiceous ignimbrite units, ring dykes, and stocks. All syenite (trachyte) and granite (rhyolite) compositions (Giret, 1983; Gagnevin et al., 2003) plot within WPG, A-type and A1-subtype fields.

In Iceland, there is a high proportion of silicic rocks that are confined to central volcanoes. The volume exposed amounts to between 3 and 15% and two groups are identified (Jónasson et al., 1992). The first group is widespread throughout the island. Central volcanoes (e.g., Thingmuli) and intrusive complexes (e.g., Austurhorn) display tholeiitic or transitional basalt lavas and dykes, intermediate icelandite lavas, granodiorite–granite stocks and dykes, dacite–rhyolite pumiceous ignimbrites and domes, and layered gabbro intrusions. Anhydrous phase assemblages and high-Fe contents of silicic rocks indicate generation in a shallow magma chamber. Comparable ranges in incompatible trace element ratios suggest derivation from common parent magmas and the fractionating assemblage is consistent with the observed mineralogy of the cumulative layered gabbro (Furman et al., 1992). Though exposed near a diverging plate boundary, the silicic rocks fit all requirements for A-type granite, e.g., major element and Ga/Al ratios, (Zr+Ce+Y+Nb) contents, etc., and plot within WPG, not ORG, field. Surprisingly, fairly high Y/Nb ratios indicate the post-collision A2, not the rift-related A1, subtype.

The second group, restricted to the Króksfjördur central volcano, NW Iceland (Jónasson et al., 1992), is more intriguing. It is composed of Mg# ≈50, calc-alkaline dacites, which are Ca- and Al-rich and slightly peraluminous ($1.0<\mathrm{ASI}<1.1$), significantly poor in HFSE and, though unrelated to subduction, plot in the VAG field. Some samples contain hydrous phases (biotite and amphibole) or their relics. Xenoliths of cumulate gabbro and hornfelses suggest that calc-alkaline dacites originated from dehydration melting reaction of amphibolite–facies basic rocks at a depth of about 5 km within the crust. Jónasson et al. (1992) observed that it is remarkable that rocks similar to calc-alkaline dacites are not found elsewhere in Iceland, nor are there other rocks with trace element signatures resembling these, and concluded that mafic crustal rocks in Iceland do not melt easily to yield anatectic magmas.

The plagiogranite clan, issued from protracted fractional crystallisation of MORB-type magma and/or low-pressure liquid–liquid immiscibility (Dixon Spulber and Rutherford, 1983), shares also many features with A-type granites, the major differences being that it occurs within oceanic basins, not continents and that it has with low to very low K and Rb contents and specific LREE-depleted patterns. It constitutes the ORG group of Pearce et al. (1984). The cause of K, Rb, and Ba depletion may in part be due to removal of these elements by hydrothermal leaching. The occurrence in the Faeroe–Shetland Basin of a sill complex of intrusions containing plagiogranite within tholeiitic olivine dolerite provides direct evidence that extreme differentiation can produce a low-K ORG granitic residual liquid, with 0.09 wt.% K_2O and 2 ppm Rb (Kanaris-Sotiriou and Gibb, 1989). But K-rich granite is also found in oceanic ridge systems. One of the first described occurrences is the “quartz monzonite”, actually a 3.3 wt.% K_2O biotite hornblende granodiorite, filling up a 1 cm-wide dykelet crosscutting a granophyric diabase (Engel and Fisher, 1975). Contrasting chemistries indicate WPG and A-type affinities to granodiorite and ORG type to granophyric diabase and related K-poor (down to 0.07 wt.% K_2O) trondhjemite aplite. All rock types yield identical Sr isotopic initial ratio of 0.7034, illustrating that cogenetic K-rich and K-poor differentiates can be produced from MORB-type magmas. In old metamorphosed and deformed formations, the probability that K-rich oceanic granitoids with fairly high LILE and HFSE contents could be mistaken as WPG and A-type continental rocks, leading to erroneous palinspatic reconstructions, should be taken into account.

5.3. Terrestrial planets

The terrestrial planets and the asteroid belt (Table 3) display the same internal structure as the Earth and granitic magmas have been produced (Bonin et al., 2002; Bonin and Bébien, 2005).

On Moon, 4.4–3.9 Ga granite clasts display a pristine [quartz+Or80-95 alkali feldspar+An85-65 plagioclase+fayalite+pyroxenes+ilmenite+accessory minerals+troilite+Fe–Ni metal] assemblage, indicating fayalite–iron–quartz (FIQ) buffering conditions (Warren et al., 1983). Large K/Ca enrichment coupled with low REE abundances in granite relative to KREEP parental magmas are consistent with silicate liquid–liquid immiscibility, a process also observed in melt inclusions within olivine of lunar basalts. Despite incomplete chemical data (Y and Nb are lacking, but Yb and Ta have

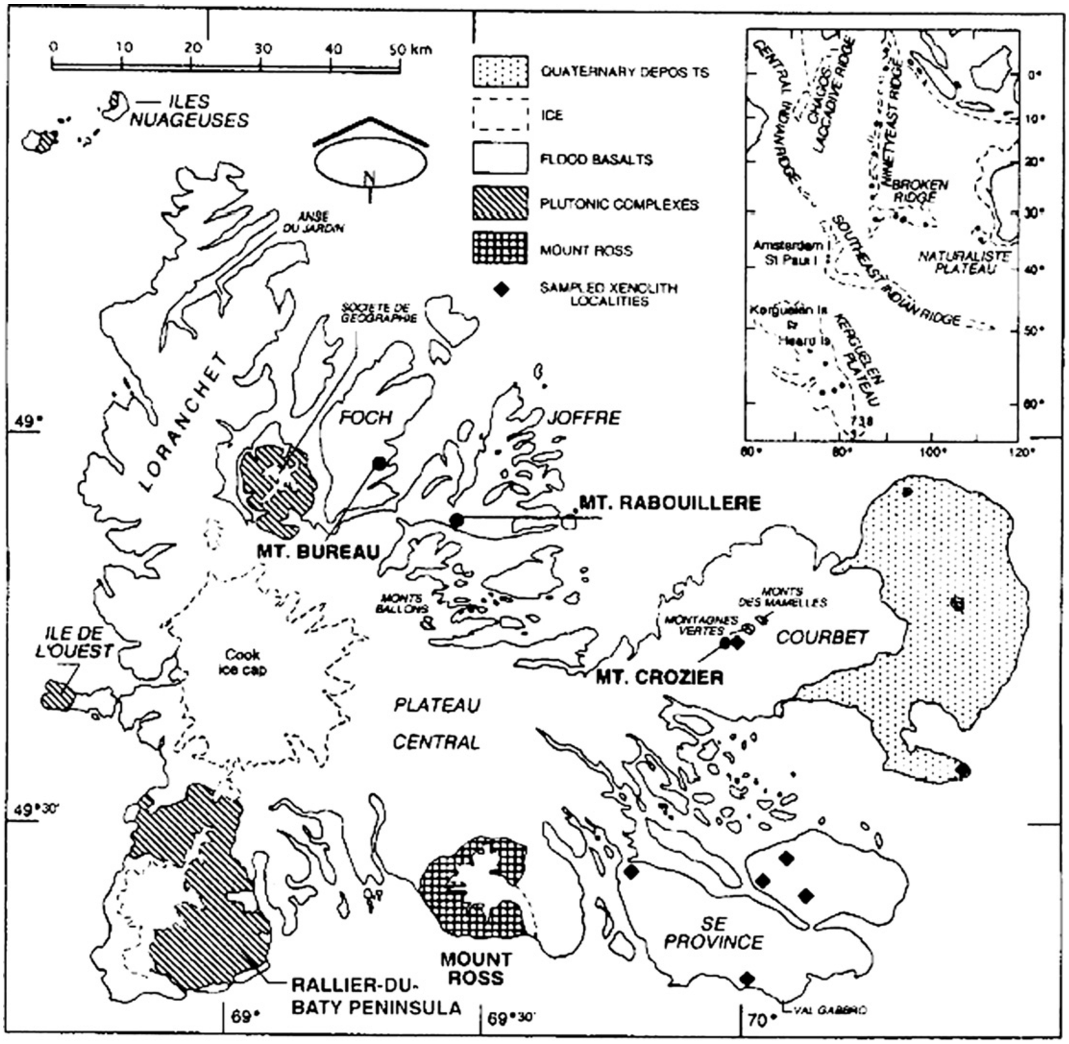

Fig. 3. Map of the Kerguelen Archipelago, showing the location of the Rallier-du-Baty Peninsula and the major features of the main island (after Gagnevin et al., 2003, Bonin et al., 2004). Diamonds: localities where lower crust xenoliths were sampled; dots: localities where stratigraphic sections of flood basalts were extensively sampled. Inset: position of the Kerguelen Archipelago within the Indian Ocean; dots: drilling and dredging sites.

been analysed), the samples yield striking affinities to WPG and A-type high-silica granites (Fig. 4), with the exception of very low Na_2O contents, resulting in an exotic feldspar association.

On Mars, the evidence is more tenuous, as no trace element contents within silicic rocks are available. SNC meteorites are either picritic to basaltic magmas, or mafic cumulates. Field evidence for felsic igneous rocks comes from analysis in the Pathfinder site of a sulphur-free rock of andesite–dacite composition (McSween et al., 1999) and from thermal emission imaging system (THEMIS) and spectrometry (TES), suggesting the occurrence of plagioclase, alkali feldspar, and quartz (Bandfield et al., 2004). Gravity evidence shows that extinct magma chambers and plumbing systems underlie shield volcanoes, like on Earth (Kiefer, 2004). The nature, igneous vs. sedimentary, of high-silica rocks is a matter of discussion (McLennan, 2003), as recent observations substantiate that siliceous sedimentary formations, bearing clay minerals and possibly opal-like silica, have been deposited on Mars during ancient periods of time (Michalski et al., 2005). The strongest, but indirect, evidence for felsic igneous rocks on Mars comes from melt inclusions in SNC meteorites (for a review, see Bonin and Bébien, 2005) and from experimental studies. Crystallisation paths were conducted in glass representing the parent magma of Chassigny (Minitti and Rutherford, 2000) and in

Shergotty meteorite (Dann et al., 2001). In both cases, hydrous (~1.5–1.8 wt.% H_2O) conditions at 20 to 200 MPa and QFM buffer yield a liquid line of descent toward, after 60% crystallisation, andesite–dacite compositions close to the Pathfinder sulphur-free rock, i.e. 62–66 wt.% SiO_2 and 0.4–1.6 wt.% K_2O contents. These liquid compositions yield the low alumina contents and high Fe/Mg ratios postulated for A-type granite, but K/Na ratios and K_2O contents are too low and no trace element contents are available. Whether A-type granite can occur on Mars (Nekvasil, written communication, 2005) remains an open question.

In addition to lunar granite samples and to melt inclusions within SNC Martian meteorites, meteorites scavenged from the asteroid belt, such as different types of chondrites, IIE irons, and the howardite–eucrite–diogenite (HED) suite, contain coarse-grained quartz feldspar assemblages (Bonin et al., 2002) and high-silica melt inclusions (Bonin and Bébien, 2005). Venus evidence is more ambiguous. The specific “pancake” domes were interpreted as either implying silicic composition (Fink et al., 1993), or representing flat-topped basaltic cones emplaced under high pressure (Clague et al., 2000).

A-type granites could be not typical of Earth. They may be the dominant silicic rock type on other planets, even though it is a relatively modest proportion of granitoids on Earth. Though produced in tiny volumes relative to the total volume of all magma types in terrestrial planets, they were generated in environments that differed markedly from those prevailing currently on Earth. Such occurrences afford strong evidence that, contrary to the conventional wisdom, the association of liquid water, continental crust and plate tectonics does not constitute a prerequisite for generation of A-type granitic liquids. From lunar evidence, it is tempting to suggest that the first granites produced on Earth could have been A-type granites that would have been ultimately subducted out of the geologic record. Further re-examinations of the element and isotope compositions of >4.3 Ga zircons could provide supplementary arguments.

6. Structural levels in A-type magmatism

6.1. Geological facts

To understand why and how A-type granites differ apparently by their petrography and chemical compositions, it is time to go back to the field. Many petrogenetic models rely on partial melting of crustal rocks, mantle-derived magmas playing only the role of heat source. Natural tests are offered by crustal xenoliths carried by volcanic lavas and pyroclastites. They display quenched glasses issued from incongruent melting of

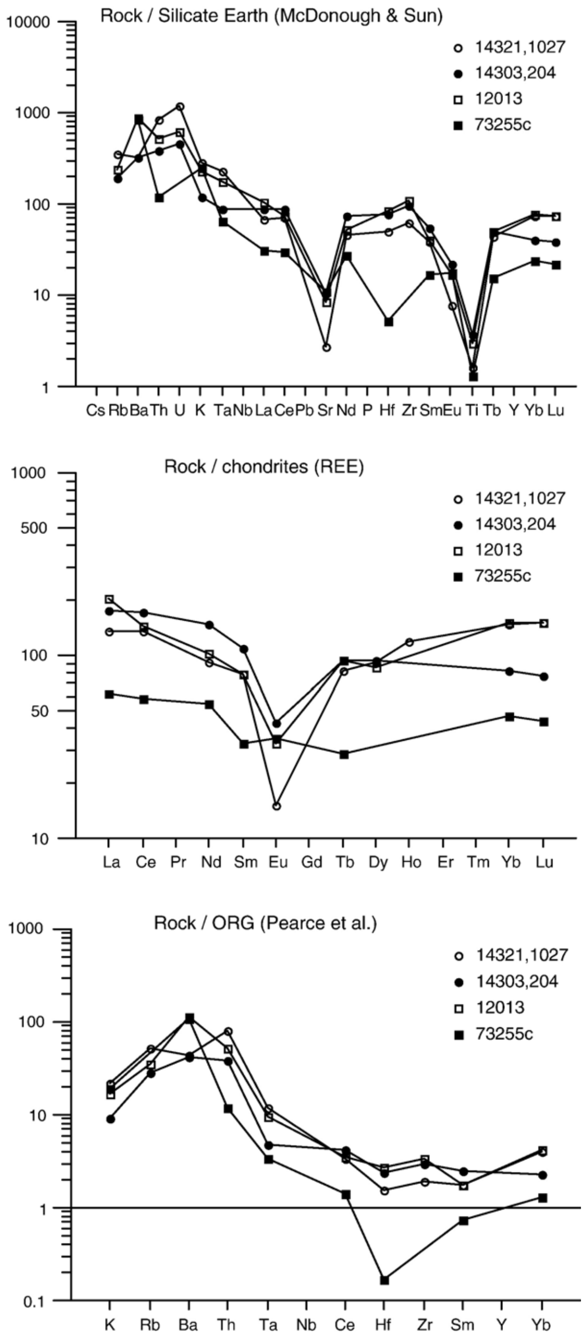

Fig. 4. Chemical compositions of Lunar granite clasts (Warren et al., 1983) plotted in multi-element diagrams: A. Bulk silicate earth normalized spidergrams (normalizing values from McDonough and Sun, 1995). B. Chondrite-normalized REE patterns (normalizing values from McDonough and Sun, 1995). C. Oceanic ridge granite (ORG)-normalized spidergrams (normalized values from Pearce et al., 1984).

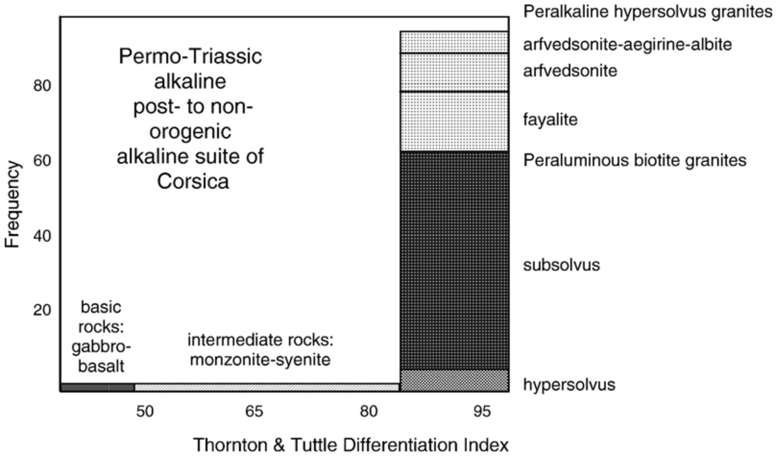

Fig. 5. Histogram showing the distribution of rock types as a function of DI for the Permian–Triassic alkaline province of Corsica. Low-DI basic rocks (2%) are gabbro-norite–anorthosite association and rare basalt–hawaiite lava flows and dykes. Intermediate rocks (2%) range from monzodiorite to monzonite to syenite. High-DI silicic rocks are alkali feldspar granites defining two evolutionary trends: the peralkaline suite (32%) comprises hypersolvus metaluminous fayalite-bearing–peralkaline arfvedsonite–strongly peralkaline aegirine arfvedsonite granites, the more voluminous peraluminous suite (64%) is made up of hypersolvus transsolvus subsolvus biotite granites (from Bonin et al., 1994).

hydrous rock-forming minerals. Glass compositions are always high K/Na, strongly peraluminous and high-silica, i.e. akin to S-type leucogranite, even in the case of partially melted peralkaline A-type quartz-bearing syenite (Harris and Bell, 1982). Partially melted fenitized granite gneiss xenoliths (Morogan and Martin, 1985) yield glasses that have not A-type granite compositions.

No migmatitic terranes have shown any leucosomes of A-type mineralogy and chemistry, implying that A-type magmas cannot be simply derived from crustal sources. Experimental studies at pressures corresponding to crustal depths were performed on various types of rocks, including A-type rocks (Beard et al., 1994). They invariably failed to produce A-type liquids, contrary to what is claimed sometimes (for a review, see Bonin, 1996, pages 204–206, and references therein). Metaluminous liquids coexisting with noritic residues were produced from tonalite and granodiorite by incongruent melting of hornblende and biotite at 950 °C and 0.4 GPa (Patiño Douce, 1997, 1999), but their high-silica compositions are too calcic and yield too high K/Na ratios to match A-type granite compositions. The possibility to heat a large volume of crustal rocks during an adequate time to yield a homogeneous temperature of about 950 °C at a depth of less than 15 km, i.e. under thermal gradients higher than 65 °C-km^{-1}, appears physically untenable, especially in within-plate stable environments, in which Moho temperatures are not expected to exceed 600 °C (Black and Liégeois, 1993). Numerical simulations of repeated episodes of underplating and/or sill intrusions (Petford and Gallagher, 2001; Annen and Sparks, 2002) reveal that mafic magmas, even with a total thickness of up to 8 km, cannot supply enough heat to melt a fertile crust at depths of less than 17 km.

On the contrary, cumulates and related liquid lines of descent are substantiated in caldera-related ring complexes (e.g., Chapman and Williams, 1935; Bonin et al., 1994; Gagnevin et al., 2003), rapakivi batholiths (Rämö and Haapala, 1995) and AMCG suites (Duchesne and Wilmart, 1997). Bimodal distribution of alkaline rocks was noticed by Bunsen (1851), but is known as the ‘Daly gap’, because Daly identified it in his 1925 study of Ascension Island (Clague, 1978). The Daly gap, a normal consequence of magmatic differentiation, corresponds to vanished parental magmas (Bonin and Giret, 1990). Bimodal mafic–felsic as well as nearly unimodal felsic-dominated suites (Bonin et al., 1994) can be interpreted as evidence for cogenetic associations (Fig. 5).

6.2. Chemical–physical roles played by the crust and the upper mantle

A-type granites are famous for their high isotopic variability, from standard depleted mantle compositions to values mimicking upper crustal signatures (Table 2). Lacks of correlation with element variability suggest that various sources contributed to generation of A-type magmas. Mafic rocks deviate frequently from isotopic compositions of the depleted mantle reservoir and

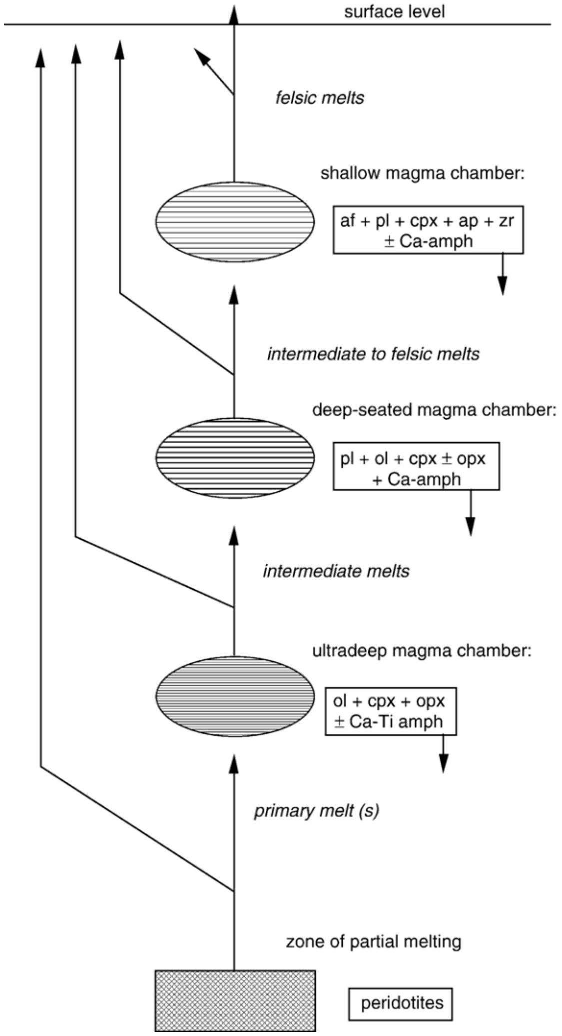

Fig. 6. Fractional crystallisation processes within a network of magma chambers emplaced at various depths. Primary magmas originate from partial melting of upper mantle and evolve ultimately into felsic residual liquids. At each level, the average fractionating mineral assemblage, which precipitates as cumulates, is specified (from Bonin et al., 1994).

indicate enriched mantle sources. Associated quartz-bearing felsic rocks can produce a more 'crustal' signature, implying a supplementary process of crustal assimilation–contamination (e.g., Foland et al., 1993; Jung et al., 2005), with frequent cases of non-altered peralkaline types showing a depleted mantle-like ancestry and metaluminous to peraluminous rocks containing a supplementary older crustal component (e.g., Poitrasson et al., 1995; Kemp et al., 2005b).

To identify crustal sources within the Earth is unexpectedly a difficult issue to address. The fundamental question is not so much *what* they are, but *where* they are, a problem connected to the nature of enriched OIB sources (Weaver, 1991; Niu and O'Hara, 2003). Coesite-bearing metagranitoids (Compagnoni and Rolfo, 1999) and diamondiferous quartz-rich rocks (Massonne, 2003) illustrate that continental crust can experience upper mantle conditions, at least since the Neoproterozoic (Chopin, 2003). Indirect evidence can be found in the Tuscan lamproites that yield trace element abundances and ratios, and isotopic signatures revealing involvement of a continental upper crust having the composition of the coesite-bearing A-type metagranites of Dora Maira (Poli and Peccerillo, 2003). Helmstaedt and Schulze (1989) elaborated that lithosphere cratonic keels are produced by the stacking of buoyant depleted peridotite mantle and dense subducted eclogite crustal slices, as evidenced by xenoliths and by mineral inclusions within diamond (Shirey et al., 2004; Tappert et al., 2005). The possibility that continental crust can participate to the generation of A-type parental magmas within the upper mantle, and not above, should be explored. Experimental studies at 1.0–1.3 GPa on parental magmas of massif anorthosites favour an origin by melting of gabbronorite, not by fractionation of mantle-derived magmas (Longhi et al., 1999). Duchesne et al. (1999) inferred that AMCG magmas could come from mafic crustal 'tongues' subducted at 40–50 km depths, heated and partially melted by lithospheric delamination and asthenospheric uprise.

The corollary of these observations is that isotopic and element crustal signatures do not show unequivocally that A-type suites have their sources within the crust they intrude ultimately. There is no doubt that A-type granite magmas move up and pass through the crust. Their levels of emplacement, from the mantle-crust boundary to the surface (Fig. 6), are controlled mainly by the mechanical discontinuities within solid rocks, favouring propagation of buoyant magmas, and by wall rock density and strength, tending to arrest them (Fig. 7). Then, crust operates as a density filter for migrating magmas (Bonin, 1996).

The deepest levels of emplacement (Fig. 8), at the base of and within the lower crust, are occupied by massif anorthosite complexes, layered mafic cumulate lopoliths and jotunite–mangerite–charnockite–granite intrusions (Duchesne and Wilmart, 1997; Elliott et al., 1998). Buoyant anorthosite crystal mushes were emplaced forcefully up to depths of 15–11 km under 0.4–0.3 GPa pressures (Duchesne et al., 1985). Layered lopoliths display igneous foliations and lineations indicating negative buoyancy and late-stage foundering of the intrusions (Glazner, 1994; Bolle et al., 2002).

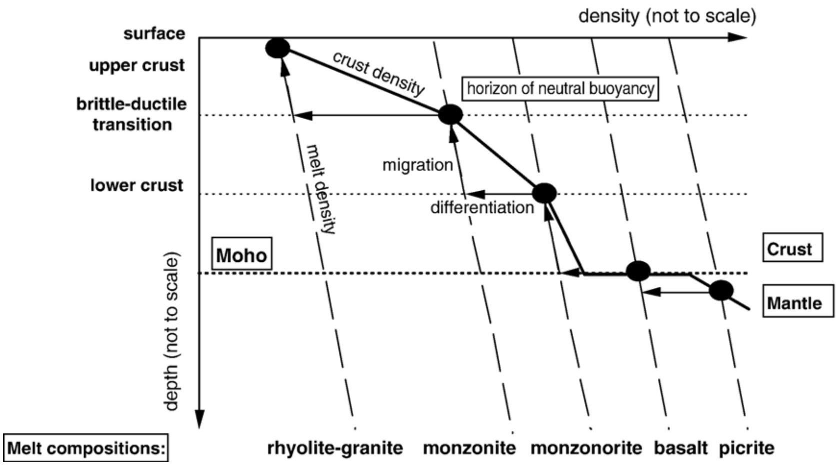

Fig. 7. Density versus depths within upper mantle and crust. Each liquid of a specific composition is capable to migrate upwards to its horizon of neutral buoyancy, where it is stored within a magma chamber and differentiates into less dense and more evolved residual liquids. Residual liquids can in turn migrate upwards to their own horizons of neutral buoyancy and/or to a depth where wall rocks are strong enough to stop their upward movement. Magmas can erupt only in the case of extension-driven decompression and displacement along widening conduits open well below their horizons of neutral buoyancy (after Bonin, 1996).

The rapakivi granite suite form intrusions located preferentially at the quartz-related ductile–brittle transition zone in the mid-crust (Fig. 8) and/or along structural discontinuities, such as basement-sedimentary cover unconformities, competent layers in volcanic–sedimentary basins, etc. Repetitive injections and lateral spreading of intermediate to felsic magmas filled up large, thick batholiths (Haapala et al., 2005), because sharply increasing strengths of roof rocks prevent buoyant magmas to continue to move up. Ultimate fracturation in the upper crust would favour transport through dykes and sills, which were filled up with bimodal mafic–felsic magmas. Caldera-related ring complexes (Fig. 8), emplaced at shallow depths, contain syenites and high-silica granites corresponding to low-pressure thermal minimum residual liquids (Bonin, 1986). A comparatively small volume of mafic and felsic buoyant magmas can reach the surface and build up shield volcanoes, where explosive eruptions of felsic magmas generated caldera structures (Fig. 8), filled up with pumiceous ignimbrites and related formations (Gagnevin et al., 2003; Bonin et al., 2004).

A-type granites are derived from a liquid line of descent from variously contaminated mantle-derived mafic magmas. Petrological, mineralogical, and chemical differences in discrete A-type granite provinces are controlled by (i) varying amounts of cumulates vs. liquids in the rocks, (ii) the intensity of intrinsic thermodynamic parameters governing emplacement, crystallisation, and cooling of plutonic to volcanic magmas, and (iii) characteristics of crustal wall rocks (Fig. 8).

7. Summary and conclusion: future avenues to explore

Though formally defined as A-type in 1979 only, a distinctive group of granitoids has long been recognized by different lines of supporting evidence: it is largely exposed within cratonizing areas, ages of emplacement are apparently unrelated to major orogenic events in the vicinity, Fe-rich mafic mineralogy is produced predominantly under reducing conditions, and whole-rock chemistries are marked by high alkali, LILE, and HFSE contents, high Fe/Mg ratios, and OIB-type compositions. A-type granites characterize Earth's within-plate areas, where crustal blocks are stabilized enough to move as a single plate, but were emplaced during a period of time when lithosphere does not yet, or no longer, contain the thick mantle root, or keel, typical of cratonic areas. A fact probably not expected by Loiselle and Wones is that A-type granites occur in terrestrial planets other than Earth. If anhydrous and more reduced composition is recorded from the Moon, Mars evidence suggests hydrous conditions resembling those prevailing in Earth's A-type granites.

Two future avenues to explore seem to be promising. The first concerns ultimate sources of magmas and the second concerns structural settings and metallic potentialities. Accurate determination of possible sources of

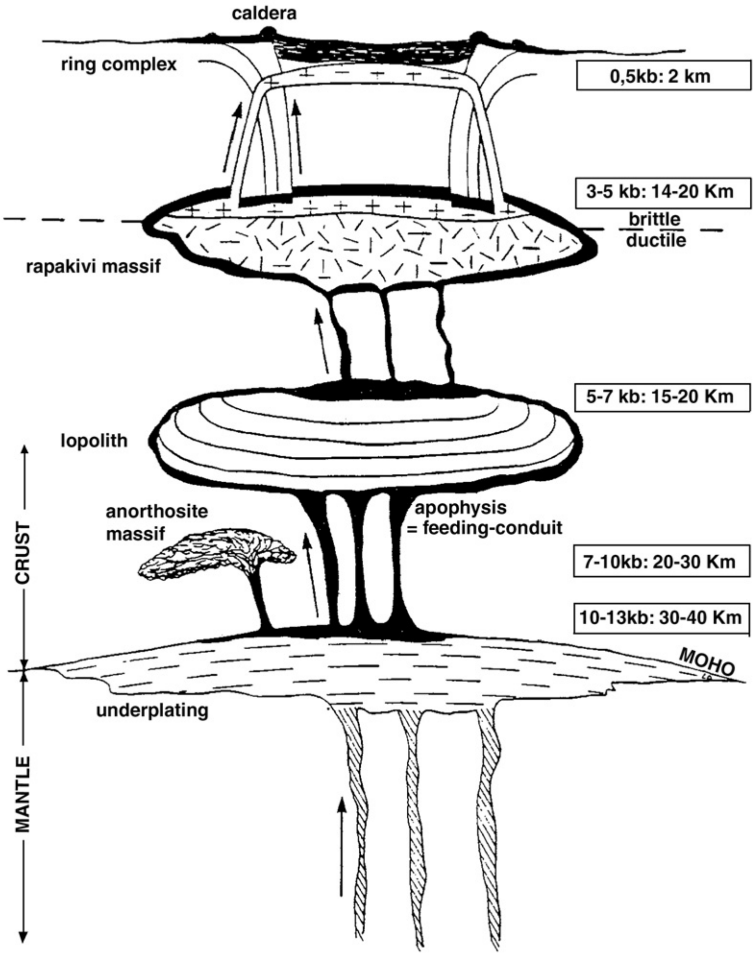

Fig. 8. Structural levels of A-type granite magmatism (updated after Bonin, 1986, 1996). The depth values are only approximate and evolve slightly as a function of the physical parameters of wall rocks and magmas. Surface level: caldera volcano, feeder radial and ring dykes, and domes. Subvolcanic 1–4 km-deep level: ring complex, cone sheets, and dyke swarms. Intermediate 7–15 km-deep level: mixed cumulate-liquid rapakivi granite batholiths, and quartz-alkali feldspar cumulates. AMCG complex, 15–30 km-deep plutonic level: mafic to intermediate layered lopoliths from which felsic residual liquids can escape, and associated massif anorthosite complexes. Underplating zone at the 30–40 km-deep mantle-crust boundary: ultramafic layered sheets. Though inappropriate, the term 'underplating' is maintained because it is widely used, 'intraplating' would be more adequate. Partial melting zones are located at greater depths within upper mantle.

A-type granites should take account of the wide variety of their occurrences, in continental as well as in oceanic areas on Earth, and in tiny places in the other terrestrial planets. The immediate conclusion that comes to mind is that nature of the crust perforated by A-type magmas does not matter so much in terms of modal and major element compositions of the magmas, though it can influence trace element and isotope compositions. The source enigma is merely a mantle conundrum, related to the highly debated problem of nature and structure of the upper mantle. The statistical upper mantle assemblage (SUMA) model, challenging the ancient theory of distinct, isolated geochemical reservoirs and extensive convective stirring, is based on the ubiquitous distribution of small-scale, i.e. 0.1 to 100 km only, heterogeneity throughout the upper mantle (Meibom and Anderson, 2003). Enriched mantle end-members are re-interpreted as a mixture of depleted mantle residues and recycled crustal 'curds' of various sizes, ages, and compositions. Such a theory explain the extremely varied signatures found in A-type granite suites by random sampling of heterogeneities of contrasting compositions, aided by small degrees of partial melting, and generation of small volumes of primary magmas. Heterogeneity is an inherent feature of A-type granite.

The structural settings of A-type granite are also a hot topic related to physical control exerted by brittle rocks of the lithosphere. Partial melting of A-type sources requires supply of supplementary heat, as A-type complexes are mostly emplaced within stable, cooling areas of thickening lithosphere. Heat supply, whatever its origin, results into thermal erosion and/or mechanical delamination of lithospheric roots (Black and Liégeois, 1993). Various scenarios are proposed that relate lithospheric delamination either to hot materials coming from below as mantle plumes, or to strike-slip movements along shear zones (Liégeois et al., 2005). Lithospheric control by large-scale shear zones is evidenced by long-lasting fluid percolation, alteration of primary rock compositions, perturbation of isotopic signatures (e.g., Azzouni-Sekkal et al., 2003), and associated concentrations of economic interest, e.g., Sn–W–Mo, Au, U–Th, high-tech metals (Nb, Ta, REE, etc.). Fluids, evidenced by precipitation of fluorite and topaz, are characterized by high fluorine contents, which favour entrainment of HFSE by complexing ions and their subsequent deposition. Brittle fracture zones, occupied by cataclastic rocks, channelled ore-bearing fluids and controlled largely the location of ore deposits. Whether fluids are magmatic in origin, or are remobilised from the country rocks, remains a challenge for the future.

Provisional conclusions should emphasize two conflicting facts: (i) A-type granites form a comparatively small, yet distinctive, group in the Earth's granite realm, (ii) they are the best represented, if not the only, group of granites generated in the other terrestrial planets and in the asteroid belt. The ongoing IGCP510 on A-type granites will provide a welcome forum to discuss in detail the topics addressed in this review, and others as well. The unique characteristics of A-type granites in the inner part of the Solar system will be hopefully understood, but only with careful, multi-disciplinary examination of the various occurrences.

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References

Åhäll, K.-I., Connelly, J.N., Brewer, T.S., 2000. Episodic rapakivi magmatism due to distal orogenesis? Correlation of 1.69–1.50 Ga orogenic and inboard "anorogenic" events in the Baltic Shield. Geology 28, 823–826.

Anderson, E.M., 1936. The dynamics of the formation of cone sheets, ring-dykes, and cauldron-subsidence. Proceedings of the Royal Society of Edinburgh 56, 128–163.

Anderson, J.L., Bender, E.E., 1989. Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America. Lithos 23, 19–52.

Anderson, J.L., Morrison, J., 2005. Ilmenite, magnetite, and peraluminous Mesoproterozoic anorogenic granites of Laurentia and Baltica. Lithos Ilmari Haapala Volume (80), 45–60.

Andrieux, P., 1982. Conditions de cristallisation et évolution paragénétique d'une charnockite hercynienne: le complexe granulitique d'Ansignan (massif de l'Agly, Pyrénées-Orientales). Bulletin de Minéralogie 105, 253–266.

Annen, C., Sparks, R.S.J., 2002. Effects of repetitive emplacement of basaltic intrusions on thermal evolution and melt generation in the crust. Earth and Planetary Science Letters 203, 937–955.

Ayer, J.A., 1998. The mafic minerals of the Falcon Island ultrapotassic pluton, Lake of the Woods, Ontario: progressive reduction during fractionation. Canadian Mineralogist 36, 49–66.

Azzouni-Sekkal, A., Liégeois, J.P., Bechiri-Benmerzoug, F., Belaidi-Zinet, S., Bonin, B., 2003. The "Taourirt" magmatic province, a marker of the closing stages of the Pan-African orogeny in the Tuareg Shield: review of the available data and Sr–Nd isotope evidence. Journal of African Earth Sciences 37, 337–350.

Bain, A.D.N., 1934. The younger intrusive rocks of the Kudaru Hills, Nigeria. Quarterly Journal of the Geological Society of London 90, 201–239.

Bandfield, J.L., Hamilton, V.E., Christensen, P.R., McSween Jr., H.Y., 2004. Identification of quartzofeldspathic materials on Mars. Journal of Geophysical Research 109, E10009. doi:10.1029/2004JE002290.

Barbarin, B., 1990. Granitoids: main petrogenetic classifications in relation to origin and tectonic setting. Geological Journal 25, 227–238.

Barker, F., Wones, D.R., Sharp, W.N., Desborough, G.A., 1975. The Pikes Peak batholith, Colorado Front Range, and a model for the origin of the gabbro–anorthosite–syenite–potassic granite suite. Precambrian Research 2, 97–160.

Barros, C.E.M., Barbey, P., Boullier, A.M., 2001. Role of magma pressure, tectonic stress and crystallization progress in the emplacement of syntectonic granites. The A-type Estrela Granite Complex (Carajás Mineral Province Brazil). Tectonophysics 343, 93–109.

Barth, T.F.W., 1945. Studies of the Igneous Rock Complex of the Oslo Region. II. Systematic petrography of the plutonic rocks. Skrifter utgitt av det Norske Videnskaps-Akademi i Oslo. I. Matematisk-naturvidenskapelig Klasse, vol. 9. 104 pages.

Bates, R.L., Jackson, J.A., 1980. Glossary of Geology, 2nd Edition. American Geological Institute, Falls Church, VA. 751 pages.

Beard, J.S., Lofgren, G.E., Sinha, A.K., Tollo, R.P., 1994. Partial melting of apatite-bearing charnockite, granulite, and diorite: melt compositions, restite mineralogy, and petrologic implications. Journal of Geophysical Research 99, 21,591–21,603.

Billings, M.P., 1945. Mechanics of igneous intrusion in New Hampshire. American Journal of Science Daly Volume (243-A), 40–68.

Black, R., 1965. Sur la signification pétrogénétique de la découverte d'anorthosites associées aux complexes subvolcaniques du Niger. Comptes Rendus des Séances de l'Académie des Sciences de Paris 260, 5829–5832.

Black, R., Liégeois, J.P., 1993. Cratons, mobile belts, alkaline rocks and continental lithospheric mantle: the Pan-African testimony. Journal of the Geological Society (London) 150, 89–98.

Black, R., Jaujou, M., Pellaton, C., 1967. Notice explicative sur la carte géologique de l'Aïr à l'échelle du 1/500 000. Éditions du Bureau de Recherches Géologiques et Minières, Paris. 57 pages.

Black, R., Morton, W.H., Rex, D.C., Shackleton, R.M., 1972. Sur la découverte en Afar (Ethiopie) d'un granite hyperalcalin miocène: le massif de Limmo. Comptes Rendus de l'Académie des Sciences, Paris 274, 1453–1456.

Black, R., Lameyre, J., Bonin, B., 1985. The structural setting of alkaline complexes. Journal of African Earth Sciences 3, 5–16.

Bolle, O., Trindade, R.I.F., Bouchez, J.L., Duchesne, J.C., 2002. Imaging downward granitic magma transport in the Rogaland Igneous Complex, SW Norway. Terra Nova 14, 87–92.

Bonin, B., 1986. Ring Complex Granites and Anorogenic Magmatism. Studies in Geology. North Oxford Academic, Oxford. 188 pages.

Bonin, B., 1988. Peralkaline granites in Corsica: some petrological and geochemical constraints. Rendiconti della Società italiana di Mineralogia e Petrologia 43, 281–306.

Bonin, B., 1990. From orogenic to anorogenic settings: evolution of granitoid suites after a major orogenesis. Geological Journal 25, 261–270 (W.S. Pitcher Special Issue).

Bonin, B., 1996. A-type granite ring complexes: mantle origin through crustal filters and the anorthosite–rapakivi magmatism connection. In: Demaiffe, D. (Ed.), Petrology and Geochemistry of Magmatic Suites of Rocks in Continental and Oceanic Crusts. A Volume Dedicated to Professor Jean Michot. Université Libre de Bruxelles, Royal Museum for Central Africa, Tervuren, pp. 201–218.

Bonin, B., 2004. Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal, sources? A review. Lithos 78, 1–24.

Bonin, B., Bébien, J., 2005. The granite-upper mantle connection in terrestrial planetary bodies: an anomaly to the current granite paradigm? Lithos Ilmari Haapala Volume (80), 131–145.

Bonin, B., Giret, A., 1985. Contrasting roles of rock-forming minerals in alkaline ring-complexes. Journal of African Earth Sciences 3, 41–49.

Bonin, B., Giret, A., 1990. Plutonic alkaline series: Daly gap and intermediate compositions for liquids filling up crustal magma chambers. Schweizerische Mineralogisch und Petrographische Mitteilungen 70, 175–187.

Bonin, B., Lameyre, J., 1978. Réflexions sur la position et l'origine des complexes magmatiques anorogéniques. Bulletin de la Société Géologique de France, 7° série, vol. XX, pp. 45–59.

Bonin, B., Sørensen, H., 2003. The granites of the Mykle region in the southern part of the Oslo igneous province, Norway. Norske Geologiske Undersøkelse Bulletin 441, 17–24.

Bonin, B., Platevoet, B., Vialette, Y., 1987. The geodynamic significance of alkaline magmatism in the western Mediterranean compared with West Africa. In: Bowden, P., Kinnaird, J.A. (Eds.), African Geology Reviews. Geological Journal, Thematic Issue, vol. 22, pp. 361–387.

Bonin, B., Bardintzeff, J.M., Giret, A., 1994. The distribution of felsic rocks within the alkaline igneous centres. In: Schlich, R., Giret, A. (Eds.), Géologie, géochimie et géophysique des Kerguelen. Mémoire de la Société Géologique de France, nouvelle série, vol. 166, pp. 9–24.

Bonin, B., Dubois, R., Gohau, G., 1997. Le métamorphisme et la formation des granites. Évolution des idées et concepts actuels. Fac Sciences Nathan-Université, Paris. 317 pages.

Bonin, B., Azzouni-Sekkal, A., Bussy, F., Ferrag, S., 1998. Alkali-calcic and alkaline post-orogenic (PO) granite magmatism: petrologic constraints and geodynamic settings. Lithos 45, 45–70.

Bonin, B., Bébien, J., Masson, P., 2002. Granite: a planetary point of view. Gondwana Research 5, 261–273.

Bonin, B., Ethien, R., Gerbe, M.C., Cottin, J.Y., Féraud, G., Gagnevin, D., Giret, A., Michon, G., Moine, B., 2004. The Neogene to Recent Rallier-du-Baty nested ring complex, Kerguelen Archipelago (TAAF, Indian Ocean): stratigraphy revisited, implications for cauldron subsidence. In: Breitkreuz, C., Petford, N. (Eds.), Physical Geology of High-Level Magmatic Systems. Geological Society, London, Special Publication, vol. 234, pp. 125–149.

Bowen, N.L., 1928. The Evolution of Igneous Rocks. Princeton University Press, Princeton. 334 pages.

Bowden, P., 1974. Oversaturated alkaline rocks: granites, pantellerites and comendites. In: Sørensen, H. (Ed.), The Alkaline Rocks. A Wiley-Interscience Publication. John Wiley and Sons, London-New York, pp. 109–123.

Bowden, P., 1985. The geochemistry and mineralization of alkaline ring complexes in Africa (a review). Journal of African Earth Sciences 3, 17–39.

Buddington, A.F., 1959. Granite emplacement with special reference to North America. Bulletin of the Geological Society of America 70, 671–747.

Bunsen, R.W., 1851. Über die Prozesse der vulkanischen Gesteinsbildungen Islands. Annalen der Physik und Chemie (Leipzig) 83, 197–272.

Bussell, M.A., Pitcher, W.S., Wilson, P.A., 1976. Ring complexes of the Peruvian Coastal Batholith: a long-standing subvolcanic regime. Canadian Journal of Earth Sciences 13, 1020–1030.

Calzia, J.P., Rämö, O.T., 2005. Miocene rapakivi granites in the southern Death Valley region, California, USA. Earth-Science Reviews 73, 221–243.

Capaldi, G., Chiesa, S., Manetti, P., Orsi, G., Poli, G., 1987. Tertiary anorogenic granites of the western border of the Yemen Plateau. Lithos 20, 433–444.

Castro, A., Moreno-Ventas, I., de la Rosa, J.D., 1991. H-type (hybrid) granitoids: a proposed revision of the granite-type classification and nomenclature. Earth-Science Reviews 31, 237–253.

Cawthorn, R.G. (Ed.), 1996. Layered Intrusions. Developments in Petrology, vol. 15. Elsevier, Amsterdam. 531 pages.

Cawthorn, R.G., Walraven, F., 1998. Emplacement and crystallization time for the Bushveld Complex. Journal of Petrology 39, 1669–1687.

Chapman, R.W., Williams, C.R., 1935. Evolution of the White Mountain Magma Series. American Mineralogist 20, 502–530.

Chapman, R.W., Chapman, C.A., 1940. Cauldron subsidence at Ascutney Mountain, Vermont. Bulletin of the Geological Society of America 51, 191–212.

Chappell, B.W., White, A.J.R., 1974. Two contrasting granite types. Pacific Geology 8, 173–174.

Chappell, B.W., White, A.J.R., 1992. I- and S-type granites in the Lachlan Fold Belt. Transactions of the Royal Society of Edinburgh. Earth Sciences 83, 1–26.

Chappell, B.W., White, A.J.R., Wyborn, D., 1987. The importance of residual source material (restite) in granite petrogenesis. Journal of Petrology 28, 1111–1138.

Chappell, B.W., Bryant, C.J., Wyborn, D., White, A.J.R., Williams, I.S., 1998. High- and low-temperature I-type granites. Resource Geology 48, 225–235.

Cherry, M.E., Trembath, L.T., 1978. The pressure quench formation of rapakivi texture. Contributions to Mineralogy and Petrology 68, 1–6.

Chopin, C., 2003. Ultrahigh-pressure metamorphism: tracing continental crust into the mantle. Earth and Planetary Science Letters 212, 1–14.

Christiansen, E.H., Sheridan, M.F., Burt, D.M., 1986. The geology and geochemistry of Cenozoic topaz rhyolites from the western United States. Geological Society of America Special Paper, vol. 205. 88 pages.

Christiansen, R.L., Foulger, G.R., Evans, J.R., 2002. Upper-mantle origin of the Yellowstone hotspot. Geological Society of America Bulletin 114, 1245–1256.

Clague, D.A., 1978. The oceanic basalt–trachyte association: an explanation of the Daly gap. Journal of Geology 86, 739–743.

Clague, D.A., Moore, J.G., Reynolds, J.R., 2000. Formation of submarine flat-topped volcanic cones in Hawaii. Bulletin of Volcanology 62, 214–233.

Clarke, D.B., 1992. Granitoid Rocks. Topics in the Earth Sciences, vol. 7. Chapman and Hall, London. 283 pages.

Clarke, D.B., 1996. Two centuries after Hutton's 'Theory of the Earth': the status of granite science. Transactions of the Royal Society of Edinburgh. Earth Sciences 87, 353–359.

Clemens, J.D., Holloway, J.R., White, A.J.R., 1986. Origin of an A-type granite: experimental constraints. American Mineralogist 71, 317–324.

Clough, C.T., Maufe, H.B., Bailey, E.B., 1909. The cauldron-subsidence of Glen Coe, and the associated igneous phenomena. Quarterly Journal of the Geological Society of London 65, 611–678.

Collins, W.J., Beams, S.D., White, A.J.R., Chappell, B.W., 1992. Nature and origin of A-type granites with particular reference to southeastern Australia. Contributions to Mineralogy and Petrology 80, 189–200.

Compagnoni, R., Rolfo, F., 1999. Characteristics of UHP pelites, gneisses, and other unusual rocks. International Geology Review 41, 270–552.

Conceição, H., Sabaté, P., Bonin, B., 1991. The Itiúba syenite massif, Bahia State (Brazil): mineralogical, geochemical and petrological constraints — relation to the genesis of rapakivi magmatism. Precambrian Research 51, 283–314.

Condie, K.C., 1992. Introduction. In: Condie, K.C. (Ed.), Proterozoic Crustal Evolution. Developments in Precambrian Geology, vol. 10. Elsevier, Amsterdam, pp. 1–6.

Cox, K.G., Johnson, R.L., Monkman, L.J., Stillman, C.J., Vail, J.R., Wood, D.N., 1965. The geology of the Nuanetsi igneous province. Philosophical Transactions of the Royal Society of London. Series A 257, 71–218.

Creaser, R.A., Price, R.C., Wormald, R.J., 1991. A-type granites revisited: assessment of a residual-source model. Geology 19, 163–166.

Crisp, J.A., 1984. Rates of magma emplacement and volcanic output. Journal of Volcanology and Geothermal Research 20, 177–211.

Dall'Agnol, R., Scaillet, B., Pichavant, M., 1999. An experimental study of a Lower Proterozoic A-type granite from the Eastern Amazonian Craton, Brazil. Journal of Petrology 40, 1673–1698.

Dall'Agnol, R., Teixeira, N.P., Rämö, O.T., Moura, C.A.V., Macambira, M.J.B., de Oliveira, D.C., 2005. Petrogenesis of the Paleoproterozoic rapakivi A-type granites of the Archean Carajás metallogenic province, Brazil. Lithos Ilmari Haapala Volume (80), 101–129.

Daly, R.A., 1903. Geology of Ascutney Mountain, Vermont. U.S. Geological Survey Bulletin 209, 1–122.

Dann, J.C., Holzheid, A.H., Grove, T.L., McSween Jr., H.Y., 2001. Phase equilibria of the Shergotty meteorite: constraints on pre-eruptive water contents of Martian magmas and fractional crystallization under hydrous conditions. Meteoritics & Planetary Science 36, 793–806.

Dempster, T.J., Jenkin, G.R.T., Rogers, G., 1994. The origin of rapakivi texture. Journal of Petrology 35, 963–981.

Dickin, A.P., Moorbath, S., Welke, H.J., 1981. Isotope, trace element and major element geochemistry of Tertiary igneous rocks, Isle of Arran, Scotland. Transactions of the Royal Society of Edinburgh. Earth Sciences 72, 159–170.

Dickin, A.P., Fallick, A.E., Halliday, A.N., Macintyre, R.M., Stephens, W.E., 1986. An isotopic and geochronological investigation of the younger igneous rocks of the Seychelles microcontinent. Earth and Planetary Science Letters 81, 46–56.

Dixon Spulber, S., Rutherford, M.J., 1983. The origin and rhyolite and plagiogranite in oceanic crust: an experimental study. Journal of Petrology 24, 1–25.

Duchesne, J.C., Wilmart, E., 1997. Igneous charnockites and related rocks from the Bjerkreim–Sokndal layered intrusion (southwest Norway). A jotunite (hypersthene monzodiorite)-derived A-type granitoid suite. Journal of Petrology 38, 337–369.

Duchesne, J.C., Maquil, R., Demaiffe, D., 1985. The Rogaland anorthosites: facts and speculations. In: Tobi, A.C., Touret, J.L.R. (Eds.), The Deep Proterozoic Crust in the North Atlantic Province. Reidel Publishing Company, Amsterdam, pp. 449–476.

Duchesne, J.C., Liégeois, J.P., Vander Auwera, J., Longhi, J., 1999. The crustal tongue model and the origin of massive anorthosites. Terra Nova 11, 100–105.

Duffield, W.A., 1968. The petrology and structure of the El Pinal tonalite, Baja California, Mexico. Geological Society of America Bulletin 79, 1351–1374.

Eby, G.N., 1990. The A-type granitoids: a review of their occurrence and chemical characteristics and speculations on their petrogenesis. Lithos 26, 115–134.

Eby, G.N., 1992. Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. Geology 20, 641–644.

Eklund, O., Shebanov, A.D., 1999. The origin of rapakivi texture by sub-isothermal decompression. Precambrian Research 95, 129–146.

Eklund, O., Frödjö, Lindberg, B., 1993. Magma mixing, the petrogenetic link between anorthositic suites and rapakivi granites, Åland, SW Finland. Mineralogy and Petrology 47, 705–730.

Elliott, B.A., 2003. Petrogenesis of the post-kinematic magmatism in the Central Finland Granitoid Complex II. Sources and magmatic evolution. Journal of Petrology 44, 1681–1701.

Elliott, B.A., Rämö, O.T., Nironen, M., 1998. Mineral chemistry constraints on the evolution of the 1.88–1.87 Ga post-kinematic granite plutons in the Central Finland Granitoid Complex. Lithos 45, 109–129.

Emslie, R.F., 1978. Anorthosite massifs, rapakivi granites, and Late Proterozoic rifting of North America. Precambrian Research 7, 61–98.

Emslie, R.F., Hunt, P.A., 1990. Ages and petrogenetic significance of igneous mangerite–charnockite suites associated with massif anorthosites, Grenville Province. Journal of Geology 98, 213–231.

Emslie, R.F., Hamilton, M.A., Thériault, R.J., 1994. Petrogenesis of a mid-Proterozoic anorthosite–mangerite–charnockite–granite (AMCG) complex: isotopic and chemical evidence from the Nain Plutonic Suite. Journal of Geology 102, 539–558.

Engel, C.G., Fisher, R.L., 1975. Granitic to ultramafic rock complexes of the Indian Ocean ridge system, western Indian Ocean. Geological Society of America Bulletin 86, 1553–1578.

Ferré, E., Caby, R., Peucat, J.J., Capdevila, R., Monié, P., 1998. Pan-African, post-collisional, ferro-potassic granite and quartz–monzonite plutons of Eastern Nigeria. Lithos 45, 255–279.

Fink, J.H., Bridges, N.T., Grimm, R.E., 1993. Shapes of venusian "pancake" domes imply episodic emplacement and silicic composition. Geophysical Research Letters 20, 261–264.

Fitton, J.G., Upton, B.G.J. (Eds.), 1987. Alkaline Igneous Rocks. Special Publication, vol. 30. Geological Society, London. 568 pages.

Foland, K.A., Quinn, A.W., Giletti, B.J., 1971. K–Ar and Rb–Sr Jurassic and Cretaceous ages for intrusives of the White Mountain Magma Series, Northern New England. American Journal of Science 270, 321–330.

Foland, K.A., Landoll, J.D., Henderson, C.M.B., Chen, J.F., 1993. Formation of cogenetic quartz and nepheline syenites. Geochimica et Cosmochimica Acta 57, 697–704.

Frost, C.D., Frost, B.R., 1997. Reduced rapakivi-type granites: the tholeiite connection. Geology 25, 647–650.

Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001. A geochemical classification for granitic rocks. Journal of Petrology 42, 2033–2048.

Fryda, J., Breiter, K., 1995. Alkali feldspars as a main phosphorus reservoirs in rare-metal granites: three examples from the Bohemian Massif (Czech Republic). Terra Nova 7, 315–320.

Furman, T., Frey, F.A., Meyer, P.S., 1992. Petrogenesis of evolved basalts and rhyolites at Austurhorn, southeastern Iceland: the role of fractional crystallization. Journal of Petrology 33, 1405–1445.

Gagnevin, D., Ethien, R., Bonin, B., Moine, B., Féraud, G., Gerbe, M.C., Cottin, J.Y., Michon, G., Tourpin, S., Mamias, G., Perrache, C., Giret, A., 2003. Open-system processes in the genesis of silica-oversaturated alkaline rocks of the Rallier-du-Baty Peninsula, Kerguelen Archipelago (Indian Ocean). Journal of Volcanology and Geothermal Research 123, 267–300.

Gilluly, J., chairman, 1948. Origin of Granite. Geological Society of America Memoir 28 (conference of the Geological Society of America held in Ottawa, Canada, 30 December 1947), 139 pages.

Giret, A., 1983. Le plutonisme océanique intraplaque. Exemple des Iles Kerguelen. Unpublished D.Sc. Thesis, Université Pierre et Marie Curie, Paris, 290 pages.

Giret, A., 1990. Typology, evolution, and origin of the Kerguelen plutonic series, Indian Ocean: a review. Geological Journal 25, 239–247 (W.S. Pitcher Special Issue).

Giret, A., Bonin, B., Léger, J.M., 1980. Amphibole compositional trends in the oversaturated and undersaturated alkaline plutonic ring-complexes. Canadian Mineralogist 18, 481–495.

Glazner, A.F., 1994. Foundering mafic plutons and density stratification of continental crust. Geology 22, 435–438.

Glazner, A.F., Miller, D.M., 1997. Late-stage sinking of plutons. Geology 25, 1099–1102.

Goldschmidt, V.M., 1911. Die Kontaktmetamorphose im Kristianiagebiet. Skrifter utgitt av Videnskabsselskabet i Kristiania, I, Matematisk-naturvidenskapelig Klasse, vol. 11.

Greenwood, R., 1951. Younger intrusive rocks of Plateau Province, Nigeria, compared with the alkalic rocks of New England. Bulletin of the Geological Society of America 62, 1151–1178.

Guitard, G., 1960. Sur la présence et l'âge d'un granite à hypersthène d'affinité chanockitique dans le massif de l'Agly (Pyrénées-Orientales). Comptes rendus des séances de l'Académie des Sciences, Paris 251, 2554–2555.

Haapala, I., 1977. Petrography and geochemistry of the Eurajoki stock, a rapakivi–granite complex with greisen-type mineralization in southwestern Finland. Geological Survey of Finland 286. 128 pages.

Haapala, I., Rämö, O.T., 1992. Tectonic setting and origin of the Proterozoic rapakivi granites of southeastern Fennoscandia. Transactions of the Royal Society of Edinburgh. Earth Sciences 83, 165–171.

Haapala, I., Rämö, O.T., Frindt, S., 2005. Comparison of Proterozoic and Phanerozoic rift-related basaltic–granitic magmatism. Lithos Ilmari Haapala Volume (80), 1–32.

Harker, A., 1909. The natural history of igneous rocks. Methuen and Co., London, and Macmillan, New York. 377 pages.

Harris, C., Bell, J.D., 1982. Natural partial melting of syenite blocks from Ascension Island. Contributions to Mineralogy and Petrology 79, 107–113.

Hatton, C.J., Schweitzer, J.K., 1995. Evidence for synchronous extrusive and intrusive Bushveld magmatism. Journal of African Earth Sciences 21, 579–594.

Helmstaedt, H.H., Schulze, D.J., 1989. Southern African kimberlites and their mantle sample: implications for the Archean tectonics and lithosphere evolution. Proceedings of the Fourth International Kimberlite Conference, Perth. Special Publication, vol. 14. Geological Society of Australia, pp. 358–368.

Hibbard, M.J., 1981. The magma mixing origin of mantled feldspars. Contributions to Mineralogy and Petrology 76, 158–170.

Hirschmann, M., 1992. Origin of the Transgressive Granophyres from the Layered Series of the Skaergaard intrusion, East Greenland. Journal of Volcanology and Geothermal Research 52, 185–207.

Hong, D., Wang, S., Han, B., Jin, M., 1996. Post-orogenic alkaline granites from China and comparisons with anorogenic alkaline granites elsewhere. Journal of Southeast Asian Earth Sciences 13, 13–27.

Hutton, J., 1794. Observations on granite. Transactions of the Royal Society of Edinburgh 3, 77–85.

Hutton, J., 1795. Theory of the Earth, with Proofs and Illustrations, vols. 1 and 2. Cadell, Davies and Creech, Edinburgh-London.

Hutton, J., 1899. In: Geikie, A. (Ed.), Theory of the Earth, with Proofs and Illustrations, vol. 3. The Geological Society of London, Burlington House.

Iddings, J.P., 1892. The origin of igneous rocks. Bulletin of the Philosophical Society of Washington 12, 89–213.

Jacobson, R.R.E., MacLeod, W.N., Black, R., 1958. Ring complexes in the Younger Granite province of northern Nigeria. Geological Society of London Memoir 1, 72 pages.

Johnson, C.M., Czamanske, G.K., Lipman, P.W., 1989. Geochemistry of intrusive rocks associated with the Latir volcanic field, New

Mexico, and contrasts between evolution of plutonic and volcanic rocks. Contributions to Mineralogy and Petrology 103, 90–109.

Jónasson, K., Holm, P.M., Pedersen, A.K., 1992. Petrogenesis of silicic rocks from the Króksfjördur central volcano, NW Iceland. Journal of Petrology 33, 1345–1369.

Judd, J.W., 1893. On composite dykes in Arran. Quarterly Journal of the Geological Society of London 49, 536–564.

Jung, S., Hoernes, S., Hoffer, E., 2005. Petrogenesis of cogenetic nepheline and quartz syenites and granites (Northern Damara Orogen, Namibia): enriched mantle versus crustal contamination. Journal of Geology 113, 651–672.

Kanaris-Sotiriou, R., Gibb, F.G.F., 1989. Plagiogranite differentiates in MORB-type sills of the Faeroe–Shetland Basin. Journal of the Geological Society (London) 146, 607–610.

Kemp, A.I.S., Whitehouse, M.J., Hawkesworth, C.J., Alarcon, M.K., 2005a. A zircon U–Pb study of metaluminous (I-type) granites of the Lachlan Fold Belt, southeastern Australia: implications for the high/low temperature classification and magma differentiation processes. Contributions to Mineralogy and Petrology 150, 230–249.

Kemp, A.I.S., Wormald, R.J., Whitehouse, M.J., Price, R.C., 2005b. Hf isotopes in zircon reveal contrasting sources and crystallization histories for alkaline and peralkaline granites of Temora, southeastern Australia. Geology 33, 797–800.

Key, R.M., 1989. A note on the Jibisa Ring Complex of northern Kenya. Journal of African Earth Sciences 8, 113–125.

Kiefer, W.S., 2004. Gravity evidence for an extinct magma chamber beneath Syrtis Major, Mars: a look at the magmatic plumbing system. Earth and Planetary Science Letters 222, 349–361.

Kilpatrick, J.A., Ellis, D.J., 1992. C-type magmas: igneous charnockites and their extrusive equivalents. Transactions of the Royal Society of Edinburgh: Earth Sciences 83, 155–164.

Kingsley, L., 1931. Cauldron-subsidence of the Ossipee Mountains. American Journal of Science 22, 139–168 (5th series).

Kleeman, G.J., Twist, D., 1989. The compositionally-zoned sheet-like granite pluton of the Bushveld Complex: evidence bearing on the nature of A-type magmatism. Journal of Petrology 30, 1383–1414.

Klimm, K., Holtz, F., Johannes, W., King, P.L., 2003. Fractionation of metaluminous A-type granites: an experimental study of the Wangrah Suite, Lachlan Fold Belt, Australia. Precambrian Research 124, 327–341.

Lameyre, J., Rocci, G., Didier, J., 1974. Granites orogéniques et granites cratoniques: réflexions sur un aspect fondamental de la géotectonique. Géologie des Domaines Cristallins, Centenaire de la Société Géologique de Belgique, Liège, pp. 183–221.

Lasserre, M., 1966. Confirmation de l'existence d'une série de granites tertiaires au Cameroun (Afrique équatoriale). Bulletin du B.R.G.M. (3), 141–148.

Lauri, L.S., Rämö, O.T., Huhma, H., Mänttäri, Räsänen, J., 2006. Petrogenesis of silicic magmatism related to the ~2.44 Ga rifting of Archean crust in Koillismaa, eastern Finland. Lithos 86, 137–166.

Lavecchia, G., Stoppa, F., 1996. The tectonic significance of Italian magmatism: an alternative view to the popular interpretation. Terra Nova 8, 435–446.

Le Maitre, R.W., 1982. Numerical Petrology. Developments in Petrology, vol. 8. Elsevier, Amsterdam. 281 pages.

Le Maitre, R.W., editor, Streckeisen, A., Zanettin, B., Le Bas, M.J., Bonin, B., Bateman, P., Bellieni, G., Dudek, A., Efremova, S., Keller, J., Lameyre, J., Sabine, P.A., Schmid, R., Sørensen, H., Woolley, A.R., 2002. Igneous Rocks. A Classification and Glossary of Terms. Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks, 2nd Edition. Cambridge University Press, Cambridge. 236 pages.

Leake, B.E., Brown, G.C., Halliday, A.N., 1980. The origin of granite magmas: a discussion. Journal of the Geological Society of London 137, 93–97.

Liégeois, J.P. (Ed.), 1998. Post-Collisional Magmatism. An issue in Honour of Professor Russell Black, EUG, Strasbourg, France, 25–27 March 1997, Symposium 55. Lithos, vol. 45. 563 pages.

Liégeois, J.P., Black, R., 1984. Pétrographie et géochronologie Rb–Sr de la transition calco-alcaline–alcaline fini-Panafricaine dans l'Adrar des Iforas (Mali): Accrétion crustale au Précambrien supérieur. In: Klerkx, J., Michot, J. (Eds.), Géologie africaine — African geology, Volume en hommage à L. Cahen, Tervuren, pp. 115–145.

Liégeois, J.P., Sauvage, J.F., Black, R., 1991. The Permo-Jurassic alkaline province of Tadhak, Mali: Geology, geochronology and tectonic significance. Lithos 27, 95–105.

Liégeois, J.P., Navez, J., Hertogen, J., Black, R., 1998. Contrasting origin for post-collisional high-K calc-alkaline and shoshonitic versus alkaline and peralkaline granitoids. The use of sliding normalization. Lithos 45, 1–28.

Liégeois, J.P., Benhallou, A., Azzouni-Sekkal, A., Yahiaoui, R., Bonin, B., 2005. The Hoggar swell and volcanism, Tuareg shield, Central Sahara: intraplate reactivation of Precambrian structures as a result of Alpine convergence. In: Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L. (Eds.), Plates, Plumes and Paradigms. Geological Society of America Special Paper, vol. 388, pp. 379–400.

Loiselle, M.C., Wones, D.R., 1979. Characteristics and origin of anorogenic granites. Abstracts of papers to be presented at the Annual Meetings of the Geological Society of America and Associated Societies, San Diego, California, November 5–8, vol. 11, p. 468.

London, D., 1992. Phosphorus in S-type magmas: the P_2O_5 content of feldspars from peraluminous granites, pegmatites, and rhyolites. American Mineralogist 77, 126–145.

Longhi, J., Vander Auwera, J., Fram, M.S., Duchesne, J.C., 1999. Some phase equilibrium constraints on the origin of Proterozoic (massif) anorthosites and related rocks. Journal of Petrology 40, 339–362.

Maaløe, S., 1985. Principles of Igneous Petrology. Springer-Verlag, Berlin-Heidelberg. 374 pages.

Mahood, G.A., Hildreth, W., 1986. Geology of the peralkaline volcano at Pantelleria, Strait of Sicily. Bulletin of Volcanology 48, 143–172.

Martin, R.F., 2006. A-type granites of crustal origin ultimately result from open-system fenitization-type reactions in an extensional environment. Lithos 91, 125–136.

Martin, R.F., Bonin, B., 1976. Water and magma genesis: the association hypersolvus granite–subsolvus granite. Canadian Mineralogist 14, 228–237.

Martin, H., Bonin, B., Capdevila, R., Jahn, B.M., Lameyre, J., Wang, Y., 1994. The Kuiqi peralkaline granitic complex (SE China): petrology and geochemistry. Journal of Petrology 35, 983–1015.

Martin, H., Smithies, R.H., Rapp, R., Moyen, J.F., Champion, D., 2005. An overview of adakite, tonalite–trondhjemite–granodiorite (TTG), and sanukitoid: relationships and some implications for crustal evolution. Lithos 79, 1–24.

Massonne, H.J., 2003. A comparison of the evolution of diamondiferous quartz-rich rocks from the Saxonian Erzgebirge and the Kokchetav Massif: are so-called diamondiferous gneisses magmatic rocks? Earth and Planetary Science Letters 216, 347–364.

McBirney, A.R., 1996. The Skaergaard Intrusion. In: Cawthorn, R.G. (Ed.), Layered Intrusions. Developments in Petrology, vol. 15. Elsevier, Amsterdam, pp. 147–180.

McDonough, W.F., Sun, S.-s., 1995. The composition of the Earth. Chemical Geology 120, 223–253.

McKerrow, W.S., Atkins, F.B., 1985. Isle of Arran. A Field Guide for students of geology. The Geologists' Association, Ongar, Essex. 96 pages.

McLennan, S.M., 2003. Sedimentary silica on Mars. Geology 31, 315–318.

McSween Jr., H.Y., Murchie, S.L., Crisp, J.A., Bridges, T., Anderson, R.C., Bell III, J.F., Britt, D.T., Brückner, J., Dreibus, G., Economou, T., Ghosh, A., Golombek, M.P., Greenwood, J.P., Johnson, J.R., Moore, H.J., Morris, R.V., Parker, T.J., Rieder, R., Singer, R., Wänke, H., 1999. Chemical, multispectral, and textural constraints on the composition and origin of rocks at the Mars Pathfinder landing site. Journal of Geophysical Research 104, 8679–8715.

Meibom, A., Anderson, D.L., 2003. The statistical upper mantle assemblage. Earth and Planetary Science Letters 217, 123–139.

Michalski, J.R., Kraft, M.D., Sharp, T.G., Williams, L.B., Christensen, P.R., 2005. Mineralogical constraints on the high-silica martian surface component observed by TES. Icarus 174, 161–177.

Minitti, M.E., Rutherford, M.J., 2000. Genesis of the Mars Pathfinder "sulfur-free" rock from SNC parental liquids. Geochimica et Cosmochimica Acta 64, 2535–2547.

Miyashiro, A., 1974. Nature of alkalic volcanic rock series. Contributions to Mineralogy and Petrology 66, 91–104.

Moore, I., Kokelaar, P., 1997. Tectonic influences in piecemeal caldera collapse at Glencoe Volcano, Scotland. Journal of the Geological Society (London) 154, 765–768.

Moore, M., Davis, D.W., Robb, L.J., Jackson, M.C., Grobler, D.F., 1993. Archean rapakivi granite–anorthosite–rhyolite complex in the Witwatersrand basin hinterland, southern Africa. Geology 21, 1031–1034.

Morgan IV, G.B., London, D., 2005. Phosphorus distribution between potassic alkali feldspar and metaluminous haplogranitic liquid at 200 MPa (H_2O): the effect of undercooling on crystal-liquid systematics. Contributions to Mineralogy and Petrology 150, 456–471.

Morogan, V., Martin, R.F., 1985. Mineralogy and partial melting of fenitized crustal xenoliths in the Oldoinyo Lengai carbonatitic volcano, Tanzania. American Mineralogist 70, 1114–1126.

Morogan, V., Sørensen, H., 1994. Net-veined complexes in the Oslo Rift, southeast Norway. Lithos 32, 21–45.

Morra, V., Secchi, F.A., Assorgia, A., 1994. Petrogenetic significance of peralkaline rocks from Cenozoic calc-alkaline volcanism from SW Sardinia, Italy. Chemical Geology 118, 109–142.

Morris, G.A., Page, L., Martinez, V., 2005. New dates (415 Ma) for the Etive Dyke Swarm and the end of the Caledonian Orogeny in the SW Grampian Highlands of Scotland. Journal of the Geological Society (London) 162, 741–744.

Naslund, H.R., 1989. Petrology of the Basistoppen Sill, East Greenland: a calculated magma differentiation trend. Journal of Petrology 30, 299–319.

Neumann, E.R., 1978. Petrology of the plutonic rocks. In: Dons, J.A., Larsen, B.T. (Eds.), The Oslo Paleorift. A Review and Guide to Excursions. Norges Geologiske Undersøkelse, vol. 337, pp. 25–34.

Neumann, E.R., 1980. Petrogenesis of the Oslo Region larvikites and associated rocks. Journal of Petrology 21, 499–531.

Nielsen, T.F.D., 1987. Tertiary alkaline magmatism in East Greenland: a review. In: Fitton, J.G., Upton, B.G.J. (Eds.), Alkaline Igneous Rocks. Special Publications, vol. 30. Geological Society, London, pp. 489–515.

Nironen, M., Elliott, B.A., Rämö, O.T., 2000. 1.88–1.87 Ga post-kinematic intrusions of the Central Finland Granitoid Complex: a shift from C-type to A-type magmatism during lithospheric convergence. Lithos 53, 37–58.

Niu, Y., O'Hara, M., 2003. Origin of ocean island basalts: a new perspective from petrology, geochemistry, and mineral physics considerations. Journal of Geophysical Research 108. doi:10.1029/2002JB002048.

Oftedahl, C., 1978. Cauldrons of the Permian Oslo Rift. Journal of Volcanology and Geothermal Research 3, 343–371.

Oyawoye, M.O., 1972. Bauchite: a fayalite-bearing quartz monzonite. 24th International Geological Congress, Montreal, pp. 251–266. Section 2.

Patiño Douce, A.E., 1991. Experimental generation of hybrid silicic melts by reaction of high-Al basalt with metamorphic rocks. Journal of Geophysical Research 100, 15,623–15,639.

Patiño Douce, A.E., 1997. Generation of metaluminous A-type granitoids by low-pressure melting of calc-alkaline granitoids. Geology 25, 743–746.

Patiño Douce, A.E., 1999. What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas? In: Castro, A., Fernández, C., Vigneresse, J.L. (Eds.), Understanding Granites. Special Publications, vol. 168. Geological Society, London, pp. 55–75.

Peacock, M.A., 1931. Classification of igneous rocks. Journal of Geology 39, 54–67.

Pearce, J.A., 1983. Role of subcontinental lithosphere in magma genesis at active continental margins. In: Hawkesworth, C.J., Norry, M.J. (Eds.), Continental Basalts and Mantle Xenoliths. Shiva Publishing, Nantwich, UK, 230–249.

Pearce, J.A., 1987. An expert system for the tectonic characterization of ancient volcanic rocks. Journal of Volcanology and Geothermal Research 32, 51–65.

Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology 25, 956–983.

Peccerillo, A., 1992. Potassic and ultrapotassic magmatism: compositional characteristics, genesis and geological significance. Episodes 15, 243–251.

Peccerillo, A., Donati, C., 2003. Miocene–Quaternary magmatism in central–southern Italy. Periodico di Mineralogia 72, 11–23.

Petford, N., Gallagher, K., 2001. Partial melting of mafic (amphibolite) lower crust by periodic influx of basaltic magmas. Earth and Planetary Science Letters 193, 483–499.

Pitcher, W.S., 1993. The Nature and Origin of Granite. Blackie Academic and Professional, Chapman and Hall, London-Glasgow. 321 pages.

Poitrasson, F., Duthou, J.L., Pin, C., 1995. The relationship between petrology and Nd isotopes as evidence for contrasting anorogenic granite genesis: example of the Corsican Province (SE France). Journal of Petrology 36, 1251–1274.

Poli, G., Peccerillo, A., 2003. Lamproitic rocks from the Tuscan Magmatic Province. Periodico di Mineralogia 72, 225–231.

Raguin, E., 1946. Géologie du Granite. Masson, Paris. 275 pages.

Rahaman, M.A., van Breemen, O., Bowden, P., Bennett, J.N., 1984. Age migrations of anorogenic ring complexes in northern Nigeria. Journal of Geology 92, 173–184.

Rämö, O.T., 1991. Petrogenesis of the Proterozoic rapakivi granites and related basic rocks of southeastern Fennoscandia: Nd and Pb isotopic and general geochemical constraints. Geological Survey of Finland Bulletin 355. 161 pages.

Rämö, O.T., Haapala, I., 1995. One hundred years of rapakivi granites. Mineralogy and Petrology 52, 129–185.

Read, H.H., 1957. The Granite Controversy. Thomas Murby and Co., London. 430 pages.

Richey, J.E., 1928. The structural relations of the Mourne Granites (Northern Ireland). Quarterly Journal of the Geological Society of London 83, 653–687.

Richey, J.E., 1932. Tertiary ring structures in Britain. Transactions of the Geological Society of Glasgow 19, 42–140.

Richey, J.E., MacGregor, A.G., Anderson, F.W., 1961. Scotland: the tertiary volcanic districts, British Regional Geology, 3rd Edition. Her Majesty's Stationery Office, Edinburgh. 120 pages.

Robinson, P.T., Elders, W.A., Muffler, L.J.P., 1976. Quaternary volcanism in the Salton Sea geothermal field, Imperial Valley, California. Geological Society of America Bulletin 87, 347–360.

Roubault, M., Sadran, G., organisers, 1955. Les échanges de matières au cours de la genèse des roches grenues acides et basiques. Colloques Internationaux du Centre National de la Recherche Scientifique, Nancy, 4 au 11 Septembre 1955, LXVIII. 312 pages.

Salonsaari, P., 1995. Hybridization in the subvolcanic Jaala–Iitti complex and its petrogenetic relation to rapakivi granites and associated mafic rocks of southeastern Finland. Bulletin of the Geological Society of Finland 67, 1–104.

Sardinha, A.S., Barros, C.E.M., Krymsky, R., 2006. Geology, geochemistry, and U–Pb geochronology of the Archean (2.74 Ga) Serra do Rabo granite stocks, Carajás Metallogenetic Province, northern Brazil. Journal of South American Earth Sciences 20, 327–339.

Schärer, U., Wilmart, E., Duchesne, J.C., 1996. The short duration and anorogenic character of anorthosite magmatism: U–Pb dating of the Rogaland complex, Norway. Earth and Planetary Science Letters 139, 335–350.

Schweitzer, J.K., Hatton, C.J., de Waal, S.A., 1995. Regional lithogeochemical stratigraphy of the Rooiberg Group, upper Transvaal Supergroup: a proposed new subdivision. South African Journal of Geology 98, 245–255.

Sederholm, J.J., 1891. Über die finnländischen Rapakiwigesteine. Tschermaks Mineralogische und Petrographische Mitteilungen 12, 1–31.

Shand, S.J., 1922. The problem of the alkaline rocks. Proceedings of the Geological Society of South Africa 25, 19–33.

Shirey, S.B., Richardson, S.H., Harris, J.W., 2004. Integrated models of diamond formation and craton evolution. Lithos 77, 923–944.

Sial, A.N., Ferreira, V.P., Mariano, G., 1987. Proterozoic granitoids, western Pernambuco and Paraiba States, Northeast Brazil. International Symposium on Granites and Associated Mineralizations, Excursion Guides, pp. 9–29.

Sibiya, V.B.B., 1988. The Gaborone Granite Complex, Botswana, southern Africa: an atypical rapakivi granite-massif anorthosite association. Ph.D. Thesis, Vrije Universiteit te Amsterdam. 449 pages.

Smith, I.E.M., Chappell, B.W., Ward, G.K., Freeman, R.S., 1977. Peralkaline rhyolites associated with andesitic arcs of the Southwest Pacific. Earth and Planetary Science Letters 37, 230–236.

Smithies, R.H., Champion, D.C., 1999. Late Archean felsic alkaline igneous rocks in the Eastern Goldfields, Yilgarn Craton, Western Australia: a result of lower crustal delamination? Journal of the Geological Society (London) 156, 561–576.

Sørensen, H. (Ed.), 1974. The Alkaline Rocks. A Wiley-Interscience Publication. John Wiley and Sons, London-New York. 622 pages.

Stein, G., Lapierre, H., Charvet, J., 1992. Magmatisme alcalin "intraplaque" en contexte d'arc insulaire: le massif plutonique d'Ashizuri (Japon SO). Comptes Rendus des Séances de l'Académie des Sciences, Paris 315, 1501–1508.

Sutcliffe, R.H., Smith, A.R., Doherty, W., Barnett, R.L., 1990. Mantle derivation of Archean amphibole-bearing granitoid and associated mafic rocks: evidence from the southern Superior Province, Canada. Contributions to Mineralogy and Petrology 105, 255–274.

Tappert, R., Stachel, T., Harris, J.W., Muehlenbachs, K., Ludwig, T., Brey, G.P., 2005. Subducting oceanic crust: the source of deep diamonds. Geology 33, 565–568.

Taylor, R.P., 1992. Petrological and geochemical characteristics of the Pleasant Ridge zinnwaldite–topaz granite, southern New Brunswick, and comparisons with other topaz-bearing felsic rocks. Canadian Mineralogist 30, 895–921.

Tucker, R.D., Ashwal, L.D., Torsvik, T.H., 2001. U–Pb geochronology of Seychelles granitoids: a Neoproterozoic continental arc fragment. Earth and Planetary Science Letters 187, 27–38.

Turner, S.P., Foden, J.D., Morrison, R.S., 1992. Derivation of some A-type magmas by fractionation of basaltic magma: an example from the Pathaway Ridge, South Australia. Lithos 28, 151–179.

Turpin, L., Cuney, M., Friedrich, M., Bouchez, J.L., Aubertin, M., 1990. Meta-igneous origin of Hercynian peraluminous granites in N.W. French Massif Central: implications for crustal history reconstruction. Contributions to Mineralogy and Petrology 104, 163–172.

Tuttle, O.F., Bowen, N.L., 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. Geological Society of America Memoir 74. 153 pages.

Twist, D., Harmer, R.E.J., 1987. Geochemistry of contrasting siliceous magmatic suites in the Bushveld Complex: genetic aspects and implications for discrimination diagrams. Journal of Volcanology and Geothermal Research 32, 83–98.

Vaasjoki, M., Rämö, O.T., 1989. The Wiborg rapakivi batholith and associated rocks in south-eastern Finland. Symposium Precambrian Granitoids — Petrogenesis, Geochemistry and Metallogeny, Excursion A2. Geological Survey of Finland, Opas — Guide, vol. 30. 32 pages.

Vander Auwera, J., 2003. Preface. Origin and evolution of Precambrian anorogenic magmatism. Precambrian Research 124, 105–106.

Vander Auwera, J., Martin, H., Rämö, T. (Eds.), 2003. Origin and Evolution of Precambrian Anorogenic Magmatism. Precambrian Research, vol. 124, pp. 105–344.

Vorma, A., 1971. Alkali feldspars of the Wiborg rapakivi massif in southeastern Finland. Bulletin de la Commission Géologique de Finlande 246. 72 pages.

Vorma, A., 1976. On the petrochemistry of rapakivi granites with special reference to the Laitila massif, southwestern Finland. Geological Survey of Finland Bulletin 285. 129 pages.

Wang, L.G., McNaughton, N.J., Groves, D.I., 1991. Archean granitoids in the Murchison Province, Western Australia: petrogenetic classification and relations to gold mineralization. In: Chappell, B.W. (Ed.), 2nd Hutton Symposium on Granites and Related Rocks, Canberra 1991, Abstracts, Bureau of Mineral Resources. Geology and Geophysics Record, vol. 1991/25, p. 109.

Warren, P.H., Taylor, G.J., Keil, K., Shirley, D.N., Wasson, J.T., 1983. Petrology and chemistry of two "large" granite clasts from the Moon. Earth and Planetary Science Letters 64, 175–185.

Weaver, B.L., 1991. The origin of ocean island basalt end-member compositions: trace element and isotopic constraints. Earth and Planetary Science Letters 104, 381–397.

Wedepohl, K.H., 1991. Chemical composition and fractionation of the continental crust. Geologische Rundschau 80, 207–223.

Wegmann, C.E., 1938. Geological investigations in southern Greenland. Part I. Meddelelser om Grønland 113 (2). 148 pages.

Whalen, J.B., 2005. A-type granites: >25 years later. Abstracts of the 15th Annual V.M. Goldschmidt Conference, Moscow, Idaho, May 2005. Geochimica et Comochimica Acta 69, A84 (Special Supplement).

Whalen, J.B., Currie, K.L., Chappell, B.W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. Contributions to Mineralogy and Petrology 95, 407–419.

White, A.J.R., 1979. Sources of Granitic Magma. Abstracts of Papers to be Presented at the Annual Meetings of the Geological Society of America and Associated Societies, San Diego, California, November 5–8, 1979, vol. 11, p. 539.

Widom, E., Gill, J.B., Schmincke, H.-U., 1993. Syenite nodules as a long-term record of magmatic activity in Agua de Pão volcano, São Miguel, Azores. Journal of Petrology 34, 929–953.

Wilmart, E., Demaiffe, D., Duchesne, J.C., 1989. Geochemical constraints on the genesis of the Tellnes ilmenite deposits. Economic Geology 84, 1047–1056.

Wilson, J., Ferré, E.C., Lespinasse, F., 2000. Repeated tabular injection of high-level alkaline granites in the eastern Bushveld, South Africa. Journal of the Geological Society (London) 157, 1077–1088.

Windley, B.F., 1993. Proterozoic anorogenic magmatism and its orogenic connections. Journal of the Geological Society (London) 150, 39–50.

Young, D.A., 2003. Mind over Magma. The Story of Igneous Petrology. Princeton University Press, Princeton and Oxford. 686 pages.

Zozulya, D.R., Bayanova, T.B., Eby, G.N., 2005. Geology and age of the Late Archean Keivy alkaline province, Northeastern Baltic Shield. Journal of Geology 113, 601–608.