

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

Bernard Bonin*

“Interactions et Dynamique des Environnements de Surface”, CNRS-UPS UMR 8148, Département des Sciences de la Terre, Université de Paris-Sud, F-91405 ORSAY CEDEX, France

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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.

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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 km³ (Bonin et al., 2002). Roughly 86 vol.% of the upper continental crust is granitic in composition (Wedepohl, 1991). Granite occurs also,

* Tel.: +33 1 69 15 67 66.

E-mail address: bbonin@geol.u-psud.fr.

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 $0.03\text{--}0.10\text{ km}^3\text{ yr}^{-1}$ and of plutonic magma at $0.1\text{--}1.5\text{ km}^3\text{ yr}^{-1}$, corresponding to 1.0–2.5% of the $26\text{--}34\text{ km}^3\text{ yr}^{-1}$ global rate of magma emplacement. Oceanic island output is higher and amounts to $0.3\text{--}0.4\text{ km}^3\text{ yr}^{-1}$ of volcanic magma and $1.5\text{--}2.0\text{ km}^3\text{ yr}^{-1}$ 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 H₂O and oxygen fugacities and relatively high HF/H₂O 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	Anorthosite–gabbro–diorite		
IUGS nomenclature	Monzogabbro–monzodiorite–monzonite		
Le Maitre et al. (2002)	Syenite–alkali feldspar syenite–nepheline syenite		
Rock-forming mineralogy	Felsic assemblage	Quartz	Purple to brown to black euhedral β-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
	Accessory mineralogy	Subsolidus mica associations (Bonin, 1986; Martin et al., 1994; Azzouni-Sekkal et al., 2003)	Annite–siderophyllite; Zinnwaldite–trilithionite, Montdorite; Celadonic muscovite; Clay minerals
		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–...	
Bulk-rock chemistry		Others	Fluorite–REE fluorides±carbonates
	FeO/(FeO+MgO)>0.446+0.0046×wt.% SiO ₂ (Frost et al., 2001)		Ferroan A-type group
	FeO ^T /(FeO ^T +MgO)>0.486+0.0046× wt.% SiO ₂		
	For low Ga/Al and (Zr+Nb+Ce+Y): FeO ^T /MgO>16		
	4<FeO ^T /MgO<16		A-type granites
	FeO ^T /MgO<4 (Whalen et al., 1987)		Fractionated felsic granites (FG)
	ASI= A/CNK = molar Al ₂ O ₃ /(CaO+Na ₂ O+K ₂ O)= Al/(2 Ca+Na+K) (Shand, 1922)		Unfractionated granites (OGT)
	ASI>1		
	ASI<1	NK/A=(Na+K)/Al<1	Peraluminous
		NK/A>1	Metaluminous
	For any ASI values	NK/A>0.85 (Giret et al., 1980; Whalen et al., 1987)	Peralkaline
		NK/A>0.88 (Liégeois and Black, 1984)	Alkaline or A-type suites
	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×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
	REE contents and patterns	Y/Nb>1.2	A2 subtype, post-collisional
		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 gabbro-norite 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.

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)
	Cratonic	Re-activation of transcurrent shear zones within uplifts and swells	Western Mediterranean province	280–235 Ma	Bonin et al. (1987, 1998)
			Comendite, San Pietro Island	15 Ma	Morra et al. (1994)
			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)
	Active margins	Converging plate Extensional regime	Western border of the Yemen Plateau	30–20 Ma	Capaldi et al. (1987)
			Papua-New Guinea and Mayor Island, New Zealand	5–0 Ma	Smith et al. (1977)
Oceans	Oceanic ridges	Diverging plate boundary	Ashizuri massif, S Japan	14±1 Ma	Stein et al. (1992)
			Plagiogranite, Faeroe–Shetland Basin	Eocene	Kanaris-Sotiriou and Gibb (1989)
	Oceanic islands	Within-plate	Austurhorn, SE Iceland	7–6 Ma	Furman et al. (1992)
			Argo Fracture Zone, Indian Ridge	?	Engel and Fisher (1975)
			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)
			Pathfinder site	?	McSween et al. (1999)
			SNC meteorites	4.5 Ga–180 Ma	Bonin and Bébien (2005)
	Asteroids	Chondrites, IIE irons, Howardite–eucrite–diogenite (HED)	Quartz feldspar assemblages	4.5–3.5 Ga	Bonin et al. (2002)
			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

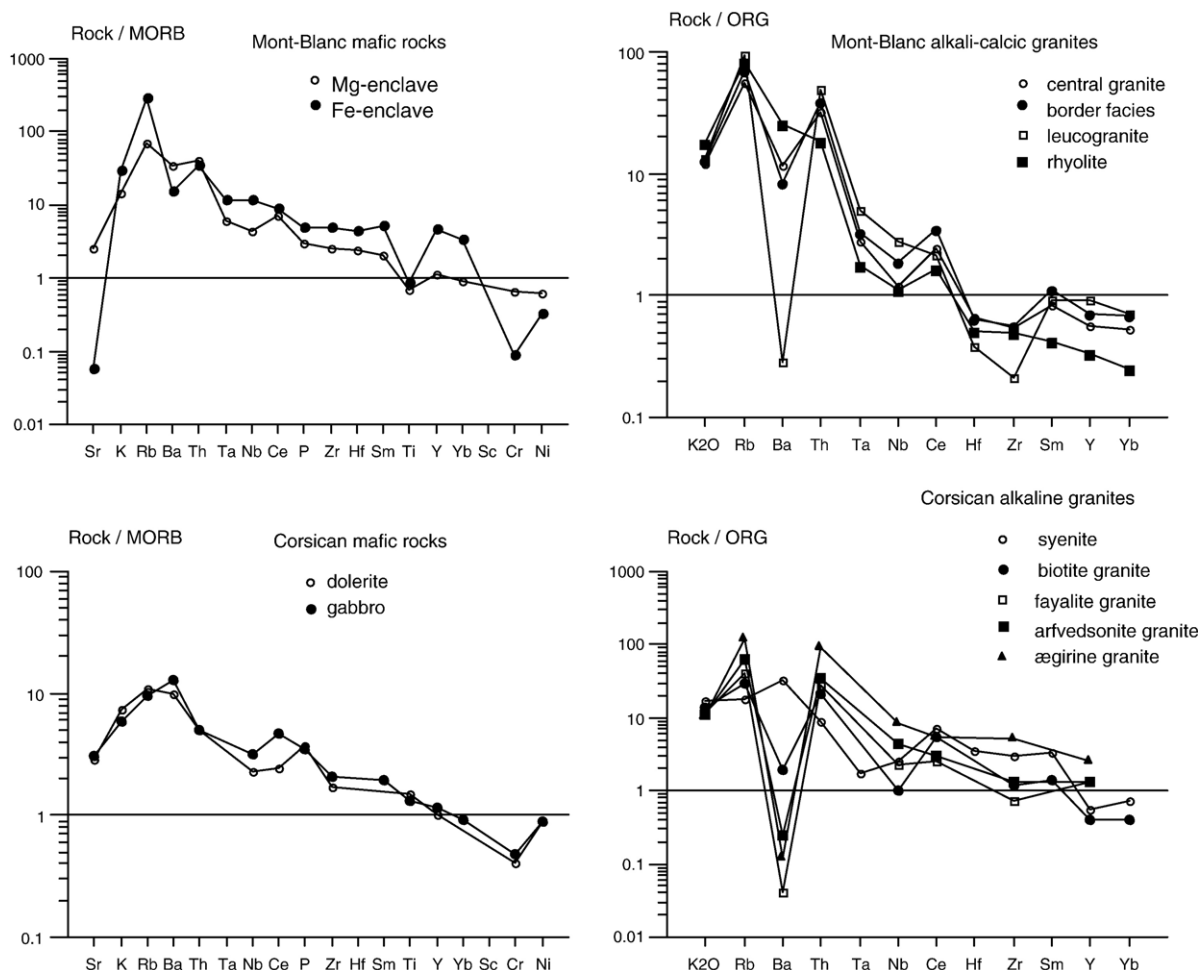


Fig. 1. Comparative chemical compositions of MORB-normalized (values from [Pearce, 1983](#)) mafic and ORG-normalized (values from [Pearce et al., 1984](#)) felsic rocks of Corsica and Mont-Blanc (after [Bonin et al., 1998](#)).

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

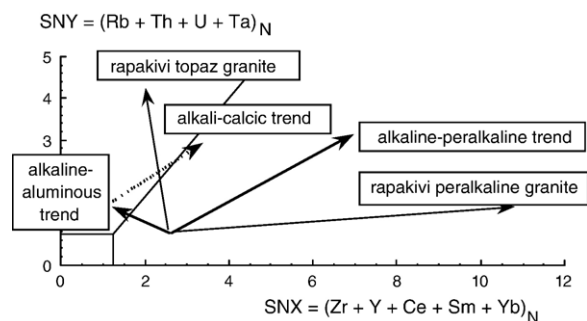


Fig. 2. Chemical compositions of different A-type suites plotted in the sliding-normalization diagram of Liégeois et al. (1998). The reference suite used for normalization is the alkali-calcic A-type Yenchichi–Telabit dyke swarm, Adrar des Iforas, Mali. Fields correspond to: syn-collision suites (lower 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 Kudara 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 $(\text{Na}_2\text{O} + \text{K}_2\text{O}) : \text{Al}_2\text{O}_3 : \text{SiO}_2$ 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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 through 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 sub-continental 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 H₂O. 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 CO₂, 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 Króksfjörður central volcano, NW Iceland (Jónasson et al., 1992), is more intriguing. It is composed of Mg# $\approx$ 50, calc-alkaline dacites, which are Ca- and Al-rich and slightly peraluminous ($1.0 < ASI < 1.1$), 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 hornfels 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.% K₂O 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.% K₂O 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.% K₂O) 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

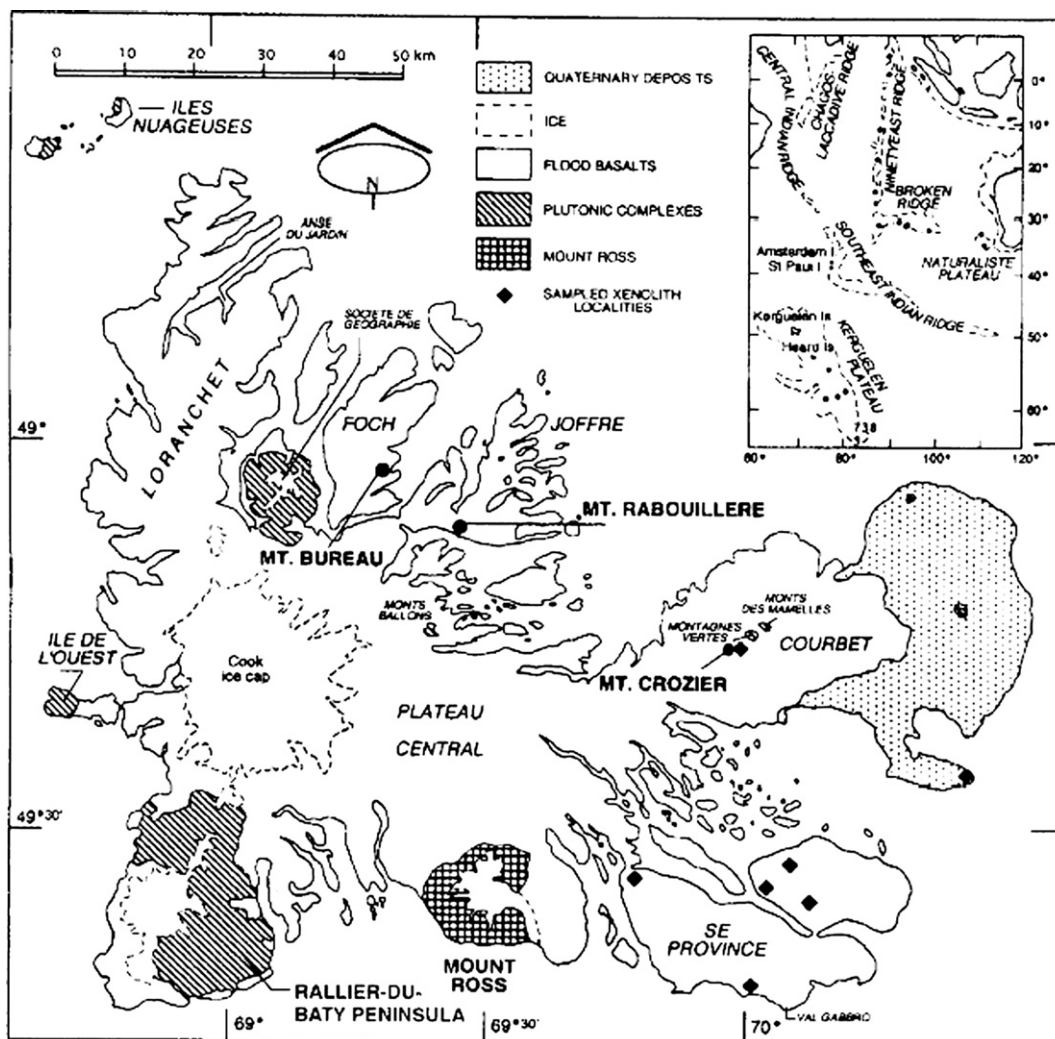


Fig. 3. Map of the Kerguelen Archipelago, showing the location of the Rallier-du-Baty Peninsula and the major features of the main island (after Gagnevin et al., 2003, Bonin et al., 2004). Diamonds: localities where lower crust xenoliths were sampled; dots: localities where stratigraphic sections of 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.% H₂O) 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.% SiO₂ and 0.4–1.6 wt.% K₂O contents. These liquid compositions yield the low alumina contents and high Fe/Mg ratios postulated for A-type granite, but K/Na ratios and K₂O 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

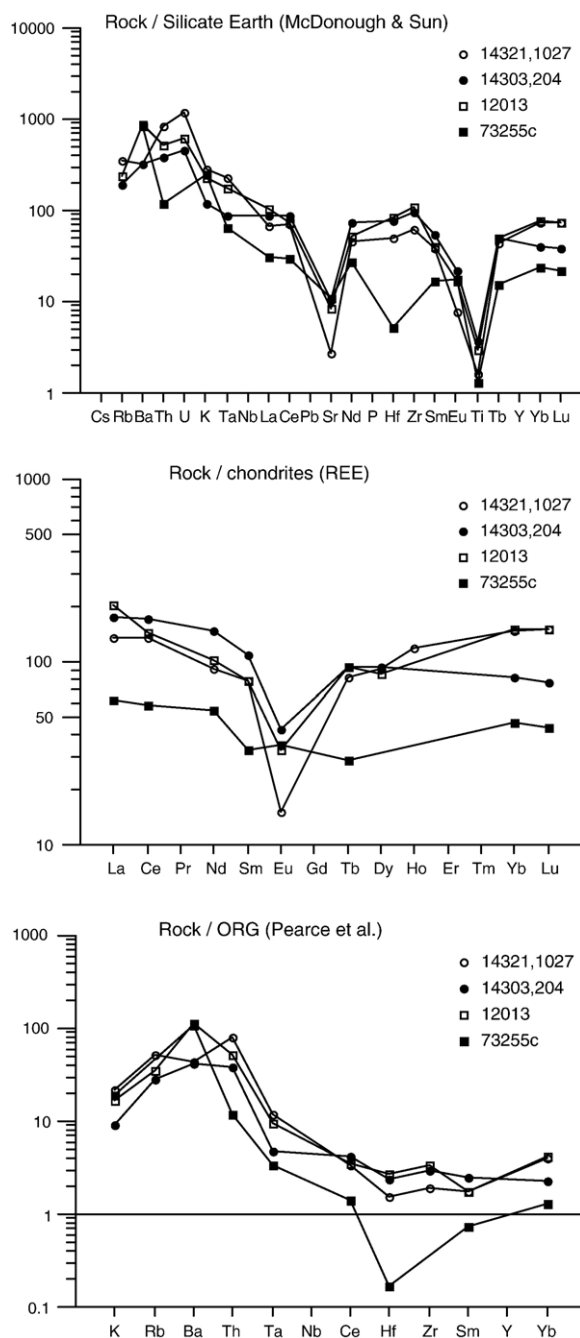


Fig. 4. Chemical compositions of Lunar granite clasts (Warren et al., 1983) plotted in multi-element diagrams: A. Bulk silicate earth normalized spidergrams (normalizing values from McDonough and Sun, 1995). B. Chondrite-normalized REE patterns (normalizing values from McDonough and Sun, 1995). C. Oceanic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

heat source. Natural tests are offered by crustal xenoliths carried by volcanic lavas and pyroclastites. They display quenched glasses issued from incongruent melting of

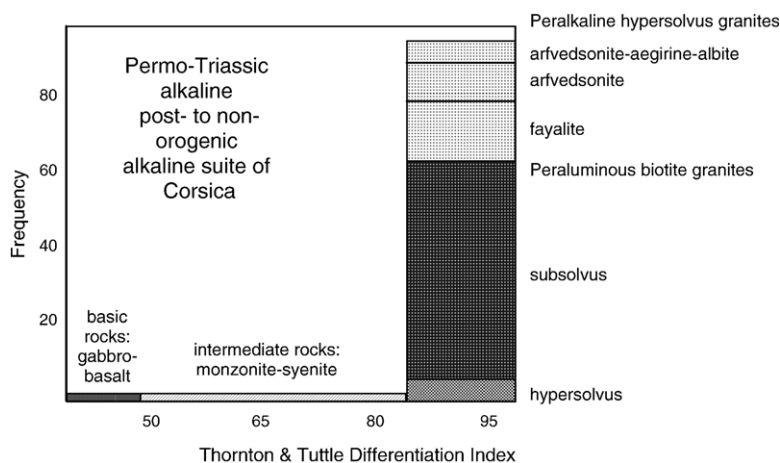


Fig. 5. Histogram showing the distribution of rock types as a function of DI for the Permian–Triassic alkaline province of Corsica. Low-DI basic rocks (2%) are gabbro-norite–anorthosite association and rare basalt–hawaiite lava flows and dykes. Intermediate rocks (2%) range from monzodiorite to monzonite 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

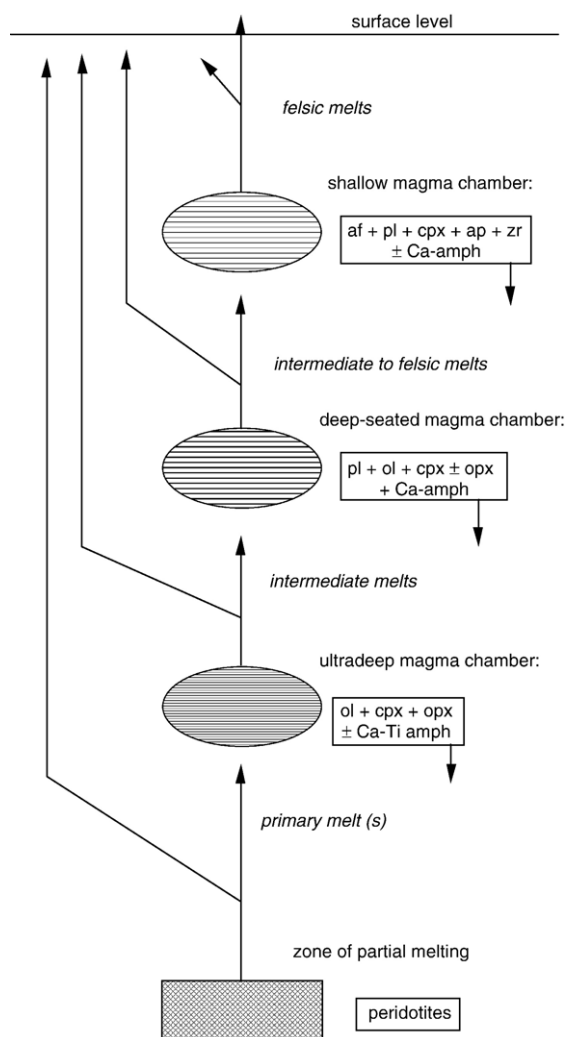


Fig. 6. Fractional crystallisation processes within a network of magma chambers emplaced at various depths. Primary magmas originate from partial melting of upper mantle and evolve ultimately into felsic residual liquids. At each level, the average fractionating mineral assemblage, which precipitates 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 funda-

mental 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 gabbro-norite, 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).

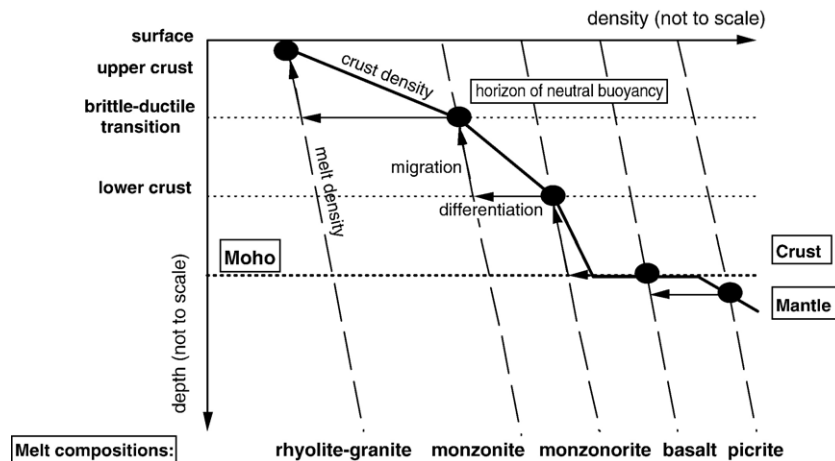


Fig. 7. Density versus depths within upper mantle and crust. Each liquid of a specific composition is capable to migrate upwards to its horizon of neutral buoyancy, where it is stored within a magma chamber and differentiates into less dense and more evolved residual liquids. Residual liquids can in 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

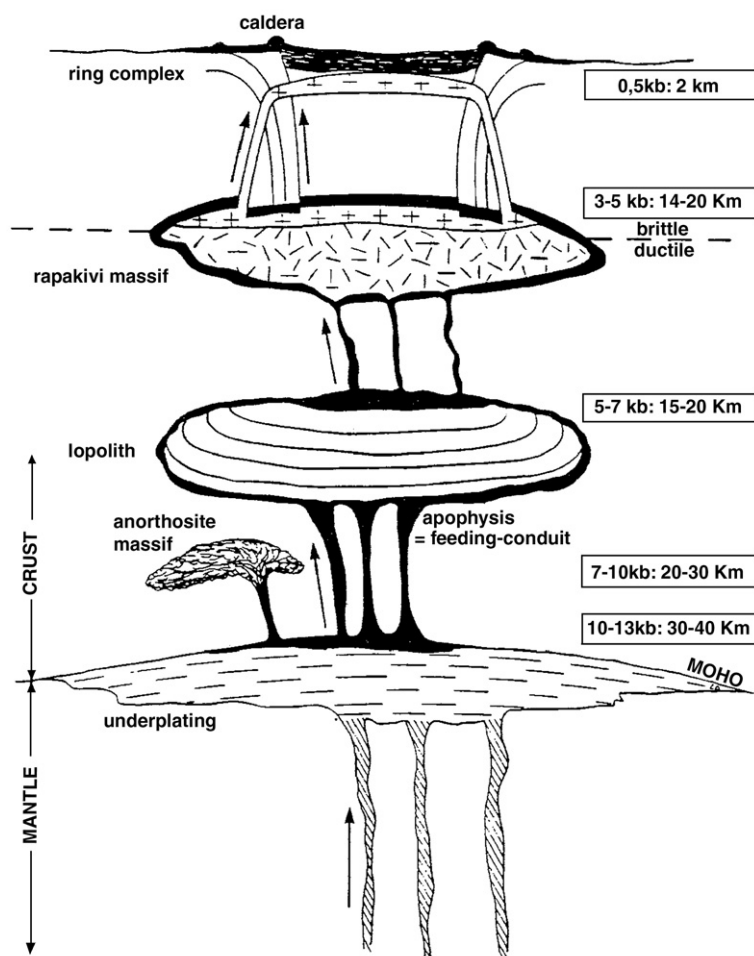


Fig. 8. Structural levels of A-type granite magmatism (updated after Bonin, 1986, 1996). The depth values are only approximate and evolve slightly as a function of the physical parameters of wall rocks and magmas. Surface level: caldera volcano, feeder radial and ring dykes, and domes. Subvolcanic 1–4 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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