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A review of the relationships between granitoid types, their origins and their geodynamic environments

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Abstract

Granitoids are divided into several types according to their mineral assemblages, their field and petrographical features, and their chemical and isotopic characteristics. This typology complements most of the recent classifications because it is not based solely on chemical and isotopic criteria but also on the field, petrographical and mineralogical criteria. It thus has the advantage of distinguishing the various granitoid types in the field, in most cases. The proposed classification shares many similarities with the twenty most used genetic classifications of granitoids. Both types of peraluminous granitoids are of crustal origin; the «tholeiitic», alkaline and peralkaline granitoids are of mantle origin; and both types of calc-alkaline granitoids are of mixed origin and involve both crustal and mantle materials. Each granitoid type is generated and emplaced in a very specific tectonic setting. Each stage of the Wilson cycle is characterised by typical associations of granitoids. Well-typed and precisely-dated granitoids can then complement structural approaches and indicate on the geodynamic environment. With reference to some case-studies, the use of granitoids as tracers of the geodynamic evolution is also proposed and discussed.

Keywords: Granite; Granitoid; Tectonics; Geodynamics; Classification

1. Introduction

Granitic rocks or granitoids, i.e., granular igneous rocks that generally contain quartz and two feldspars, display great diversity because of the variety of their origins, sources, subsequent genesis and evolution processes, emplacement at different structural levels and under different tectonic regimes, in distinct geodynamic environments.

About twenty petrogenetic classifications of granitoids are proposed in the literature. From their comparison, a synthetic classification was established (Barbarin, 1990). This classification is not widely used because of the complexity of the criteria, the absence of neat distinction between the types, the initials used to designate each type, and also because the links between granitoid types and geodynamic environments were not fully elaborated. In this re-

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port, granitoids are divided into fewer types, according firstly to field criteria such as mineralogical or petrographical parameters, then to chemical and isotopic criteria. The initials used to designate each type reflect both the typical AFM minerals and the chemical features. The origin and petrogenesis of each type are discussed in detail. To each geodynamic environment is associated but a space-related or time-related association of granitoid types rather than the most common granitoid type.

In the first part of the paper, granitoids are divided into several types according to their mineral assemblages as well as their field, petrographical and emplacement criteria. Chemical and isotopic data are then used to group the types with the same origin: peraluminous granitoids of crustal origin, «tholeiitic» and alkaline granitoids of mantle origin, and calc-alkaline granitoids of mixed origin with various proportions of crustal and mantle-derived components. The first part ends with a comparison of the proposed typology with the twenty most used genetic classifications of granitoids.

In the second part of the paper, granitoid types are related to geodynamic environments. The goal is to use well-typed and well-dated granitoid types as indicators of geodynamic environments, and in some cases as tracers of geodynamic evolution. Because granitoids are the main components of the continental crust, it is then also possible to deduce, from the origins and evolutions of granitoids, the importance

(a)

MINERALS	MPG	CPG	KCG	ACG	RTG	PAG
Biotite	x	x x x	x x x	x x	x	x x
Muscovite	x x x	x	x	o	o	x
Cordierite	o	x x	o	o	o	o
Sill.-And.	o	x	o	o	o	o
Amphibole	o	o	x	x x x	x x x	alk. amph.
Pyroxene	o	o	o	x x	x x	alk. pyr.
Apatite	x x x	x x x	x x	x x	x x	x x
Zircon	x	x x	x x x	x x x	x x x	x x x
Monazite	x	x	o	o	o	o
Garnet	x x	x	o	o	o	x
Tourmaline	x x x	x x	o	o	o	o
Allanite	o	x	x x	x x	x	x x
Titanite	o	o	x x	x x x	x	x
Ilmenite	x	x	x	x	x	x x
Magnetite	o	o	x	x x	x x	x x
Plag.-An%	0 - 20	15 - 40	15 - 30	20 - 50	20 - 50	0 - 10

(o : absent; x : rare; xx : common; xxx : abundant)

Fig. 1. Principal mineral assemblages (A), field and petrographical (B), major elements and isotopes (C) features of the main types of granitoid. (M.E.: microgranular enclaves).

(b)

PETROGRAPHY	MPG	CPG	KCG	ACG	RTG	PAG
Petrographic types	Leucogranites (Granites)	(Leucogranites) Granites Granodiorites (Qz diorites)	(Leucogranites) Granites Granodiorites Qz diorites	(Granites) Granodiorites Tonalites Gabbros	Plagiogranites Trondjhemites Tonalites Gabbros	Alk. granites Alk. syenites Syenites Granites (Gabbros) (Anorthosites)
Associated rocks						
Metamorphic	o	Migmatites Anatexites	o	o	o	o
Volcanic	o	o	Acid lavas ("Tuffs")	Andesites & Dacites	Olivine-bearing Tholeites	Alkaline lavas
Mafic	o	Qz diorites (Vaugnerites)	Qz diorites Gabbros (Appinites)	Gabbros (in large amounts)	Gabbros (in large amounts)	Gabbros (in large amounts)
Enclaves						
Xenoliths	x	o - x	x	x	x	x
Restites	x	x x x	x	o	o	o
Felsic M. E.	x	o - x	x	x	x	x
Mafic M. E.	o	x	x x	x x x	x x x	x
			(o : absent; x : rare; xx : common; xxx : abundant)			
Differentiation processes	fractional crystallization	fractional crystallization or restite unmixing	fractional crystallization and magma mixing	strong fractional crystallization and magma mixing	extreme fractional crystallization	extreme fractional crystallization and subsolidus interactions

Fig. 1 (continued).

of genesis and recycling of the continental crust in various geodynamic environments.

2. Nomenclature of granitoids

Firstly, it is necessary to distinguish the purely descriptive from the genetic typologies. Purely descriptive typologies allow petrologists to give a precise name to the granitic rocks. They are based either on the mineral contents and modes, or the chemical compositions and norms of the granitoid samples (e.g., Lacroix, 1933; Streckeisen, 1976; de La Roche et al., 1980 (R1–R2); Le Maître, 1989). Because minerals are fairly easy to recognise in plutonic rocks and modes of granitoids can be quickly obtained, descriptive typologies based on the absence or presence of major felsic minerals (i.e., quartz, plagioclase, and alkaline feldspar), and on their relative abundances, are favoured. Currently, most geologists world-wide used the descriptive typology set up by the IUGS commission (Streckeisen, 1976; Le Maître, 1989).

3. Granitoid types

When granitoid rocks are well-defined and with a precise name, it is then important to consider their

(c)

CHEMISTRY	MPG	CPG	KCG	ACG	RTG	PAG
Alumina Index A / KCN (molar)	A ≥ CNK ≥ 1		CNK > A > NK < 1			A ≤ NK alkaline
Al_2O_3	x x x	x x x	x x	x x	x x	x
CaO	x	x	x x	x x x	x x	x
Na_2O	x x	x x	x x	x x	x x x	x x x
K_2O	x x	x x x	x x x	x x	x	x x x
FeOt+MgO+MnO	x	x x	x x	x x x	x x	x x
$Fe^{3+}/(Fe^{3+}+Fe^{2+})$	x	x	x x	x x x	x x x	x x
FeOt/(FeOt+MgO)	< 0.8	< 0.8	0.8 - 1.0	< 0.8	> 0.8	> 0.8
$^{87}Sr / ^{86}Sr$	.706 to .760	> .708	.706 to .712	.706 to .708	≤ .704	.704 to .712
ε_{Nd}	- 4 to -17	- 6 to - 9	- 4 to - 9		-	-
$\delta\ ^{18}O$ (‰)	+ 10 to +14	+ 10 to + 13	+ 5 to + 10		-	-
$\delta\ ^{34}S$ (‰)	- 12 to + 2		+ 5 to + 20		-	-

(x : low; xx : medium; xxx : high)

Fig. 1 (continued).

AFM mineral assemblages and their field, petrographical and emplacement data. Biotite, and accessory apatite and zircon, are present in various abundances in most granitoids (Fig. 1A).

Muscovite can be accessory in many types of granitoids, but large flakes of primary and zoned muscovite (Roycroft, 1991) are abundant only in one single type (MPG). These felsic muscovite-rich leucogranites or two-mica granites frequently contain tourmaline, garnet and monazite (Fig. 1A). They are generally intrusive and extremely poor in enclaves. Where present, enclaves are generally xenoliths of country rocks or fragments of chilled margins, and rare restites (Fig. 1B). Exceptional two-mica granites can be rooted in metamorphic rocks and then contain restites as enclaves. The Manaslu and other High Himalayan leucogranites (e.g., Le Fort, 1981) and most two-mica granites of the Hercynian belt of Western Europe (Lameyre et al., 1980; de La Roche et al., 1980) are good examples of this type.

Cordierite, associated with sillimanite, rare andalusite and a few small flakes of primary muscovite, is distinctive of a second type of granitoids (CPG). Cordierite may be present to abundant (e.g., Zen, 1988; Barbarin, 1992); it generally occurs as pinnitised idiomorphic prisms, and more exceptionally as nodules consisting of associations of cordierite and quartz (Didier and Dupraz, 1985). The biotite-rich cordierite-bearing granites and granodiorites also contain tourmaline, garnet and monazite (Fig. 1A). They are either intrusive or deep-seated. The enclaves consisting of many mica-rich restites and some mafic microgranular enclaves (e.g., Didier and Barbarin, 1991) are especially abundant where the granitoids are still rooted in high-grade metamorphic rocks, or where they are associated with these rocks to form anatectic complexes (Fig. 1B). The S-type cordierite-rich granitoids of the Lachlan Fold Belt, south-eastern Australia (White and Chappell, 1983; Chappell and White, 1992a,b), are the best examples of this type. The cordierite-poor K-feldspar porphyritic granites and granodiorites from the Hercynian belt of Massif Central, France (e.g., Couturié, 1977), and from other places, also belong to this type. These generally intrusive granitoids are frequently associated with quartz-diorites (vaugnerites).

In comparison with these two first types, the other granitoids contain amphibole, pyroxene and accessory titanite and magnetite (Fig. 1A). The abundance and nature of amphibole vary considerably from one type to another. Calcic amphibole and titanite are ubiquitous and even abundant, and pyroxene also occurs, in the granodiorites and tonalites (ACG). Xenoliths and felsic microgranular enclaves are common near the margins of these intrusive granitoids. Mafic magmatic enclaves are especially abundant and form several meter-scale enclave swarms (Barbarin, 1991, 1995). No restitic enclaves are observed (Fig. 1B). The amphibole-rich granodiorites and tonalites are clustered into vast batholiths topped by huge andesitic volcanoes. They are also called cordilleran or Andean granitoids because they are the main components of the cordillera that stretch along the western margins of the American continents from Patagonia to northern Canada (Bartholomew and Tarney, 1984; Pitcher et al., 1985; Bateman, 1983, 1992), and probably all around the Pacific Ocean. Most I-type granitoids of the Lachlan Fold Belt of south-eastern Australia (White and Chappell, 1983; Chappell and White, 1992a,b) belong to this type.

A very special granitoid type contains only rare amphibole, no pyroxene and some titanite (Fig. 1A). The K-feldspar porphyritic texture is the main feature of these granites and (less frequently) granodiorites (KCG). Like the ACG type, they are intrusive and contain xenoliths and felsic microgranular enclaves. Enclave swarms are however exceptional and the mafic magmatic enclaves are never as abundant as in the ACG. Furthermore, some restitic enclaves occur (Fig. 1B). These K-feldspar porphyritic and amphibole-poor granites and occasionally granodiorites are also called shoshonitic, sub-alkaline granitoids. They are generally associated with peraluminous granitoids and are especially abundant in the Caledonian plutons of the northern British Isles (e.g., Brown et al., 1981; Halliday and Stephens, 1984) and in the Hercynian belt of Western Europe (e.g., Barrière, 1977; Pagel and Leterrier, 1980; Lameyre et al., 1980). It is not always very easy to distinguish the KCG type from the ACG type on one hand, and the KCG type from some K-feldspar porphyritic CPG type, on the other hand.

The very scarce plagiogranites, trondjhemites, tonalites and gabbros of the RTG type occur within the oceanic crust in which they form dikes or small plutons (Coleman and Peterman, 1975; Coleman and Donato, 1979). These amphibole-rich and pyroxene-bearing rocks (Fig. 1A) differ from the other types mainly because of their associations with the oceanic mafic rocks (Fig. 1B). These granitoids were described in many ophiolitic complexes (e.g., Pedersen and Malpas, 1984; Bébien et al., 1997).

The last type of granitoids also contains amphibole and pyroxene, but these minerals are sodic rather than calcic (Fig. 1A). The perthitic alkali feldspar granites to syenites (PAG) are very homogeneous rocks; mafic magmatic enclaves are scarce and the rare enclaves mainly consist of xenoliths and felsic microgranular enclaves (Fig. 1B). They commonly form ring complexes topped by caldera and alkaline lavas. The sodic amphibole- and pyroxene-bearing granitoids are present in the Monteregian Hills, Canada, and White Mountains, USA (e.g., Eby et al., 1992), in Corsica (Bonin, 1988; Egeberg et al., 1993), in the Sahara desert, Africa (e.g., Black and Liégeois, 1993), in Yemen (Capaldi et al., 1987) or in the Kerguelen Islands (Giret, 1990). Rapakivi granitoids such as those that occur in the Oslo graben are special PAG (Bonin, 1996).

The main problem with the proposed approach concerns the granitoids in which biotite is the only AFM phase. It is then necessary to go through the entire pluton to seek other AFM minerals. In some granitoids such as the Margeride granite, Massif Central, France, cordierite is very scarce and occurs only at a few localities (Couturié, 1977). Another way to address this problem is to look at the granitoid types, the enclave populations, the shape of the plutons, and the chemistry. Biotite compositions and zircon morphologies may also indicate to which types theirs hosts belong. Aluminium-enrichment decreases from muscovite- or cordierite-bearing granitoids, through amphibole-bearing granitoids, to sodic amphibole- and pyroxene-bearing granitoids (Nachit et al., 1985; Abdel-Rahman, 1994). Biotites from sodic mineral-bearing granitoids are also depleted in magnesium. Zircons that are ubiquitous in most granitoids display very distinct morphologies (Pupin, 1980).

4. Granitoid types and origins of magmas

Compositions of igneous biotites actually reflect the magma compositions because experimental work has shown that biotite continuously equilibrates with the host liquids. The other AFM minerals also reflect the whole rock compositions, and subsequently, the origins of the granitoids.

Some petrologists still consider that most granitoids only derive from the continental crust (Chappell and White, 1974, 1992a,b; Chappell et al., 1987). The diversity of granitoid rocks then does not result from different origins but from the various sources that can be melted in the continental crust to form granitic magmas (Chappell, 1979). They cannot however explain the genesis of granitoids in some areas where there is no continental crust present. As an example, in the middle of the Indian Ocean, the Kerguelen granitoids are not related to any continental crust (e.g., Lameyre et al., 1976; Giret, 1990). Furthermore, the abundant cordilleran granitoids display isotopic features which are intermediate between those of the continental crust and those of mantle materials (e.g., DePaolo, 1981). Most petrologists actually consider three possible origins: a crustal origin, a mantle-derived origin, and a mixed origin that involves both crustal and mantle-derived components.

Because crustal and mantle-derived materials have distinct chemical signatures, the resulting granitoids can be distinguished by their chemical features. The aluminium saturation index (ASI = molar $Al_2O_3/[CaO + Na_2O + K_2O]$) is the chemical discriminant between peraluminous granitoids (ASI > 1) and metaluminous granitoids (ASI < 1) (e.g., Shand, 1943; Zen, 1988). Metaluminous compositions can also be divided into calc-alkaline granitoids (molar $Al_2O_3 > Na_2O + K_2O$) or alkaline to peralkaline granitoids (molar $Al_2O_3 \leq Na_2O + K_2O$). The whole set of chemical and isotopic data suggest that peraluminous granitoids are of crustal origin, calc-alkaline granitoids are of mixed origin, and alkaline to peralkaline granitoids are of mantle origin.

The MPG and CPG types are peraluminous granitoids and generally display high to very high Sr_i (Fig. 1C). The MPG (Muscovite-bearing Peraluminous Granitoids) and the CPG (Cordierite-bearing Peraluminous Granitoids) are granitoids of crustal origin (Fig. 2). Chemistry also underlines the differences between the MPG and the CPG: the peraluminous character strongly increases with differentiation for the MPG, while it drastically decreases or slightly increases with differentiation for the CPG (Barbarin, 1996). Restitic enclaves that are produced by melting of crustal materials are frequent in both types, while scarce mafic microgranular enclaves that represent strongly modified mantle-derived materials (e.g., Barbarin and Didier, 1992a,b), only occur in CPG (Fig. 1B). Chemical and isotopic features and presence of scarce mafic magmatic enclaves indicate that some mantle-derived magmas are commonly in-

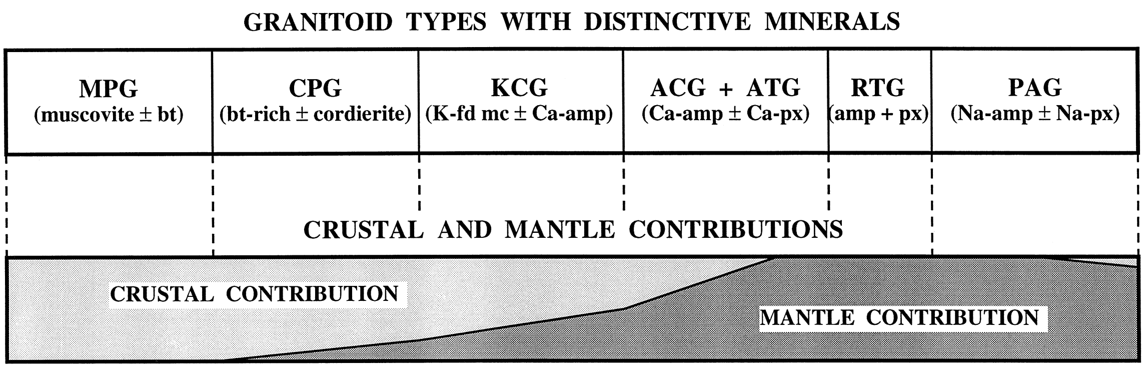


Fig. 2. Schematic diagram showing the various granitoid types, their AFM mineral assemblages, and the proportions of mantle and crustal components in each of them. (bt: biotite; K-fd mc: K-feldspath megacryst; amp: amphibole; px: pyroxene).

volved in the CPG (Fig. 2). Genesis of the two types of peraluminous granitoids is not only controlled by the nature of the sources, but mainly by the conditions of crustal anatexis (Barbarin, 1996): in peraluminous granitoids, wet and dry AFM mineral assemblages (Zen, 1989) are formed where anatexis of the crust is enhanced, respectively, by major shears or thrusts (MPG), or by underplating and local injections of mantle-derived magmas (CPG).

The PAG (Peralkaline and Alkaline Granitoids) are poor in Al_2O_3 and CaO, but rich in Na_2O, K_2O and FeO_t (Fig. 1C). The mantle origin of the PAG is questioned by some authors because some plutons display high Sr_i. Survey of many PAG indicates that limited crustal contamination, and strong postmagmatic alteration can significantly modify their initial isotopic signatures (e.g., Eby et al., 1992; Bonin, 1996). Some PAG are not purely of mantle origin but involve some crustal materials (Fig. 2). In the localities where there is no continental crust, it is difficult to not consider the PAG as the products of extreme fractionation of mantle-derived magmas.

The scarce RTG display very low Sr_i (Fig. 1C) and are associated with mafic rocks of the oceanic crust: they have a mantle origin. Their «tholeiitic» affinity and occurrence within the oceanic crust led us to call them RTG (Ridge «Tholeiitic» Granitoids). Another type of granitoid also have «tholeiitic» affinity and mantle origin. The ATG (Arc «Tholeiitic» Granitoids) are distinct from the RTG because they occur in volcanic arcs and active continental margins, where they are generally associated with the ACG. Mineral assemblages and field, petrographical, chemical and isotopic data of the scarce ATG are not specified in Fig. 1 because the ATG resemble the ACG and share most of their features with the ACG, although the ATG consist of amphibole-rich tonalites and diorites, and not granodiorites or granites like the ACG.

The KCG and ACG are calc-alkaline granitoids of mixed origin. The distinction between the KCG (K-rich and K-feldspar porphyritic Calc-alkaline Granitoids) and the ACG (Amphibole-rich Calc-alkaline Granitoids) is also underlined by the chemical data (Fig. 1C). The KCG have a low CaO-content and a constantly high K_2O-content (about 5 wt.%). Conversely, the ACG are invariably richer in CaO for the same SiO_2-content and become K_2O-rich only when it is extremely differentiated. The crustal component is dominant in the K_2O-rich and CaO-poor KCG, whereas the mantle component is dominant in the CaO-rich and K_2O-poor ACG (e.g., DePaolo and Farmer, 1984; Pitcher, 1993) (Fig. 2). A mantle origin for the cordilleran granitoids consisting of ACG and ATG was proposed by Brown (1977).

Most granitoids are believed to involve both mantle and crustal-derived components. Some of the granitoids from the crustal group may contain some mantle-derived materials. Some granitoids from the mantle group can include materials or elements from the continental crust which they intruded (Fig. 2). As suggested by Pupin (1980), it is better to distinguish the granitoids of mixed origin, granitoids with either a purely or essentially crustal origin, and granitoids with a purely or mainly mantle-derived origin.

To summarise, six granitoid types can be defined according to their mineral assemblages, field, petrographical and chemical criteria (Fig. 1). There are two types of peraluminous granitoids of purely or essentially crustal origin (MPG and CPG, respectively), two types of calc-alkaline granitoids of mixed origin (KCG and ACG), and two types of «tholeiitic» or alkaline granitoids of purely or mainly mantle-derived origin (ATG or RTG, and PAG, respectively).

5. Petrogenetic classifications of granitoids

Since Read (1956) pointed out that there are ‘granites and granites’, many typologies of granitoids have been proposed. The first were bimodal, but they quickly become more complex. In some recent typologies, up to seven types of granitoids are distinguished (Fig. 3). In some areas where one group of granitoids is specially abundant, this group can be divided into many types while the other groups are more or less neglected (Fig. 3). The majority of classifications that were proposed in recent years refer to the origin and petrogenesis of granitoids, subjects which still remain a matter of controversy. In contrast to purely descriptive classifications that are used to name individual granitoid samples, genetic typologies generally facilitate the typology of suites of granitic rocks. Because each typology is set up for granitoids from particular areas and because

PARAMETERS	AUTHORS	ORIGIN											
		CRUSTAL					MIXED			MANTLE			
FIRST CHEMICAL NOMENCLATURES	SHAND (1927 & 1943)	PERALUMINOUS rocks					METALUMINOUS rocks					PERALKALINE rocks	
	LACROIX (1933)	Roches CALCO-ALC. HYPERALUMINEUSES			Roches CALCO-ALCALINES							Roches ALCALINES	
PETROGRAPHY	CAPDEVILA & FLOOR (1970) CAPDEVILA et al. (1973)	Granites MESOCRUSTAUX			Granites MIXTES			Granites BASICRUSTAUX					
	ORSINI (1976 & 1979)				A.M. SUB-ALC. ALUMINEUX			A.M. SUB-ALC. HYPOALUM.	A.M. CALCO-ALC.				
	YANG CHAOQUN (1982)		MM-TYPE		CR-TYPE			MS-TYPE				MD-TYPE	
	TISCHENDORF & PALCHEN (1985)	S_i	S_S		S_i			I_{KK}	I_{OK}	I_{MT}		I_{MA}	
ENCLAVES	DIDIER & LAMEYRE (1969) DIDIER et al. (1982)	C-TYPE (Crustal) ("Leucogranites")					M-TYPE (Mixed or Mantle) ("Monzogranites & Granodiorites")						
MINERALOGY (QAP system)	LAMEYRE (1980) LAMEYRE & BOWDEN (1982)	"LEUCOGRANITES" (Crustal fusion)			CALC-ALKALINE Series (High K, Medium K or Low K)					THOLEIITIC Series		(PER) ALKALINE Series	
MAFIC MINERALS	ROSSI & CHEVREMONT (1987)	A.M. ALUMINOPOTASSIQUE (s.s. ou composites)						A.M. MONZONITIQUE	A.M. CALCOALCALINE	A.M. THOLEITIQUE		A.M. (PER) ALCALINE	
BIOTITE COMPOSITION	NACHIT et al. (1985)	Lignées ALUMINO-POTASSIQUES						Lignées CALCOALCALINES et SUBALCALINES				Lignées ALCALINES et HYPERALCALINES	
ZIRCON MORPHOLOGY	PUPIN (1980 & 1985)	TYPE 1	TYPE 2		TYPE 3			TYPE 4 & 5		TYPE 7		TYPE 6	
OPAQUE OXIDES	ISHIHARA (1977) CZAMANSKE et al. (1981)	ILMENITE - Series							MAGNETITE - Series				
GEOCHEMISTRY (Major Elements)	CHAPPELL & WHITE (1974 & 1983) COLLINS et al. (1982), WHALEN et al. (1987)			S - TYPE				(I - TYPE)*		M - TYPE		(A - TYPE)*	
	LA ROCHE (1986) LA ROCHE et al. (1980)	AK-L M.A.		AK-G M.A.				SA M.A.	CA M.A.	TH M.A.		A-PA M.A.	
	DEBON & LE FORT (1983 & 1988)	ALUMINOUS M.A.					ALUMINO-CAFEMIC and CAFEMIC M.A. (Subalkaline, calc-alkaline, tholeiitic, and (per)alkaline)						
	MANIAR & PICCOLI (1989)	CCG						POG	CAG	IAG	OP	RRG	CEUG
GEOCHEMISTRY (Trace Elements)	TAUSON & KOZLOV (1973)	PLUMASITIC LEUCOGR.	ULTRA-MM GRANITES			PALINGENIC GRANITES (Normal and Subalkalines)				PLAGIO-GRANITES		AGPAITIC LEUCOGRANITES	
	PEARCE et al. (1984)	COLG - Collision Granites (Syntectonic) (Post-tectonic)							VAG Volcanic Arc Granites		ORG	WPG Within Plate Granites	
ASSOCIATED MINERALIZATIONS	XU KEQIN et al. (1982)	TRANSFORMATION - TYPE (Continental crust)					SYNTEXIS - TYPE (Transitional crust)			MANTLE-DERIVED - TYPE			
TECTONIC ENVIRONMENT	PITCHER (1983 & 1987)	HERCYNOTYPE				CALEDONIAN - TYPE			ANDINOTYPE	W.PACIFIC TYPE		NIGERIA - TYPE	
SUGGESTED SYNTHETIC CLASSIFICATION		MPG		CPG				KCG	ACG	ATG	RTG	PAG	

the criteria used vary from one author to another, it is not easy to specify the relationships between the various typologies (e.g., Takahashi et al., 1980; Bowden et al., 1984; Barbarin, 1990).

The granitoid types proposed in this paper are compared to those of the twenty most used granitoid classifications (Fig. 3). Whatever the criteria and the areas surveyed, the three groups corresponding to the three origins are underlined in most typologies. The limit between granitoids of mixed origin and of mantle origin is identical in almost all typologies. The limit between granitoids of mixed origin and crustal origin is variable from one typology to another. Three explanations may be proposed: (1) the CPG form a complex type with fairly distinct granitoids from one area to another; (2) CPG and KCG both involved a crustal and a mantle component, and even if the proportions of these components are very different, some similarities remain (K-feldspar porphyritic texture and so on...), (3) CPG and KCG often occur in the same orogenic belt, and even in the same area.

Within each of the three main groups defined according to contrasted origins, means of distinction between types are also proposed. The PAG and the RTG or ATG are such distinctive granitoids that there is an agreement between authors. The division of calc-alkaline granitoids into two types is also proposed by many authors: the contrast between ACG and KCG is clearly underlined. Within the group of granitoids of crustal origin, many differences exist from one typology to another. Several authors propose a third type comprising the peraluminous granitoids that are rooted in high-grade metamorphic rocks. This distinction is only based on the emplacement criterion and concerns both MPG and CPG. If it is accepted that either MPG or CPG can be deep-seated and still rooted in high-grade metamorphic rocks, there is no need to have a third type of crustal granitoids.

The S, I, M, A types (Chappell and White, 1974, White and Chappell, 1983) are also reported on Fig. 3. Although these authors do not agree with origins other than crustal for their types, mineral assemblages, field, petrographical and chemical features of these types are very similar to the granitoids of crustal, mixed and mantle origins. In detail, in the Lachlan Fold belt, most S-type granitoids are CPG and only some exceptional are MPG; most I-type granitoids are ACG and only a few are KCG; the A-type are PAG.

The SIMA typology, as many others, is mainly based on geochemical data. Chemical criteria are also used to complement the other data in order to constrain the origins of the MPG, CPG, KCG, ACG, ATG, RTG and PAG types. Geochemical criteria should however be used only with caution because of chemical convergence. For example, granitoids of mixed or mantle origin can acquire peraluminous compositions after extreme amphibole fractionation, volatile interaction, or pelitic rock assimilation (e.g., Clarke, 1992).

6. Granitoid types and geodynamic environments

Many authors have proposed relating granitoid types to tectonic settings (e.g., Floyd and Winchester, 1975; Petro et al., 1979; Pitcher, 1983; Pearce et al., 1984; Maniar and Piccoli, 1989; Barbarin, 1990; Foerster et al., 1997). Relationships that link the main granitoid types to geodynamic environments however remain a subject of controversy. Many petrologists also question the use of granitoids as indicators of geodynamic evolution.

First of all, a granitoid can be used as a geodynamic indicator only when it is correctly typed and

Fig. 3. Comparison between the proposed granitoid typology and the twenty main petrogenetic classifications of granitoids. Leading criteria used by the authors are specified (Lacroix, 1933; Shand, 1943; Didier and Lameyre, 1969; Capdevila et al., 1973; Tauson and Kozlov, 1973; Chappell and White, 1974; Orsini, 1976, 1979; Ishihara, 1977; Collins et al., 1980; de La Roche et al., 1980; Lameyre, 1980; Pupin, 1980, 1988; Czamanske et al., 1981; Didier et al., 1982; Lameyre and Bowden, 1982; Xu et al., 1982; Yang, 1982; Debon and Le Fort, 1983, 1988; Pitcher, 1983, 1987; Pearce et al., 1984; Nachit et al., 1985; Tischendorf and Pälchen, 1985; de La Roche, 1986; Rossi and Chevremont, 1987; Whalen et al., 1987; Maniar and Piccoli, 1989). This table permits correlations between the divisions proposed in the different classifications and in the synthetic granitoid types. (M.A. or A.M.: magmatic associations).

also precisely dated. It is also clear that granitoids should not be used alone but in association with structural data. Many examples exist where there are excellent correlations between the structural, geodynamic and petrologic approaches. In the case of the geodynamic environment of the western Mediterranean Sea and its evolution during Permian and Triassic times, data provided by granitoid typology fit perfectly with structural data (Bonin, 1990). Last, it is important to remember that although the use of granitoid types as geodynamic indicators is incorrect in a few cases, careful application of granitoid types to geodynamic problems is often successful. Granitoids in most cases should be a natural complementary approach to other approaches in the study of the evolution of the geodynamic environments with time.

The combination of petrologic, structural and geodynamical studies indicates that the genesis of the different types of granitoids is strongly constrained by geodynamic environment. A survey of localities where both granitoid types and geodynamic environments at the time of emplacement of these granitoids are well-defined, permits each granitoid type to be related to a specific geodynamic environment (Fig. 4).

The peraluminous granitoids (CPG and MPG) are mainly emplaced where there is crustal thickening resulting from the convergence of two continental lithospheres. The CPG are dispersed through the mountain belt while the MPG are concentrated along the transcurrent shear and thrust zones that crosscut the thick crust (e.g., Barbarin, 1996).

Calc-alkaline and arc «tholeiitic» granitoids (ACG and ATG) are invariably emplaced above subduction zones. The ATG are associated with abundant andesites in volcanic arcs. In the active continental margins, ATG are scarcer and ACG form vast batholiths, elongate parallel to the trench. Huge andesitic volcanoes frequently form the tops of these batholiths. More mature subduction zones are associated with more abundant ACG.

Ridge «tholeiitic» plagiogranites (RTG) are associated with oceanic spreading, whereas alkaline and peralkaline granites and syenites (PAG) are related to continental up-doming and rifting zones.

High-K calc-alkaline granites and granodiorites (KCG) are present in various geodynamic environments. They actually indicate more a variation of the tectonic regimes than a specific geodynamic environment. KCG occur either during periods of relaxation that separate periods of culmination within a collision event, or transition from a compressional regime to a tensional regime (Lameyre, 1988; Bonin, 1990). KCG are thus abundant in the orogenic belts related to continental collision particularly at the time when collision is ending. KCG are also associated with PAG and ACG.

In the literature, some authors who study areas where one of the above granitoid types is particularly abundant, use the tectonic setting to make more

GRANITOID TYPES		ORIGIN	GEODYNAMIC ENVIRONMENT
Muscovite-bearing Peraluminous Granitoids	**MPG**	**CRUSTAL ORIGIN** PERALUMINOUS GRANITOIDS	**CONTINENTAL COLLISION**
Cordierite-bearing Peraluminous Granitoids	**CPG**		
K-rich Calc-alkaline Granitoids (High K - Low Ca)	**KCG**	**MIXED ORIGIN (Crust + Mantle)** METALUMINOUS AND CALC-ALKALINE GRANITOIDS	**TRANSITIONAL REGIMES**
Amphibole-bearing Calc-alkaline Granitoids (Low K - High Ca)	**ACG**		**SUBDUCTION**
Arc Tholeiitic Granitoids	**ATG**	**MANTLE ORIGIN** THOLEIITIC, ALKALINE AND PERALKALINE GRANITOIDS	
Mid-ocean Ridge Tholeiitic Granitoids	**RTG**		**OCEANIC SPREADING OR CONTINENTAL DOMING AND RIFTING**
Peralkaline and Alkaline Granitoids	**PAG**		

Fig. 4. Synthetic table showing the relationships between petrogenetic types, their origins, and the geodynamic environment.

precise distinctions and divide this type into several further types. For example, Eby (1990, 1992) distinguishes several types of PAG and relates each to various tensional regimes. To keep the proposed granitoid typology useful, we prefer to underline the differences between the main types. Further details of each main type can be obtained from the appropriate publications.

7. Granitoid types and the Wilson cycle

The best way to illustrate the strong relationship between granitoid types and geodynamic environments is to detail the successive stages of the cycle of Wilson (1966) and to specify which granitoid types are associated with each of these stages. Case-studies of granitoids are also given for each stage (Fig. 5).

7.1. Continental tension and major rifting

The cycle starts with an eroded continental crust which is involved in a divergence process. During the thinning and fracturing of this continental crust, formation of vast grabens and upwelling of the upper mantle lead to the rise of alkaline magmas along normal faults and the emplacement of peralkaline and alkaline granitoids (PAG).

Among the many cases of PAG provinces, some, such as the following, are very informative.

–Permian PAG of Corsica are associated with the end of the Hercynian orogeny, and the opening of the Tethys. They form ring complexes on the top of which calderas filled with alkaline rhyolites can be locally preserved from erosion (Bonin, 1986, 1988; Egeberg et al., 1993).

–Oligocene PAG are present along the both sides of the Red Sea (Capaldi et al., 1987; Manetti et al., 1991). Emplacement of these Tertiary PAG ends when an oceanic crust starts to form in the Red Sea.

–In Brazil, the Cretaceous Cabo alkaline granite (Sial et al., 1987), which is exposed on the coast about 50 km south of Recife, dates the opening of the southern Atlantic Ocean.

PAG are associated with major continental rift zones. They occur when extension affects continental crust. There are however no further PAG when an oceanic crust starts to form in the area (e.g., the case of the Red Sea).

7.2. Mid-ocean ridges

The plagiogranites (RTG) occur within oceanic crust. Where large amount of tholeiitic mantle-derived magmas are trapped for a period of time beneath mid-ocean ridges, RTG are obtained as a result of extreme fractionation. RTG occur as fairly scarce plagiogranite dikelets in the active oceanic ridges (e.g., Engel and Fisher, 1975; Hedge et al., 1979; Jauzein, 1981). Detailed mapping (Wilson, 1959; Glennie et al., 1974; Pedersen and Malpas, 1984) indicates that although RTG are ubiquitous in most ophiolites, they represent less than 2% of the total exposure of ophiolites.

In the western Jurassic ophiolite belt of Albania, plagiogranites form metric scale dikes to kilometric scale plutons that crosscut all the different levels of the ophiolite except the peridotites (Bébien et al., 1997). RTG are generally emplaced beneath the sheeted-dike complexes.

7.3. Subduction and volcanic arcs

Change in plate motion produces convergence of the two oceanic lithospheres and the formation of volcanic island arcs above the subducted older and thicker plate. The association of calc-alkaline diorites to tonalites and granodiorites (ACG) with minor arc tholeiitic gabbro to quartz-monzodiorites (ATG) are typical plutonic rocks of the volcanic arcs. Their abundance remains however fairly low compared to the abundance of their volcanic counterparts, mainly consisting of calc-alkaline and tholeiitic basalts and some andesites.

In the many island arcs that surround the Pacific Ocean, ACG are fairly common (Perfit et al., 1980; Chivas et al., 1982; Whalen, 1985), whereas only a few ATG are described (Kay et al., 1983). ACG and ATG generally form shallow level plutons and are closely associated with volcanic rocks. All these Tertiary igneous rocks are comagmatic: they share similar chemical and isotopic signatures and same mantle origin. Nevertheless, they are differently fractionated and ACG can also involve some magma

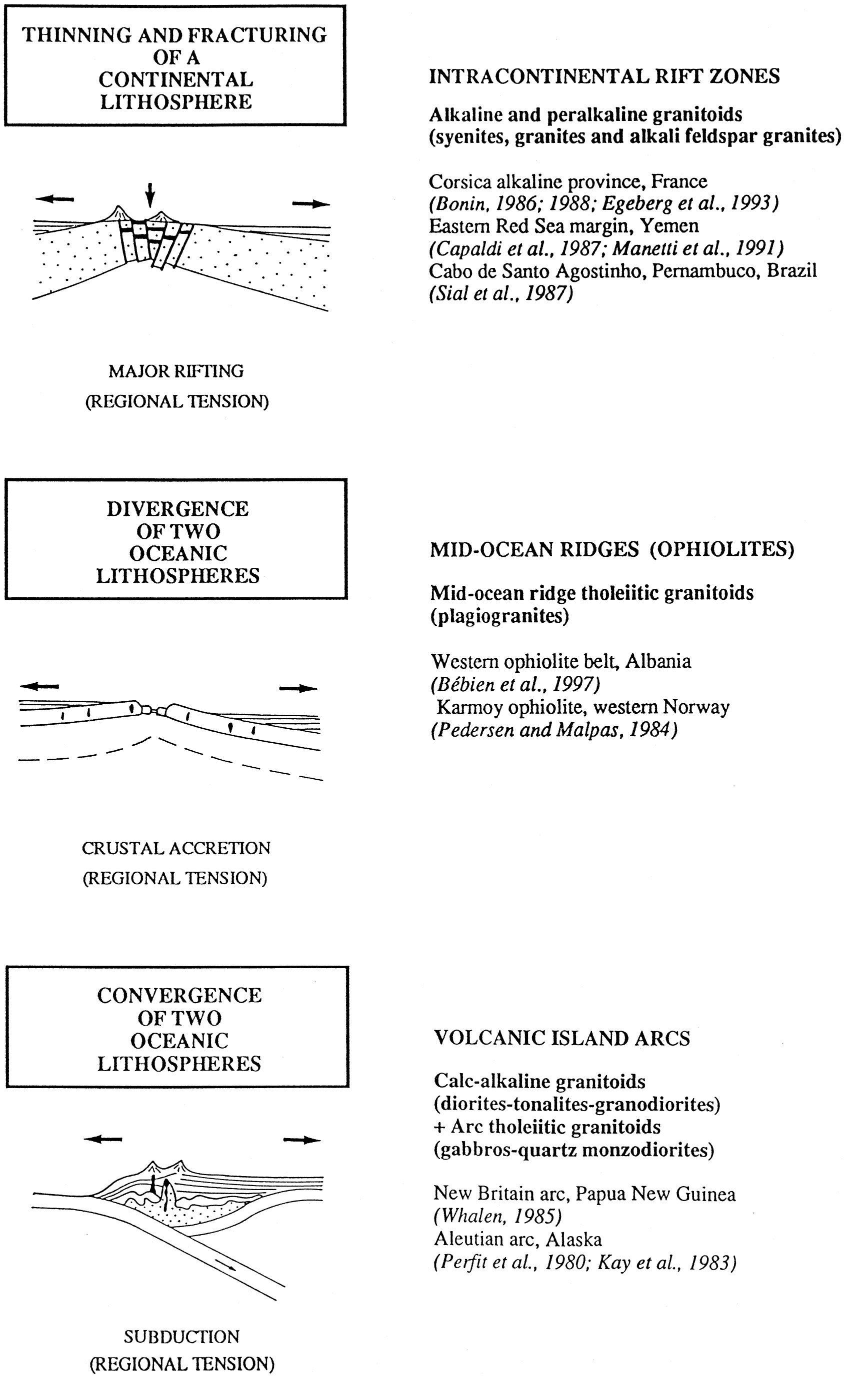
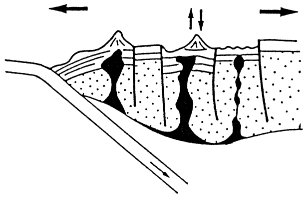


Fig. 5. The various granitoid types associated with successive stages of a Wilson cycle. Granitoid bodies are in black in the successive cross sections. For each stage, the nature of the lithospheres involved, plate motion, tectonic regimes, granitoid types and case-studies are specified.

CONVERGENCE OF OCEANIC AND CONTINENTAL LITHOSPHERES



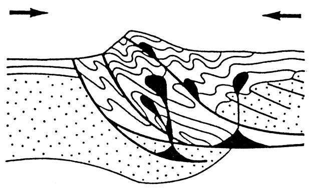
SUBDUCTION
(REGIONAL TENSION)

ACTIVE CONTINENTAL MARGINS

Calc-alkaline granitoids
(tonalites-granodiorites)
± K-rich calc-alkaline granitoids
(monzogranites)

Coastal batholith, Peru, and Patagonian batholith, Chile
(Pitcher et al., 1985; Bartholomew and Tarney, 1984)
Sierra Nevada batholith, California
(Bateman, 1983, 1992)

CONVERGENCE OF TWO CONTINENTAL LITHOSPHERES



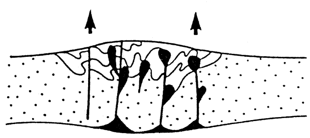
COLLISION
(REGIONAL COMPRESSION)
(LOCAL TENSION)

COLLISIONAL OROGENS

Peraluminous granitoids
(granodiorites and leucogranites)
+ K-rich calc-alkaline granitoids
(monzogranites)

Massif Central and Brittany, France
(Lameyre et al., 1980; de La Roche et al., 1980)
High Himalaya leucogranites
(Le Fort, 1981)
Lachlan Fold belt S-type granitoids, Australia
(Chappell and White, 1992)

RELAXATION OF A CONTINENTAL LITHOSPHERE



POST COLLISION UPLIFT
(REGIONAL TENSION)

FORMER COLLISION BELTS

K-rich calc-alkaline granitoids
(monzogranites)

Caledonian plutons of the northern British Isles
(Halliday and Stephens, 1984)
Ploumanac'h intrusive complex, Brittany, France
(Barrière, 1977)
Ballons intrusive complex, Vosges, France
(Pagel and Leterrier, 1980)
Montagne Bourbonnaise plutons, Massif Central, France
(Lameyre et al., 1980; Barbarin, 1983)

Fig. 5 (continued).

mixing. Even if ATG do not represent the dominant magmatic contribution, like the ACG, they participate to the genesis of new continental crust in volcanic arc subduction zones.

Above subduction zones, both in the volcanic arcs and the active continental margins, a very specific type of granitoids consists of the Archean TTG (trondhjemites–tonalites–granodiorites) and their modern equivalents, the adakitic granitoids (Martin, 1987, 1998). These Na-rich granitoids are directly produced through melting of the subducted oceanic crust and not of the mantle wedge above (Martin, 1998). Although they share many features with the ACG and ATG, they are neither ACG nor ATG because they do not originate in the upper mantle or the continental crust, but in the oceanic crust.

7.4. Subduction and active continental margins

Convergence of oceanic and continental lithospheres mainly generates abundant low-potassium and high-calcium calc-alkaline tonalites and granodiorites (ACG). Batholiths consisting of clusters of hundreds of ACG plutons, form cordillera which extend over hundreds of kilometres, parallel to the continental margins and the trenches (e.g., Pitcher, 1993). Above these subduction zones, cordilleran ACG batholiths only occur where the voluminous andesitic volcanoes are reduced by erosion.

In active continental margins, ACG are the most abundant granitoids but other granitoid types are also present. ATG are discrete along the trench where the continental crust begins. Toward the continent, scarce KCG often separate the ACG from the PAG associated with back-arc basins. The large variety of granitoids and spatial zonation successively with, from the trench, some ATG, abundant ACG, rare KCG and some PAG, are typical of an active continental margin.

Above the subduction zone, there is alternatively tension and compression (Pitcher, 1993). Magmas, mainly from the melting of the mantle wedge, are trapped at the interface between upper mantle and crust during the compression period: there, they pond, differentiate and also mix with crustal magmas produced by melting of crustal materials, induced by contact with large volumes of hot mafic magmas.

Various types of granitoids are present in the Coastal batholith of Peru (Pitcher et al., 1985) and the Patagonian batholith of Chile (Bartholomew and Tarney, 1984). These Mesozoic granitoids and mainly the abundant ACG contribute to the formation of the thick Andean continental crust ($>$ 60 km). The Sierra Nevada batholith of California consists mainly of some Jurassic and abundant Cretaceous ACG (Bateman, 1983, 1992). Within the $700 \times \sim 100$ km Cretaceous batholith, there are two types of zonation. The regional zonation consists of a change in the chemical and isotopic compositions from the western gabbros and tonalites to the eastern mafic to felsic granodiorites. The easterly increase in K-content, Sr_i (Kistler and Peterman, 1973), and decrease in ε_{Nd} (Bennett and DePaolo, 1987) are clearly related to crustal thickening and the involvement of more crustal materials in the genesis of the calc-alkaline granitoids. Mainly on the east side of the batholith, each intrusive suite is also zoned. In the normally-zoned Tuolumne Intrusive complex, from the margins toward the centre occur successively the tonalite of May Lake, the mafic granodiorite of Half Dome, the felsic and K-feldspar porphyritic granodiorite of Cathedral Peak, and the Johnson monzogranite (Bateman and Chappell, 1979).

Several granitoid types are present in the active continental margins which, however, display a neat zonation. Although components of various origins are involved in their genesis, the cordilleran ACG display fairly homogeneous compositions. These cordilleran granitoids represent the most important contribution of the mantle to the genesis of the continental crust.

7.5. Collision between two continental lithospheres

Where there is no more oceanic crust and continental collision replaces subduction, melting of continental crust produces peraluminous granitoids (MPG and CPG) and also participate to the generation of K-rich calc-alkaline granitoids (KCG). MPG, CPG and KCG are scattered throughout the mobile belt and there is no real spatial organisation. The MPG will occur where the thick continental crust is crosscut by major shear and thrust zones, while the CPG form either vast and thin laccoliths or rounded-shape plutons, locally rooted in the high-grade metamorphic rocks (e.g., Lameyre et al., 1980). The CPG and MPG are associated with the climax of orogenesis, while the KCG are supposed to have emplaced during the relaxation phases. As in the active continental margins, magmas form during the compressive tectonics and are only emplaced when there is tension either along some shear zones (trans-tension) or during local relaxation. Activity of a convergence zone probably consists of successive periods of compression and piling of the crustal fragments on one hand, and tension on other hand, to permit respectively genesis of magmas and alternating emplacement of peraluminous granitoids and KCG. When KCG become largely dominant, then the convergence geodynamic declines before completely stops. The KCG are commonly considered to be postorogenic rocks although they can also have the same ages as the peraluminous granitoids (e.g., Lameyre et al., 1980).

The three types of granitoid occur in the portion of the Hercynian belt of Western Europe formed by Brittany and the Massif Central, France (Lameyre et al., 1980; de La Roche et al., 1980; Didier et al., 1982; Barbarin, 1992). MPG are invariably rooted in the major ductile shear zones of either transcurrent or overthrust type (e.g., the leucogranites along the South Armorican Shear Zone, or in the Limousin, western part of the Massif Central). The CPG form vast laccoliths (e.g., Margeride or Guéret) or anatectic complexes (e.g., Velay). The CPG are frequently K-feldspar porphyritic because they are fairly rich in potassium. They are also locally enriched in magnesium (e.g., Margeride pluton: Couturié, 1977).

The Lachlan Fold Belt in south-eastern Australia contains huge quantities of CPG, the so-called S-type granitoids (e.g., Chappell and White, 1992a,b). These Caledonian CPG differ from the Hercynian CPG because of the cordierite-richness and ubiquity, of the quartz abundance, of their emplacement as batholiths, and of the abundance of their enclaves, and especially of the restitic enclaves. Furthermore, MPG are exceptional in the Lachlan Fold Belt (e.g., Chappell and White, 1992a,b; Barbarin, 1992). The Lachlan Fold Belt is not unique in the world because, for example, in north-eastern Brittany, the Cadomian granitoids of the Mancellia province (Lameyre et al., 1980; Jonin, 1981) bear many resemblances to the S-type granitoids of the Lachlan Fold Belt, including abundance and ubiquity of prismatic cordierite, abundance of enclaves, no MPG, emplacement as parallel batholiths. S-type CPG are not only present in the Cadomian belts. Some are exposed in the Iberian portion of the Hercynian belt of Western Europe (e.g., Layos pluton: Barbero and Villaseca, 1992a,b).

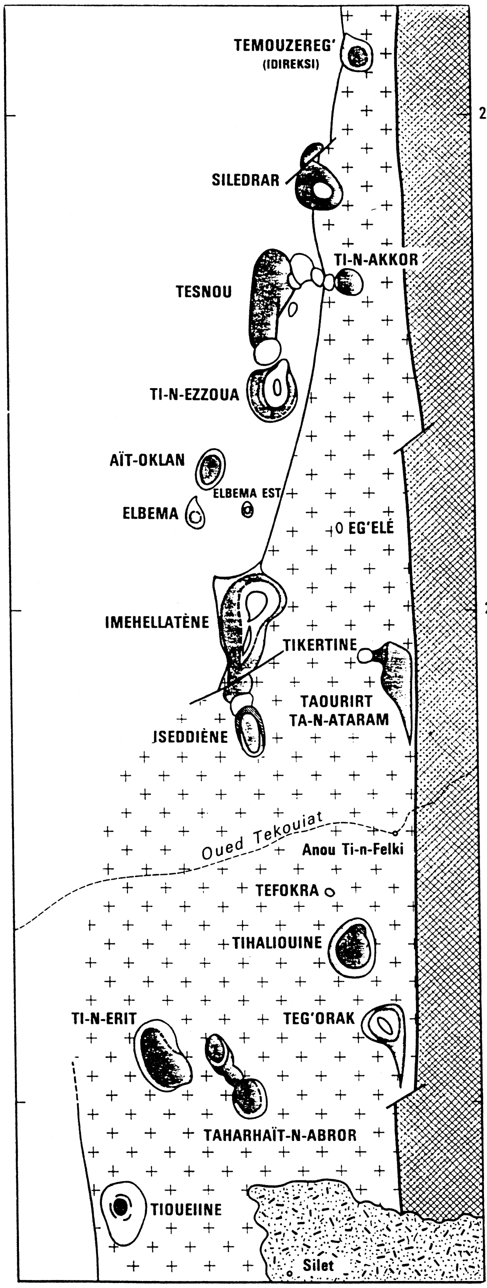
In contrast to the Lachlan Fold Belt, there is no CPG in the Higher Himalaya, but only MPG, such as the Manaslu leucogranite that are emplaced above the Main Central Thrust (Le Fort, 1981; Le Fort et al., 1987).

In the three cases of collision belts, the nature and abundance of the two types of peraluminous granitoids differ considerably. The three collision events do not have the same age (Caledonian, Hercynian, and Alpine) and do not affect the same terranes. An alternative possibility is that the different granitoid associations can also be related to distinct structural levels of a continental collision-related orogenic belt. The Himalayas may represent the upper levels; only the intrusive MPG are present. Brittany and the Massif Central may represent the middle levels; MPG, roots of these MPG, and intrusive CPG are associated. The Lachlan fold belt may represent the lower levels: only the CPG are present and some roots of the CPG are reached.

7.6. Post collision uplift

After collision, erosion continues on and during continental uplift, KCG become especially abundant. These K-feldspar porphyritic granitoids contain either white or pink K-feldspar megacrysts. They are scattered through the former orogenic belt and frequently crosscut the synorogenic granitoids. KCG plutons are fairly common in the Caledonian belt of the northern British Isles (e.g., Brown et al., 1981; Halliday and Stephens, 1984) and in the Hercynian belt of Western Europe (e.g., Barrière, 1977; Pagel and Leterrier, 1980; Lameyre et al., 1980; Barbarin, 1983).

KCG are also associated with some PAG in the back-arc basins and in the areas where old cratons are involved in regional tension. In the eastern margin of the West African craton, in the Sahara desert, KCG are combined with PAG to form ring complexes (e.g., Boissonnas, 1980; Liégeois et al., 1987). These granitoids represent the last magmatic events of Panafrican orogenesis. In many cases, KCG are emplaced where there is transition from continental plate convergence to continental plate divergence. These granitoids may be good indicators of major changes in the geodynamic environment.



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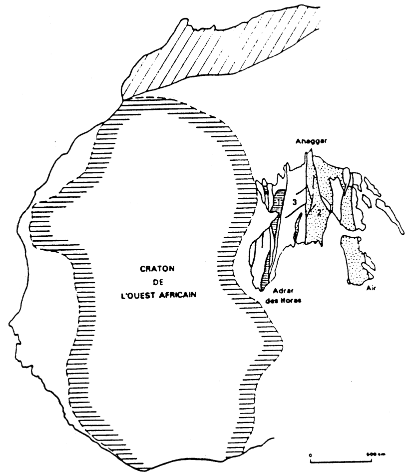

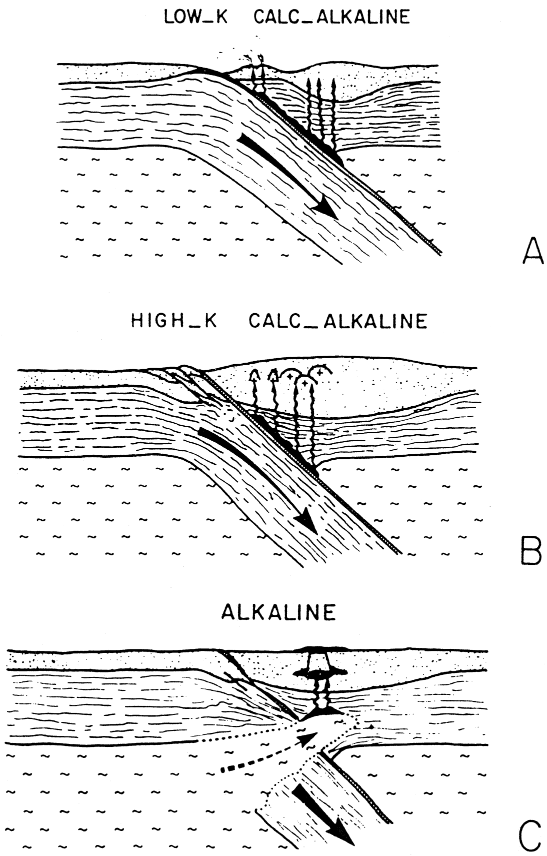

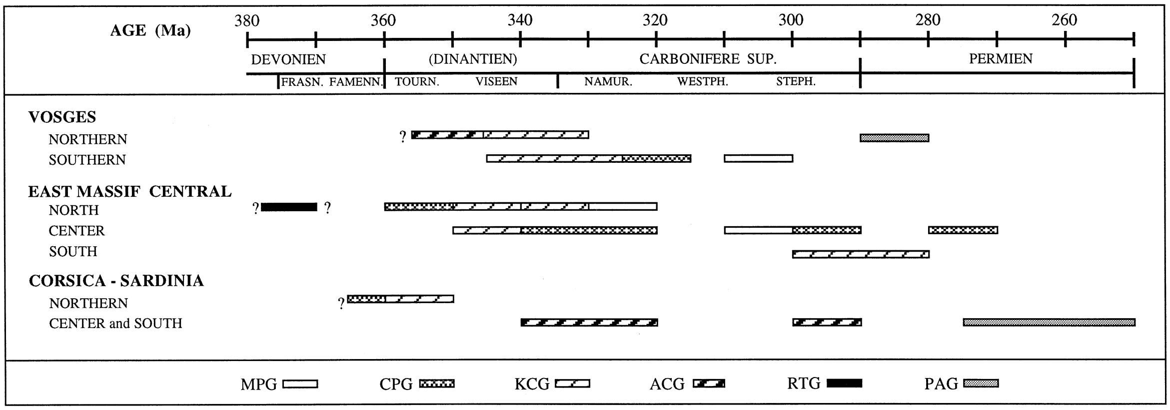

Fig. 7. Successive granitoid types emplaced during Upper Palaeozoic in a portion of the Hercynian belt consisting of the Vosges, the Eastern Massif Central, and the Corsica-Sardinia bloc. The different granitoid types and their succession provide information on the evolution of the Hercynian belt, on the location of the various tectonic events, and on their activity through time.

7.7. End of erosion and beginning of a new cycle

The continental crust is now ready for a new Wilson cycle.

A special association of granitoid types clearly characterises each stage of the cycle of Wilson (1966). Well-typed granitoids can then facilitate constraining the geodynamic environment in which they are emplaced.

8. Granitoids as tracers of geodynamic evolution

In some geodynamic environments, there is a clear spatial zonation of the various granitoid types. A time-related zonation can also occur between types from the same area. In this case, the succession of the granitoid types indicates changes in the geodynamic environment.

Taking a very simple case, in the western part of Ahaggar and in the Adrar des Iforas, huge ACG batholiths are crosscut by ring complexes consisting of KCG and PAG (Fig. 6); this time-related succession from low-K calc-alkaline, through high-K calc-alkaline, to alkaline granitoids is produced by the transition from subduction-related magmatism to within-plate magmatism by the end of the Panafrican orogenesis (Liégeois and Black, 1984; Azzouni-Sekkal and Boissonnas, 1993).

Another case study is the granitoids of France. Typology and ages of the main granitoid plutons provide the following history for the portion of the internal zone of the Hercynian belt of Western Europe, consisting of the Vosges, the eastern part of the Massif Central, and the Corsica and Sardinia unit (Fig. 7). ACG and PAG are present only on the margins of this segment. In the northern Vosges, the ACG were emplaced around 350 Ma and are quickly replaced by KCG; after a long period without magmatism, some PAG occur between 290 and 280 Ma. In the major part of Corsica and Sardinia, the ACG were emplaced at about 335 Ma, but they lasted longer and were replaced by abundant PAG only between 275 and 250 Ma. The central part of the segment does not contain ACG and PAG but abun-

Fig. 6. Granitoid exposures on a detailed map of the western Ahaggar, Algeria (Boissonnas, 1980). Ring complexes consisting of KCG (high-K calc-alkaline granitoids: black) and PAG (alkaline granitoids: white) intrude the huge ACG batholith (low-K calc-alkaline granitoids: crosses). Model proposed by Liégeois and Black (1984) to explain the same successive emplacement of ACG (A), KCG (B) and PAG (C) to the south, in the Adrar des Iforas, Mali.

dant CPG, MPG and KCP. Magmatism started at about 360 Ma with emplacement of some CPG. Many KCP indicate that there was some relaxation in the orogenic belt around 340 Ma. Emplacement of abundant CPG and MPG between 320 Ma and 300 Ma can be related to a climax in the collision mainly in the north part of the belt. The last magmatic event in the eastern Massif Central consists in the emplacement of the huge Velay anatectic dome between 280 and 270 Ma. In this case, the history provided by the various types of granitoids does not vary from the evolution or history constrained by structural geology, or the petrology of metamorphic rocks.

Many other cases can be cited to emphasise the use of granitoid types as tracers of geodynamic evolution.

9. Discussion

The main granitoid types are not randomly distributed in the various geodynamic environments. There is clear evidence of strong relationships between granitoid types and geodynamic environments. Furthermore, most geodynamic environments are not characterised by a single granitoid type, but by an association of several types, which in some cases, display a well-defined spatial zonation.

The proposed typology is based on the concept of plate tectonics and most case-studies refer to late-Precambrian to recent granitoids. Older granitoids can however be typed using the same criteria as the ones used for much younger granitoids because the plate tectonic paradigm can be applied back to the early Precambrian (Windley, 1993) and because tectonophysical and geochemical processes that produced granitoids since the early Archean have not been fundamentally different from those that operate since the Palaeozoic (Black and Liégeois, 1993). Nevertheless, only some Panafrican-Brasiliano and Eburnean-Transamazonian granitoids have been used convincingly as tracers of tectonic environment (e.g., Black and Liégeois, 1993; Yobou, 1993). The Geodynamic settings of various 2 Ga granitoids from central Ivory Coast, Africa, were obtained from the application of the proposed typology (Yobou, 1993). Users of the typology should however keep in mind that, in subduction zones for instance, the petrogenesis of Archean granitoids and younger granitoids are fairly different (Martin, 1987). In Brazil, granitoids are especially abundant and display a wide variety both in type and age. Brazil might then represent an excellent place in which to test the use of the proposed typology and to confirm that Precambrian granitoids could be good geodynamic tracers as are more recent granitoids.

When using granitoid types as geodynamic tracers, one should also keep in mind the importance of their age. Two identical types may yield fairly different ages within the same belt. Granitoids are emplaced where the generation of magmas at depth and the existence of conduits combine to allow the upward intrusion of these magmas. These two conditions do not invariably exist at the same time in the different portions of the belt. Furthermore the geodynamic environment may also be somewhat distinct in the different segments of the belt for a given time. In the Hercynian granitoids of Western Europe, the various types do not occur exactly at the same time in the different areas of the small segment consisting of the Vosges, the eastern part of the Massif Central, and the Corsica and Sardinia unit (Fig. 7).

10. Conclusions

Granitoids can be divided into several types:

– muscovite-bearing peraluminous granitoids (MPG),
– cordierite-bearing and biotite-rich peraluminous granitoids (CPG),
– K-rich and K-feldspar porphyritic calc-alkaline granitoids (KCG),
– amphibole-rich calc-alkaline granitoids (ACG),
– arc «tholeiitic» granitoids (ATG),
– ridge «tholeiitic» granitoids (RTG),
– peralkaline and alkaline granitoids (PAG).

The proposed typology, which shares many similarities with former genetic classifications, has many advantages:

– it is not defined for granitoids from a specific or limited area;
– it is based on an extensive combination of criteria, from mineral assemblages, through field, petrographical, chemical and isotopic, to structural features;

–the dominant criteria, which are the mineral assemblages combined with field and petrographical data, can be used in the field to achieve a broad discrimination;
–the number of types is reasonably practical;
–it provides information on the origin of the magmas and clearly distinguishes three origins (purely or mainly crustal, purely or mainly mantle, and mixed origin with combination of crustal and mantle components);
–it also provides information on the geodynamic environment in which the magma was generated and emplaced, and on its evolution.

Each type is both indicative of the origin, evolution, and geodynamic environment. There is a consensus concerning the origin of granitoids for the majority of petrologists. The proposed typology can then be considered as a basic material refining our understanding of the relationships between granitoid types and for dynamic environment.

One will also find some rare granitoids that share the characteristics of two of the proposed types. This can happen because some granitoids can represent transitional types, considering that granitoids form a continuum from a purely crustal pole to one or two purely mantle poles, and that division into types is artificial but necessary considering the wide variety of granitoid rocks. As an example, the genesis and evolution of a cordierite-bearing and biotite-rich peraluminous granitoid is completely different from the genesis and evolution of an amphibole-bearing calc-alkaline granitoid or a peralkaline granitoid. Many controversies or debates about granitoids have mainly resulted from the absence of clear distinction between granitoid types.

Because granitoids are the main component of the continental crust, and because of the strong link between their mineralogical assemblages, petrogenetic types, the origin of the magmas, and their geodynamic settings, granitoids correctly typed and with well-defined ages may constrain the evolution and development of the continental crust through geological times.

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